High Energy Physics and Nuclear Physics

Volume 21, Number 3

Development of Central Collective Flow in 100 MeV/u Au+Au Central Collisions

Xi Hongfei[1], Shen Wenqing[2], Zhu Yongtai[1], Jin Genming[1], and Wei Zhiyong[1]

[1](Institute of Modern Physics, The Chinese Academy of Sciences, Lanzhou, China)
[2](Shanghai Institute of Nuclear Study, The Chinese Academy of Sciences, Shanghai, China)

Using the QMD model, the time evolution of the Au+Au system at 100 MeV/u has been studied. For very central collisions, the conditions for freeze-out and how the different physical quantities approach equilibrium are investigated. The calculation results show that for 100 MeV/u Au+Au at $b = 0$ fm, the maximum density can reach $1.6\rho_0$, after which the system expands to a low density region. A position correlated central flow develops during the expansion stage. Through study of the two-particle relative momentum spectrum, it is possible to separate the central flow from random thermal motion. The dependence of this central flow on the equation of state (EOS) is also discussed.

Key words: central collision, central collective flow, QMD model.

1. INTRODUCTION

The equation of state (EOS) of the nuclear matter is one of the main objects in current intermediate and higher energy heavy ion collision studies [1,2]. The study on the characteristics of nuclear matter under extreme conditions is generally carried out in central collisions of two heavy nuclei at intermediate and higher energies. To study the EOS of nucleus, one usually first excites the nucleus to a high excitation energy and compresses it to a high density and then measures the secondary particles produced in the collision and the decay processes of the highly excited and dense

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Received on June 26, 1996. Supported by the National Natural Science Foundation of China.

system. The experimental investigations, in this respect, can be divided into two kinds: one is to measure the energy, multiplicity, and angular distribution of the fragments produced during the expansion of the high temperature and high density system to extract the information about EOS from the multifragmentation process [1], the other is too study the EOS and medium effect via the secondary particles produced in the violent nucleon-nucleon collisions [2]. Recently, the existence of a central collective flow in the central collisions of heavy nuclei is found in a series of experiments at SIS in GSI [3,4]. Assuming that the flow is proportional to the distance from the production position of the fragment to the center, the independence of the average fragment energy of the fragment mass observed in the experiment can be explained well. This phenomenon is found in very central collisions so it can be understood that the central collective flow is caused by the compression effect and may be related to EOS.

The QMD is one of the good models for describing the intermediate and higher energy heavy ion reactions [5], and is suitable to the study of intermediate and higher energy heavy ion collision processes. In this paper the time evolution process of the reaction in 100 MeV/u Au+Au collision at $b = 0$ fm is studied by using the QMD simulation calculation.

The time evolution of several physical observables is studied first to find the freeze-out time. Then, the collective motion portion and thermal motion portion are distinguished by study of the relative momentum spectrum of two correlated particles to investigate the relationship between the collective motion portion (central collective flow) and EOS.

2. TIME-EVOLUTION PROCESS OF 100 MeV/u Au+Au REACTION AT $b = 0$ fm CALCULATED BY QMD

The study of time-evolution process of the 100 MeV/u Au+Au reaction at $b = 0$ fm has been emphasized using the QMD calculation, in order to understand how the heavy system develops towards equilibrium. During the model calculation [5], the momenta $(p_{x_i}, p_{y_i}, p_{z_i})$ and coordinates (x_i, y_i, z_i) of each nucleon in the projectile and target nuclei are exported at different times of the process. Afterward, the data are analyzed and processed assuming that if the distance between two nucleons is less than 3 fm, they will belong to the same cluster [5].

In order to investigate the process in which the system develops towards equilibrium, the regulations of the change of several physical quantities are analyzed. Figure 1(a) shows the time evolution of the density in the central region of the colliding process. At $t \sim 40$ fm/c, the system reaches maximum compression and the density is 1.6 times of the normal density, after which the system starts to expand. Figure 1(b) gives the time evolution of the multiplicity of intermediate mass fragments (IMF), their mass numbers A are larger than 4, and it can be seen in the figure that the IMF multiplicity increases rapidly in the time interval of $t \sim 60$-100 fm/c and the equilibrium is basically reached after 100 fm/c. This means that the system undergoes multifragmentation at $t \sim 60$-100 fm/c, breaking into IMFs and light particles. Figure 1(c) gives the momentum distribution width of the largest cluster formed in the reaction, T_{xa}, which is defined as

$$T_{xa} = \sqrt{\sum_{i=1}^{A_{\max}} (V_{x_i} - \bar{V}_x)^2 / A_{\max}} \,, \tag{1}$$

where $\bar{V}_x = \sum_{i=1}^{A_{\max}} V_{x_i}/A_{\max}$ and $A_{\max}$ denotes the mass of the largest cluster, V_{x_i} is the projection of the momentum of the i-th nucleon on the x axis. In the calculation the z axis is along the beam direction. From the figure one may find that when $t < 40$ fm/c the projectile and target are linked together and $A_{\max} \sim 394$. At the moment of $t \sim 40$ fm/c, T_{xa} reaches its maximum due to the internal multiple

