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Influence of Central Collective Flow on Charged Particle Correlation Functions

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Influence of the central collective flow on a two-particle correlation function is discussed. The Monte Carlo calculation was used to describe how the single-particle and two-particle spectra from a hot emission source are affected by the central collective flow. The two-proton correlation function for the 100 MeV/u Ni+Ni system at $b = 0$ fm was calculated using the QMD model. The particle interchange method was developed and used to prove the existence of a central collective flow in central collisions of the 100 MeV/u Ni+Ni system. The results show that the two-particle correlation functions are indeed sensitive to the central collective flow. This might provide a method to study the central collective flow formed in central collisions for medium heavy system at energies above 100 MeV/u.

Key words: charged particle correlation function, central collision, central collective flow, QMD model.

1. INTRODUCTION

The study on the equation of the state of nuclear matter (EOS) is one of the main problems in intermediate and high energy heavy ion collisions. An efficient way to study the EOS is to measure the products emitted after compression of the nucleus to 1-2 times of the normal nuclear density in central heavy ion collisions [1]. It was found in the experiments of the 150 MeV/u Au+Au reaction that the central collective flow does exist in the central collisions [2]. It was noticed in the energy

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spectra of the intermediate mass fragments (IMF) in the center of mass system that the average energies per single particle of IMF with different masses are independent of the mass of IMF, but dependent on the bombarding energy [2]. In analyses of the experimental data it is assumed that there is an expanding central collective flow, which is proportional to the radius of the production position of the particle. The average energy of the IMF is $\langle E\rangle = 3T/2 + A\bar{E}_{\mathrm{flow}}$, here T is the contribution of the thermal motion, and $\bar{E}_{\mathrm{flow}}$ represents the collective flow [1]. From the relation between the average energy and mass of different IMFs we can get the central collective flow $\bar{E}_{\mathrm{flow}}$. At higher energies for a lighter system the yields of composite particles are relatively low. So it is a little bit difficult to analyze the central collective flow by using this method. In fact, the central collective flow can also affect the emission of the light-charged particles. However, it is difficult to define the collective flow only from the single-particle spectra, because the particle spectra are influenced by both the temperature and the collective flow. The double-proton correlation function is one of the effective methods to measure the size of a heavy ion interaction region at intermediate and higher energies, a phenomenon usually called the HBT effect [3-6]. In recent years, QMD is one of the models which can describe the intermediate and higher energy heavy ion reactions quite well [7].

2. INFLUENCE OF CENTRAL CORRECTION FLOW ON SINGLE-PARTICLE SPECTRA EMITTED BY HOT SOURCES AND TWO-PARTICLE CORRELATION FUNCTIONS

Usually it is expected that one or several emitting sources exist in heavy ion-induced reactions [8]. If the temperature of a hot emitting source is T, the single-particle energy spectra at the center of the mass system can be written as:

$$\frac{\mathrm{d}N}{\mathrm{d}E} \sim \sqrt{E - E_{\mathrm{C}}}\exp\left[-\left(\frac{E - E_{\mathrm{C}}}{T_{\mathrm{N}}}\right)\right], \tag{1}$$

where E_{C} is the Coulomb energy and T_{N} is the nuclear temperature. The single-particle energy spectra measured in the experiment can be fitted using Eq.(1), which is called the moving source model fitting. In the moving source model fitting in the intermediate and higher energy heavy ion reactions the region from where the particles are emitted can be assumed is spherical. Due to the possible expansion process a central collective flow can be formed which expands from the central region of the sphere. In Ref. [1] the central collective flow is supposed to be proportional to the radius of the production position of the emitted particle.

