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"Neck" Formation and Fragmentation in Intermediate Energy Heavy-ion Collisions

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Under different impact parameters, the collision system of 30 MeV/u ^{40}Ca + ^{40}Ca is investigated in terms of the QMD model. It is shown that the number of IMFs is largest at impact parameter $b = 6$ fm, which is due to the formation of "neck" in the collision process. It is also found that, in the process of the formation of "neck," the growth of the relative density fluctuation of the reaction system is very slow and the saturation value is small, which imply the character of the shape instability.

Key words: "neck" fragmentation, intermediate mass fragment, relative density fluctuation, shape instability, dynamical instability.

1. INTRODUCTION

The emission of intermediate mass fragments (IMFs) is a very hot topic in recent years. Multifragmentation in this area of research means that the excited nuclear system decays simultaneously into several IMFs. Many theories have been proposed to explore the mechanism of IMF emission and the mechanism includes two main viewpoints, namely, dynamical fluctuation and statistical de-excitation of a hot nucleus. The established physical pictures on the production of IMFs mainly focus on the central collisions, which are related to the global instability, i.e., the spinodal instability. In recent years, it has been found that the shape instability is also an interesting mechanism of IMF emission [1–5]. For instance, the exotic structures which are formed in central collisions, such as

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Bubble, Ring and Disklike, are all beneficial to the production of IMFs. In the peripheral collisions, especially at lower energies, the formation of "neck" is also a possible method of producing IMFs.

"Neck" wan first found in low energy deep inelastic collisions (DIC) [6]. In DIC, projectile-like and target-like residual nuclei connect each other by "neck" structure and exchange nucleons, energies, angular momentum, mass, and charges. "Neck" structure is formed at the moments when the projectile and target are going to touch or to separate each other. At the later stage of the reaction, the surface instability is amplified so that "neck" structure decays resulting in the dissociation of the projectile-like and target-like nuclei. In peripheral collisions at intermediate energies, as a mechanism of IMF emission, "neck" decay is a very interesting problem for theoretical and experimental nuclear physicists recent years.

In intermediate energy heavy-ion collisions, the "neck" structure favors the emission of IMF. To study the formation and decay of "neck," therefore, is very significant for the investigation of multifragmentation. For that, at different impact parameters, the collision system of 30MeV/u ^{40}Ca + ^{40}Ca is investigated in terms of the QMD model. It is shown that the number of IMFs is the largest at impact parameter $b = 6$ fm and the formation and decay of "neck" is clearly found in the collision process. It is also found that, in the formation process of "neck," the exponential growth of the relative density fluctuation of the reaction system is very slow and the saturation value is small, which imply the character of shape instability.

2. MODEL AND METHOD

In the quantum molecular dynamics (QMD) model, the Wigner density distribution function of the reaction system in phase space is

$$f(\boldsymbol{r},\boldsymbol{p},t) = \sum_i f_i(\boldsymbol{r},\boldsymbol{p},t) = \sum_i \frac{1}{(\pi\hbar)^3} \exp\{-[\boldsymbol{r}-\boldsymbol{r}_i(t)]^2/(2L) - [\boldsymbol{p}-\boldsymbol{p}_i(t)]^2 2L/\hbar^2\}, \quad (1)$$

where $\boldsymbol{r}_i$ and $\boldsymbol{p}_i$ represent the mean position and momentum of the ith nucleon, respectively, L is the so-called Gaussian wave packet width (here $L = 2.0$ fm^2). Equation (1) indicates that each nucleon represents a double-Gaussian in the phase space. The $\boldsymbol{r}_i$ and $\boldsymbol{p}_i$ satisfy the canonical equation of motion and the hamiltonian is given by

$$H = \sum_i \frac{\boldsymbol{p}_i^2}{2\mu} + U^{dd} + U^{Yuk} + U^{Coul} + U^{sym}, \quad (2)$$

with μ the mass of a nucleon, U^{dd} the density-dependent (Skyrme) potential, U^{Yuk} the Yukawa (surface) potential, U^{Coul} the Coulomb energy, and U^{sym} the symmetry energy term. For the forms and parameters of U^{Yuk}, U^{Coul}, U^{sym} and U^{dd}, one can refer to Ref. [7]. The symmetry energy strength $C = 0$ since the reaction of symmetrical system ^{40}Ca + ^{40}Ca is studied here.

In the N–N collision process, we use the experimental parameterization of N–N cross sections as in Ref. [7].