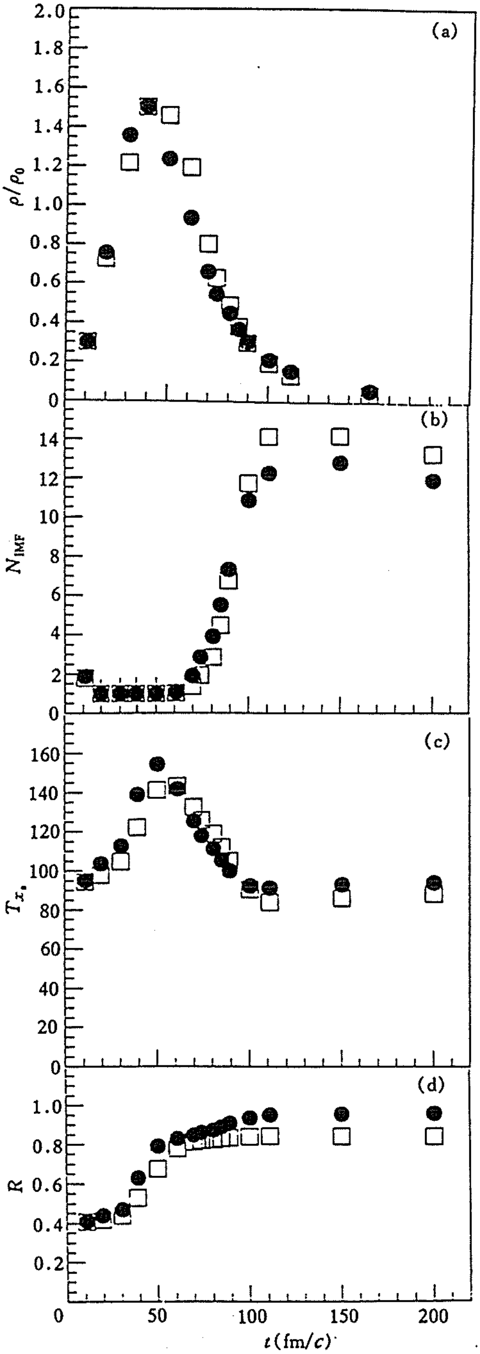

Fig. 1

Variation of several macroscopic observables with the reaction time.

(a) time evolution of the density in central region; (b) time evolution of the multiplicity of IMF ($A > 4$); (c) time evolution of the momentum distribution width of the largest nucleon cluster formed in the reaction; (d) time evolution of the asymmetry factor R in the momentum space. ● : calculated by head EOS; □ : calculated by soft EOS.

collisions among nucleons inside the system. An expansion and cooling process of the system is followed, and T_{xa} reaches its equilibrium after $t \sim 100$ fm/c. This also indicates that the emitted IMFs are mainly in the ground states after 100 fm/c.

Figure 1(d) shows the situation of the equilibrium of the reaction system in the momentum space. The asymmetry factor R in the momentum space is defined as:

$$R = \frac{\sqrt{\sum_{i=1}^{A} p_{x_i}^2} + \sqrt{\sum_{i=1}^{A} p_{y_i}^2}}{2\sqrt{\sum_{i=1}^{A} p_{z_i}^2}}\,, \tag{2}$$

where $A = 394$ is the mass number of the system. It can be seen that the distribution in the momentum space is basically equilibrated after 100 fm/c.

From the evolution process of several macroscopic observable with the reaction time (see Fig. 1), one may find that the reaction process can mainly by divided into two stages. Before 40 fm/c the system reaches a maximum temperature and maximum compression. During 40-100 fm/c, the system expands rapidly and produces many IMFs. This means that the multifragmentation happens. After 100 fm/c the system is basically equilibrated and no longer changes. We may state that the freeze-out happens at 100 fm/c.