The momentum of the collective motion $p(r)$ at the radius r is

$$p(r) = p_0\frac{r}{r_0}, \tag{2}$$

where $r_0 = 9$ fm is the largest radius of the hot source. This can explain well the experimental fact that the average energy of the complex particle is independent of the masses of different particles obtained in the experiment. In order to study the influences of the central collective flow on the proton energy spectra and double-proton correlation functions, a simple Monte Carlo simulation has been performed. It is assumed that the protons being emitted are populated homogeneously in the sphere with radius r_0, the momentum distribution of the random motion of protons is Gaussian, and the particle has a collective flow towards the outside, which is proportional to the radius of its position in the sphere. Then total momentum of the particle can be written $p = p_t + p_r$, where p_t and p_r are the random component and the radial collective component, respectively, with $p_r = p_0 \cdot r/r_0$, and $p_t \propto \exp(-p^2/2\sigma^2)$ ($\sigma = 5$ MeV/c is the momentum distribution width).

Figure 1 shows the single-particle energy spectra, obtained from this simple hot source model.

In the figure, T represents the thermal motion component, and P_0 is the largest central collective flow. From the figure one can see that the energy spectra at P_0 = 20 MeV/c, T = 120 MeV/c are similar to that obtained at P_0 = 0 MeV/c, T = 150 MeV/c. This indicates that the single-particle energy spectra are hotter when the central collective flow exists. However, it is hard to judge if the particles are emitted from a high-temperature hot source or from a lower temperature source with the existence of a central collective flow if only the single-particle energy spectra are considered. The double-proton correlation function at small momentum of relative motion is defined as [3]:

$$1 + R(q) = KN(q) \,/\, M(q), \tag{3}$$

where q is the relative momentum of the two correlated protons, $N(q)$ is the number coincidence counts with given relative momentum q, and $M(q)$ is the background spectrum which usually is obtained experimentally by using event mixing method. Theoretically the correlation function can be written as [9]:

$$1 + R(q) = \frac{\int \mathrm{d}b\mathrm{d}p_1\mathrm{d}p_2\mathrm{d}r_1\mathrm{d}r_2 f_1(p_1,\ r_1)f_2(p_2,\ r_2)\psi(q,\ |r_1 - r_2|)\,\theta_\Delta(q)}{\int \mathrm{d}b\mathrm{d}p_1\mathrm{d}p_2\mathrm{d}r_1\mathrm{d}r_2 f_1(p_1,\ r_1)f_2(p_2,\ r_2)\theta_\Delta(q)}, \tag{4}$$

where $f_1(p_1,r_1)$ is a one-body Winger distribution function, $\psi(q,\ |r_1 - r_2|)$ is the correlation term caused by the final state interaction [3], and b is the impact parameter.

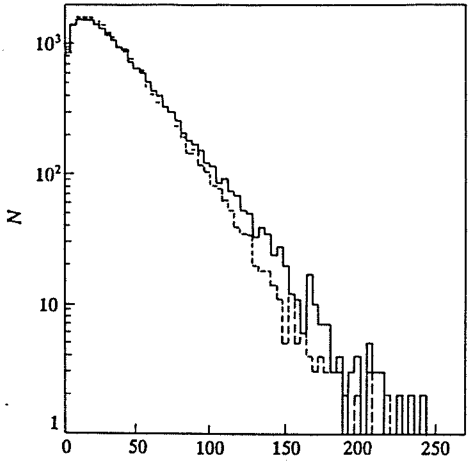

Fig. 1

The single-particle energy spectra emitted from a hot source.

——: T = 150 MeV/c; P_0 = 0; – – –: T = 120 MeV/c; P_0 = 20 MeV/c.

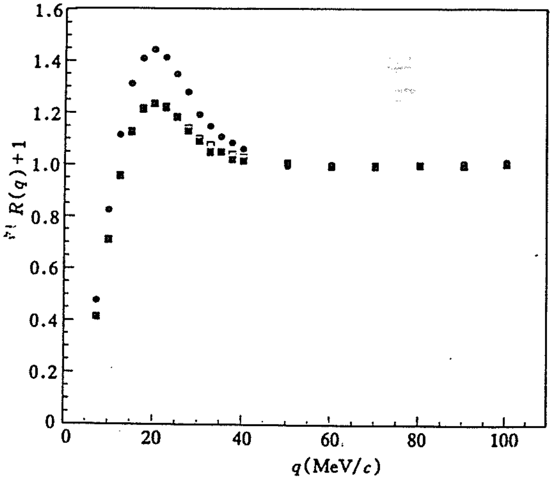

Fig. 2

The double-proton correlation function emitted by hot source.