It is well known that the mean field fluctuation reflects the dynamical fluctuation and the density fluctuation reflects the mean field fluctuation. According to the statistical method, the fluctuation of density distribution can be described by the second density moment which is defined as

$$\sigma^2 = \langle\rho^2(t)\rangle - \langle\rho(t)\rangle^2, \quad (3)$$

Then, the relative density fluctuation can be described as

$$\sigma_\rho^2 = \frac{\langle\rho^2(t)\rangle}{\langle\rho(t)\rangle^2} - 1, \quad (4)$$

Table 1
The mean multiplicity of IMFs at different impact parameters.

b(fm)	0	1	2	3	4	5	6	7	8
$\langle M_{\mathrm{IMF}} \rangle$	1.196	1.238	1.231	1.378	1.353	1.231	1.413	1.113	0.320

The forms of $\langle \rho(t) \rangle$ and $\langle \rho^2(t) \rangle$ can be found in Ref. [8]. In numerical simulation of the QMD model, the relative density fluctuation is

$$\sigma_\rho^2 = \frac{1}{N_{\mathrm{run}}} \sum_{n=1}^{N_{\mathrm{run}}} \left[\frac{\langle \rho^2(t) \rangle_n}{\langle \rho(t) \rangle_n^2} - 1 \right], \tag{5}$$

where N_{run} is the event number of the simulation. It has been shown that the relative density fluctuation grows exponentially and then saturates after a certain time. Moreover, the multiplicity of IMF depends on the saturation value [8].

In the collision process, we consider the formation of clusters as in Ref. [9] with the critical distance taken as $d_{\mathrm{cr}} = 3.5$ fm here. For the reaction system of ^{40}Ca + ^{40}Ca, the size region of IMFs is defined as $3 \leq Z \leq 12$, which is enough to discard any α's, protons, and the residual nuclei of evaporation [10]. Here Z is the charge number of clusters.

3. RESULTS AND DISCUSSIONS

Under different impact parameters and at energy of 30 MeV/u, the collision system of ^{40}Ca + ^{40}Ca is systematically studied in terms of the above model. All the following calculations correspond to 50 events. Table 1 shows the mean multiplicity of IMFs ($\langle M_{\mathrm{IMF}} \rangle$) at different impact parameters. From Table 1, one can see that $\langle M_{\mathrm{IMF}} \rangle$ changes very little at b = 0–5 fm and reduces clearly at b = 7 and 8 fm and maximizes at b = 6 fm. Here, $\langle M_{\mathrm{IMF}} \rangle$ increases in peripheral collisions, which is completely different from that at high energies. For example, for the collision system of 400 MeV/u ^{197}Au + ^{197}Au, $\langle M_{\mathrm{IMF}} \rangle$is small in nearly central collisions because of vaporization of the reaction system, while in peripheral collisions $\langle M_{\mathrm{IMF}} \rangle$ is large because of the contribution of spectators. Is the maximum $\langle M_{\mathrm{IMF}} \rangle$ at b = 6 fm due to the formation of "neck" structure at the collision process? In heavy-ion collisions at intermediate energies, especially around the Fermi energy, DIC is still an

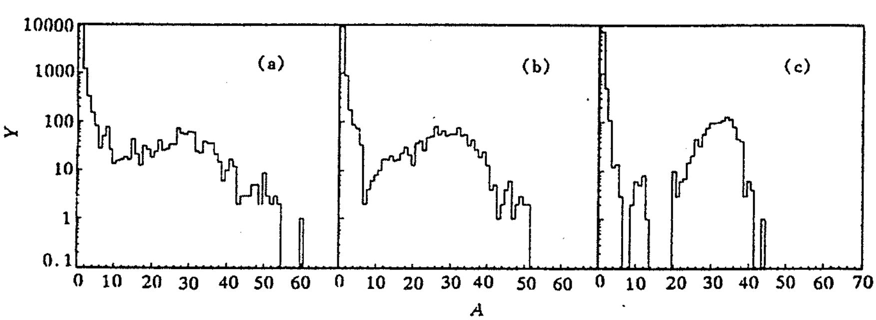

Fig. 1
The mass distributions of reaction system of 30 MeV/u ^{40}Ca + ^{40}Ca at different impact parameters:
(a) b = 6 fm; (b) b = 7 fm; and (c) b = 8 fm.

important reaction mechanism. Comparing to the low energy DIC case, the main difference in the intermediate energy DIC is that IMFs become an important component of the mass or charge distribution. At energy of 30 MeV/u and b = 6–8 fm, the ^{40}Ca + ^{40}Ca collision displays the mixture of DIC character and fragmentation. Figures 1(a)–1(c) show the mass distributions at b = 6–8 fm, respectively. It can be seen from Fig. 1, that in the case of b = 6 fm, there are many IMFs and the reaction mechanism mainly includes DIC and fragmentation, as well as a small incomplete fusion (ICF) component. In the case of b = 7 fm, the multiplicity of IMFs is reduced and the reaction mechanism mainly includes DIC along with a small fraction of ICF and fragmentation. In the case of b = 8 fm, there are even fewer IMFs and DIC is the absolutely dominant component.