3. THERMAL MOTION AND COLLECTIVE MOTION IN THE REACTION PROCESS

In order to investigate the time evolution of the collective motion and random thermal motion in the process of Au+Au collisions at 100 MeV/u at $b = 0$ fm, the reaction region is divided into four zones according to different radii (as shown in Fig. 2). A cone from the center with a top angle of 30° cuts the reaction region into zones I and II. For every event, two kinds of momentum spectra P and Q are calculated, with $Q = |p_1 + p_2|$, $P = |p_1 - p_2|$. Here p_1 denotes the momentum of one nucleon in zone I and p_2 is the momentum of another nucleon in zone II, these two nucleons are in zones of the same radius. In order to investigate the influence of the thermal motion and collective motion on the spectra P and Q, a simple Monte Carlo simulation has been made. It is assumed that all particles are distributed in a sphere with radius r_0. The momentum distribution is Gaussian, $f(p) \sim \exp(-p^2/2\sigma^2)$,

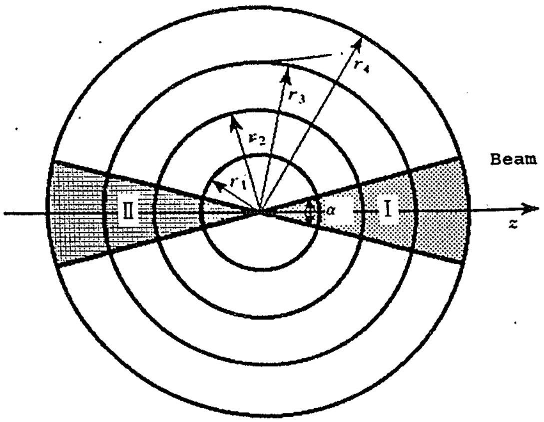

Fig. 2
Scheme of zone separation of the reaction region. $\alpha = 30°$.

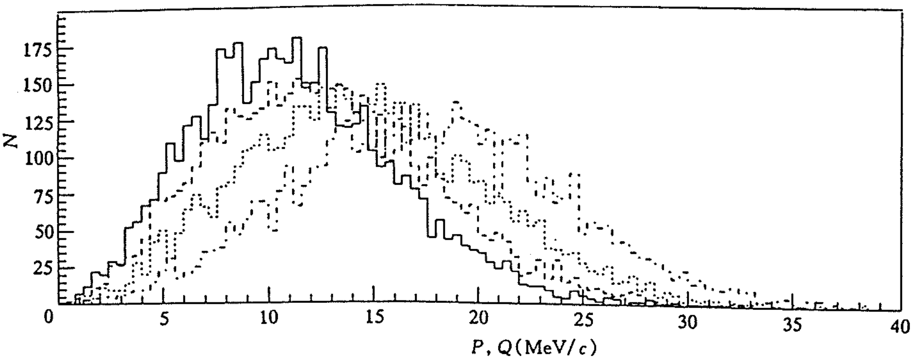

Fig. 3

P and Q spectra for different central flow in hot source model and σ = 5 MeV/c.
——: P_0 = 0 MeV/c, ----: P_0 = 3 MeV/c,·····: P_0 = 5 MeV/c, -·-·-: P_0 = 7 MeV/c.

and here σ is the width of the momentum distribution. The sphere should be cut as shown in Fig. 1, and the calculation results show that the obtained P and Q spectra with σ = 5 MeV/c are very similar.

If the collective flow P_0 is assumed to be proportional to the radius, $P_{ir} = P_0 \frac{r}{r_0}$, where r_0 is the radius of the sphere, then for each particle its momentum can be written as: $P_i = P_{iT} + P_{ir}$, where P_{iT} is the momentum of thermal motion, which follows the Gaussian distribution. Figure 3 gives the P and Q spectra for P_0 = 0, 3, 5, and 7 MeV/c, respectively. From the figure it can be seen that the P and Q spectra are different when the collective flow exists, and the Q spectrum is only dependent on the thermal motion. After the analysis of results obtained from this simple Monte Carlo simulation, the parameter T for random thermal motion can be written as:

$$T \doteq \frac{1}{2}\,\overline{Q}\,, \tag{3}$$

where $\overline{Q}$ denotes the average value of spectrum Q. The collective motion portion P_0 takes the form of $P_0 = \overline{P} - 2T$, where $\overline{P}$ is the average value of P spectrum.

Using this method the collective motion and random thermal motion can be separated well. In Fig. 4, P and Q spectra are given at different reaction times t = 30, 60, and 80 fm/c. It can be seen in the figure, P and Q are quite different at 30 fm/c, due to the relative motion of the projectile and target. The equilibrium in the momentum space is basically reached at 60 fm/c after multiple collisions of nucleons, and P and Q are nearly the same at this moment. At 80 fm/c, the system expands to a low density region, a central collective flow appears, and the P and Q spectra become different again. It can be noticed before this time that the IMF multiplicity was low, and the system was still a large cluster. So the difference between P and Q spectra reflected the fact that a collective motion existed in this large cluster. From Fig. 5 one can find that T is not sensitive to the radius, but the central flow is nearly proportional to the radius. This is in agreement with the assumption made in analysis of the experimental data [1].