□: T = 150 MeV/c; P_0 = 0; ●: T = 120 MeV/c; P_0 = 20 MeV/c; ■: calculated results by using the particle interchange method with T = 120 MeV/c; P_0 = 20 MeV/c.

Figure 2 shows the double-proton correlation function, calculated by using Eq.(4) at different conditions when the radius of the hot source $r_0 = 9$ fm. It can be seen that the peak value is increasing with the increase of the central flow in the case of $q = 20$ MeV/c. This reflects the fact that the apparent size of the source obtained from the correlation function becomes smaller due to the existence of the central collective flow. It can be seen from this simple hot source model that the central collective flow affects both the single-particle spectra and the double-particle correlation spectra. A simultaneous experimental measurement of the single-particle spectra and the double-particle correlation spectra is helpful to distinguish the thermal motion and the collective motion.

3. SIMULATION OF 100-400 MeV/u Ni+Ni CENTRAL COLLISION USING QMD METHOD

In order to study the influence of the central collective flow to the correlation function, the QMD model has been used in the dynamical simulation calculation of 100-400 MeV/u Ni+Ni collisions at $b = 0$ fm. As described in Ref. [7], when the distance between one nucleon and the remaining nucleons is larger than 3 fm, it will be treated as a free nucleon. In the calculation of the correlation function the emitting time spectra of the particles should be calculated. The particle emission time t is defined as the time when a nucleon becomes a free nucleon and keeps being a free nucleon afterwards.

From Fig. 3, one can see that most of the nucleons are emitted at $t = 70$ fm/c. It means that the multifragmentation takes place at that moment. The calculation was performed up to $t = 150$ fm/c. Figure 4 shows the scatter plot of the distance between the emitting point and the center varying with the emission time. While $t < 50$ fm/c, the emission radius r is larger than 5 fm, nucleons are mainly emitted from the surface. After $t > 60$ fm/c, r is distributed from 0. This means that the nucleons are emitted from the volume. Figure 5 gives double-proton correlation functions by using Eq.(2), based on the single-particle distribution function of the emitted particles obtained by QMD calculations. It can be seen that with increasing bombarding energy the value of the correlation functions at the peak position ($q \sim 20$ MeV/c) is increasing. Because the size of the system is nearly the same, this fact can be attributed to the influence of the central collective flow.

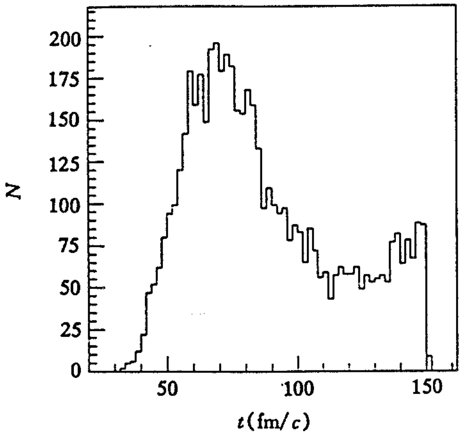

Fig. 3
Time spectra of nucleon emission for Ni+Ni collisions at 100 MeV/u at $b = 0$ fm.