At b = 6 fm, it can be assumed that IMFs mainly come from projectile fragmentation in DIC and "neck" fragmentation; meanwhile, pre-equilibrium emission and de-excitation evaporation of projectile -like and target-like residual nuclei only contribute very few IMFs since the excitation energy is too low at the beam energy of 30 MeV/u to evaporate IMFs. In order to investigate the geometry structure and time scale of the formation of "neck" in the collision process, Fig. 2 gives the time evolution of the density contour line in the reaction plane (corresponding to a single event). From Fig. 2, one can see clearly the geometry structure and time scale of "neck" formation and decay. About t = 80 fm/c the "neck" structure begins to form and until t = 160 fm/c it begins to decay into IMFs. Meanwhile, one can see a few small fragments emitted from projectile-like and target-like residual nuclei. These features indicate that "neck" fragmentation is an interesting mechanism of IMF emission.

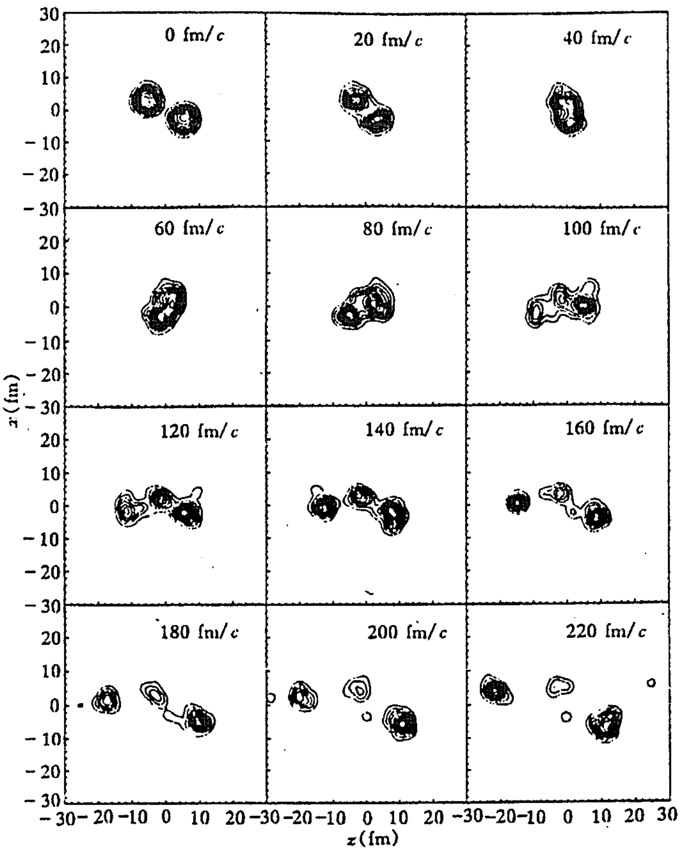

Fig. 2
The time evolution of density contour line in reaction plain.

In order to explore the relation between shape instability and dynamical instability, we study systematically the reaction system of 30 MeV/u ^{40}Ca + ^{40}Ca at different impact parameters by means of the relative density fluctuation analysis method [8]. The different growing situations of relative density fluctuation may be a way to distinguish the IMFs which come from "neck" decay or fragmentation induced by spinodal instability (dynamical instability). The relative density fluctuation induced by spinodal instability should grow exponentially while that induced by "neck" fragmentation should be very complicated and the growth should be slow since "neck" fragmentation results from shape or geometric instability. Figure 3 shows the time evolutions of relative density fluctuation at b = 0, 2, 4, 6, and 8 fm. From Fig. 3, one can see that at different impact parameters the relative density fluctuation exists exponential growth in a certain time region and then basically enters a saturation region. In the exponentially growing region, we can perform the least-square fit with formula

$$\sigma_\rho^2 = A\exp\left(\frac{t}{\tau}\right) \tag{6}$$

where A is a constant and τ is the relaxation time which reflects the growth velocity of the relative density fluctuations. The smaller the τ is, the faster the relative density fluctuation grows. The mean saturation value of relative density fluctuation is defined as an arithmetic mean of the relative density fluctuation at the saturation region. Table 2 provides the relaxation times and mean saturation values of relative density fluctuation at different impact parameters. From Table 2, one can see that the mean saturation value at b = 6 fm is less than those at b = 0–5 fm, which implies that the maximum $\langle M_{IMF} \rangle$ at b = 6 fm is not completely due to the dynamical instability. Meanwhile, it can be seen from Table 2 that at b = 6 fm the relaxation time is the longest, about 134 fm/c. The above results indicate that at b = 6 fm there exists a cold mechanism of IMF emission, i.e., "neck" fragmentation, which results from shape instability. In the formation process of "neck" structure, the relative density fluctuation grows slowly and the mean saturation value is small.