4. RESULTS AND DISCUSSION

In order to investigate the relation between the central collective flow and EOS, the average energy of IMF and its angular distribution have been calculated. The calculated dependence of average energy of IMF on its charge number fits the experimental data qualitatively, and this dependence of the average energy on the charge number of IMF is not strongly affected by the EOS.

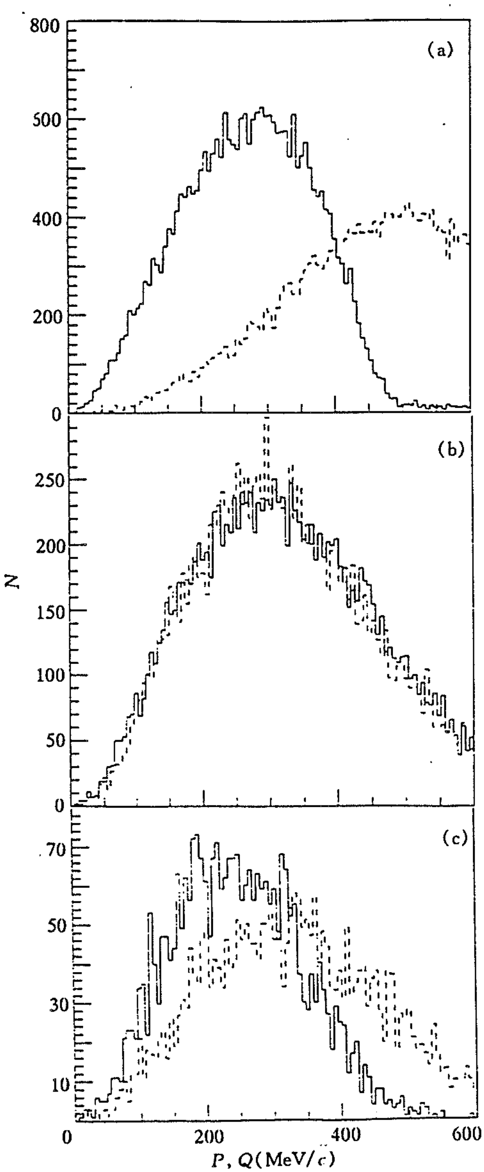

Fig. 4

P (dashed line) and Q (solid line) spectra calculated by soft EOS.
(a) $t = 30$ fm/c; (b) $t = 60$ fm/c; (c) $t = 80$ fm/c.

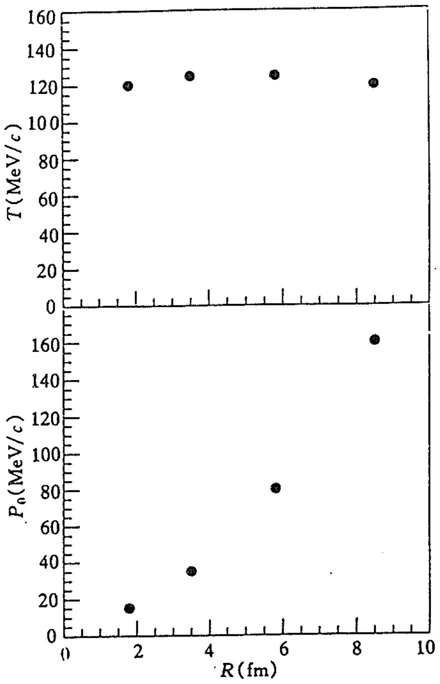

Fig. 5

Dependence of temperature parameter T and central collective flow P_0 on the radius calculated by soft EOS at $t = 80$ fm/c.

The central collective flow is one of the important phenomena found recently in the intermediate and higher energy heavy ion collisions. The results of the QMD model calculation can fit the experimental data qualitatively. Due to the existence of the energy threshold for detectors, the average energy of IMF is a little bit higher. Calculation results show that the central collective flow already starts to develop before multifragmentation, and strongly affects the production of IMFs. Experimental measurement of the angular distribution in the center of mass system is helpful for the study of EOS. This kind of experimental investigation is going on in GSI. In the theoretical calculation it is meaningful to introduce the momentum dependent potential and medium effect in nucleon-nucleon collision. This kind of research work is now in progress.

REFERENCES

[1] H. Feldmeier and W. Nörenberg, *Proceedings of the International Workshop XXII on Gross Property of Nuclei and Nuclear Excitation*, 1994.
[2] H. Feldmeier and W. Nörenberg, *Proceedings of the International Workshop XXIII on Gross Property of Nuclei and Nuclear Excitation*, 1995.
[3] S.C. Jeong *et al.*, *Phys. Rev. Lett.*, 72(1994), p. 3468.
[4] G.J. Kunde *et al.*, *GSI Scientific Report*, 1993.
[5] J. Aichelin, *Phys. Rep.*, **201**(1991), p. 233.