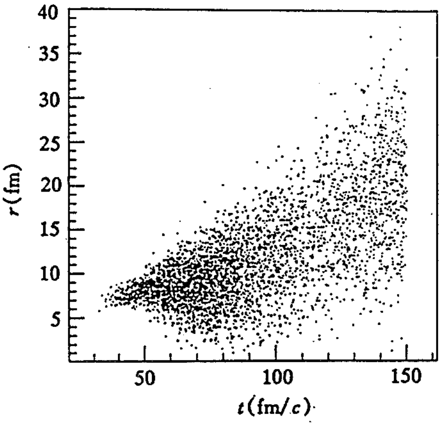

Fig. 4
The correlation between the distance from the nucleon emission point to the center and the emission time for Ni+Ni collisions at 100 MeV/u at $b = 0$ fm.

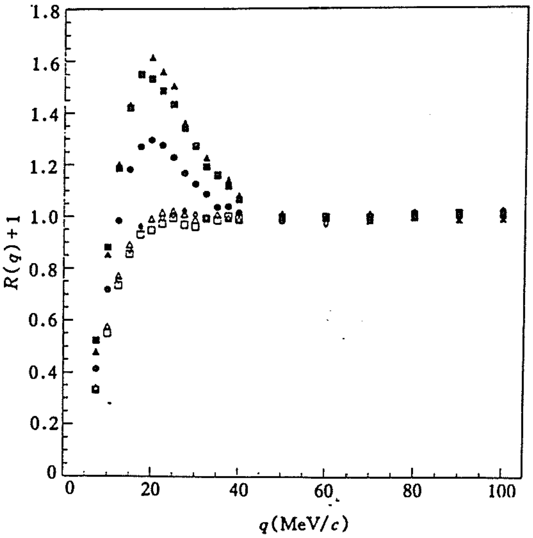

Fig. 5

The proton correlation functions for Ni+Ni collisions at b = 0 fm.
●, ■, and ▲ : 100, 250, and 400 MeV/u, respectively, calculated without particle interchange,
□, Δ, and ◇ : 100, 250, and 400 MeV/u, respectively, calculated with particle interchange.

In the following, a particle interchange calculation method is employed to further explain the fact that the increase of the correlation function $1 + R(q)$ at peak position $q \sim 20$ MeV/c with increasing bombarding energy is due to the existence of the central collective flow associated with the emission position, but not due to decrease of the size of the emission region. In this method the momenta of two correlated particles in each correlation event are interchanged. This keeps the value of $d = |r_1 - r_2|$ unchanged and will not lead to the change of the size of the emission region. There is no obvious peak at $q \sim 20$ MeV/c found in the correlation functions resulting from particle interchange calculation method (see in Fig. 5). On the contrary, it proves that the increase of correlation functions at the peak position with the increasing bombarding energy in 100-400 MeV/u Ni+Ni collisions at $b = 0$ fm is due to the increase of the central collective flow. This result is in agreement with the experimental fact that the central collective flow in very central collisions of the Au+Au system at 100-400 MeV/u increases with the increasing bombarding energy and is also in agreement with the QMD calculation results [10].

4. CONCLUSION

It was proved by a simple Monte Carlo model calculation that for a hot source a central collective flow expanding towards the outside influences both the single-particle spectrum and the double-particle correlation spectrum. The existence of the central collective flow leads to the increase of the temperature of the single-particle energy spectra, while the size of the source of two correlated particles becomes a little smaller. The QMD calculation results for the 100-400 MeV/u Ni+Ni colliding system at $b = 0$ fm show that the peak value of the correlation function at $q \sim 20$ MeV/c increases with the increasing bombarding energy. This is mainly caused by the central collective flow because the size of the projectile and target are nearly the same. The calculation using the particle interchange method proves this conclusion further. At higher energies the yields of complex particles become smaller, so a simultaneous measurement of the single-particle energy spectra of protons and double-proton correlation spectra is quite meaningful in the study of the central collective flow formed in the high energy heavy ion central collisions for a medium heavy system. Because the double-proton correlation function is sensitive to the medium nucleon-nucleon interaction cross section a comparison of the double-proton correlation function with the QMD and BUU calculations is very helpful to understand further the equation of the state in the reactions of this energy region.

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