To distinguish the IMFs which come from "neck" fragmentation or spinodal instability is still a very difficult task and here IMFs mainly come from these two aspects. However, from the calculations it is found that there are about 7 "neck" fragmentation events in 50 events at b = 6 fm. Therefore, it could be roughly estimated that, in the peripheral collisions around the Fermi energy, about one-seventh of the IMFs come from "neck" fragmentation.

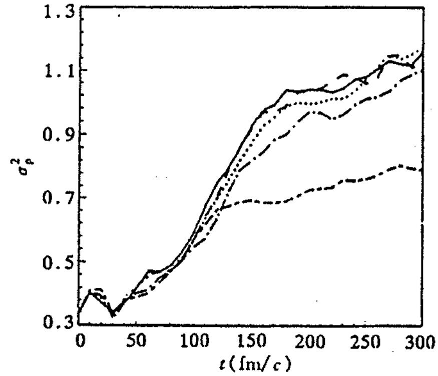

Fig. 3
The time evolutions of relative density fluctuation at different impact parameters.

Table 2
The relaxation times and mean saturation values of relative density fluctuation at different impact parameters.

b(fm)	0	1	2	3	4	5	6	7	8
τ(fm/c)	114.2	103.0	105.8	122.6	117.8	119.0	133.7	125.4	116.5
Mean saturation values	1.071	1.103	1.069	1.059	1.056	1.004	0.972	0.881	0.738

4. CONCLUSIONS

Under different impact parameters, the collision system of 30 MeV/u ^{40}Ca + ^{40}Ca has been investigated in terms of the QMD model. It is shown that the number of IMFs is the largest at impact parameter $b = 6$ fm, which is due to the "neck" fragmentation. From the time evolution of density contour line in the reaction plane, one can see clearly the geometry structure and time scale of "neck" formation and decay, e.g., about $t = 80$ fm/c, the "neck" structure begins to form and until $t = 160$ fm/c it begins to decay into IMFs.

Using the relative density fluctuation analysis method, we have studied systematically the reaction system of 30 MeV/u ^{40}Ca + ^{40}Ca at different impact parameters. It is found that at $b = 6$ fm the exponential growth of relative density fluctuation is very slow and the saturation value is small, which implies strongly that at $b = 6$ fm there exists a cold mechanism of IMF emission, e.g., "neck" fragmentation, which results from the shape instability. In addition, a rough estimation indicates that in the peripheral collisions around the Fermi energy, about one-seventh of the IMFs come from "neck" fragmentation.

The investigation in this paper may provide some probable information to the "neck" decay experiments at intermediate energy DIC.

REFERENCES

[1] L.G. Morreto *et al.*, *Phys. Rev. Lett.*, **69**(1992), p. 1884.
[2] W. Bauer, G.F. Berstch, and H. Schulz, *Phys. Rev. Lett.*, **69**(1992), p. 467.
[3] D.E. Fields *et al.*, *Phys. Rev. Lett.*, **69**(1992), p. 3713.
[4] M. Colonna *et al.*, in: *32nd Inter. Winter Meeting on Nucl. Phys., Bormio, Italy, 24-28 Jun. 1994*, p. 232.
[5] C. Montoya *et al.*, in: *32nd Inter. Winter Meeting on Nucl. Phys., Bormio, Italy, 24-28 Jun. 1994*, p. 506.
[6] W.U. Schroder and J.R. Huizenga, in: *Treatise on Heavy-Ion Science*, vol. 2, edited by D.A. Bromley, Plenum: New York, 1984, and references therein.
[7] Chen Liewen, Zhang Xiaodong, and Ge Lingxiao, *High Energy Phys. and Nucl. Phys.* (Chinese Edition), **20**(1996), p. 1091.
[8] Zhang Xiaodong and Ge Lingxiao, *High Energy Phys. and Nucl. Phys.* (Chinese Edition), **19**(1995), p. 951.
[9] H. Horiuchi, T. Maruyama, and A. Ohnishi, in: *Inter. Symp. on Heavy-Ion Phys. and Application, Lanzhou, China, Oct. 1990*, p. 25.
[10] K. Hagel *et al.*, *Phys. Rev. Lett.*, **68**(1992), p. 2141.
[11] M.B. Tsang, in: *32nd Inter. Winter Meeting on Nucl. Phys., Bormio, Italy, 24-28 Jun. 1994*, p. 512.