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Narrowing of the charge balance function and hadronization time in relativistic heavy-ion collisions

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The width of charge balance function in high energy hadron-hadron and relativistic heavy-ion collisions are studied using the Monte Carlo generators PYTHIA and AMPT, respectively. The narrowing of balance function as the increase of multiplicity is found in both cases. The mean parton-freeze-out time of a heavy-ion collision event is used as the characteristic hadronization time for the event. It turns out that for a fixed multiplicity interval the width of balance function is consistent with being independent of hadronization time.

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The relativistic heavy-ion collision experiments at CERN-SPS and especially at the relativistic heavy-ion collider RHIC in Brookhaven National Lab provide clear evidence for the production of a dense matter in the collision processes [1]. The central question is whether this matter is purely hadronic or has been going through a quark-parton phase. There exist experimental evidences in favor of the existence of a quark-parton phase at the early stage of collision processes [2], but in view of the importance of this issue, further confirmation is needed.

Recently, the rapidity correlation between oppositely charged particles, which has been used in e^+e^- [3] and hadron-hadron collisions [4] to study the hadronization in these processes, is proposed [5] as a measure of the hadronization time in relativistic heavy-ion collisions. It is argued that if the system produced in heavy-ion collisions has undergone a quark-parton phase, the hadronization will occur at a later time and, therefore, the temperature will be lower and the diffusive interaction with other particles will be lesser than those in the direct hadronization without going through a quark-parton phase. These will result in a narrower charge balance function for a system with quark-parton phase than that without such a phase.

Two heavy-ion experiments [6,7] have measured the balance function at various centralities and for different colliding nuclei. A narrowing of the balance function is indeed observed with increasing centrality of the collision and with increasing size of the colliding nuclei. These observations are consistent with the assumption that the narrowing of balance function is correlated with late hadronization.

However, recently it is reported [8] that in hadron-hadron collisions at $\sqrt{s} = 22$ GeV the balance function also becomes narrower as the increasing of multiplicity. Therefore, whether the observed narrowing of balance function in relativistic heavy-ion collisions is due to late hadronization or is simply due to the multiplicity effect is an open question.

In this letter this question is examined using the Monte Carlo generators PYTHIA [9] and AMPT [10]. The former is a standard Monte Carlo generator with string fragmentation as hadronization scheme. There is no quark-parton phase in this model and the hadronization is almost instantaneous. However, the latter is a "multiphase" model, with a transport of quark-parton before hadronization.

The results from PYTHIA will first be presented. Then the hadronization time in AMPT model is described, and its connection with the width of balance function is presented. A summary and discussion then follow.

The balance function is defined as [7]

$$B(\delta y|Y_{\rm w}) = \frac{1}{2}\left[\frac{\langle n_{+-}(\delta y)\rangle - \langle n_{++}(\delta y)\rangle}{\langle n_+\rangle} + \frac{\langle n_{-+}(\delta y)\rangle - \langle n_{--}(\delta y)\rangle}{\langle n_-\rangle}\right], \quad (1)$$

where $n_{+-}(\delta y)$, $n_{++}(\delta y)$ and $n_{--}(\delta y)$ are the numbers of pairs of opposite- and like-charged particles satisfying the criteria that all of them fall into the rapidity window Y_w and that their relative rapidity equals δy; n_+ and n_- are the numbers of positively and negatively charged particles in the interval Y_w, respectively.

The balance function $B(\delta y|Y_w)$ represents the probability that the balancing charges are separated by δy [5]. The mean of δy [7]

$$\langle \delta y\rangle_{Y_w} = \frac{\sum_i B(\delta y_i|Y_w)\delta y_i}{\sum_i B(\delta y_i|Y_w)} \quad (2)$$

is defined as the *width of balance function*.

Proton-proton collision events are generated at four center-of-mass (c.m.) energies—22, 64, 130, and 200 GeV using PYTHIA5.720 generator. The event number for each sample is 100,000. The widths $\langle \delta y\rangle_\infty$ of balance function in the full phase space are calculated for different (charged) multiplicity bins and plotted in Fig. 1.

It can be seen from the figure that in this model even for *p*-*p* collision, where no quark-parton phase is expected and the hadronization is almost instantaneous, the width of balance function decreases with the increase of multiplicity, i.e., the width of balance function is narrower for higher multiplicity. This effect has nothing to do with hadronization time.

However, by definition balance function measures the correlation length between oppositely charged particles. For comparison we have calculated the standard 2-particle

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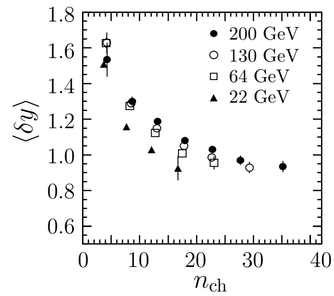

FIG. 1. The width of full-phase-space balance function for different multiplicity in p-p collisions at $\sqrt{s} = 22, 64, 130, 200$ GeV.

correlation function [11] of oppositely charged particles

$$R^{+-}(y_1, y_2) = \frac{1}{2}\left[\frac{\rho^{(2)}(y_1^+, y_2^-)}{\rho^{(1)}(y_1^+)\rho^{(1)}(y_2^-)} + \frac{\rho^{(2)}(y_1^-, y_2^+)}{\rho^{(1)}(y_1^-)\rho^{(1)}(y_2^+)}\right] - 1 \tag{3}$$

for different multiplicities in p-p collision at c.m. energy $\sqrt{s} = 200$ GeV, for $y_1 = 0$, $y_2 = y$. The results plotted in Fig. 2 show that the width of R is consistent with being independent of multiplicity. A possible explanation of the width of R is cluster decay. Comparing with the definition of balance function, Eq. (1), we see that it is the difference between the correlations of opposite- and like-charged particles that shows a clear multiplicity dependence, which is unrelated with cluster decay and is mainly due to the string fragmentation mechanism implemented in PYTHIA model.

It can also be seen from Fig. 1 that the width of balance function depends on collision energy. For the same multiplicity, the higher the collision energy is, the wider the width of balance function.

However, it should be noticed that the full rapidity region is wider for higher energy, *cf.* Fig. 3. To get rid of the influence of the width of rapidity region we calculate the width of balance function in the region $-3 \leqslant y \leqslant 3$ for all four energies. The results, presented in Fig. 4, show that when the (average) rapidity density $\Delta n/\Delta y$ is the same, the width of balance function is almost independent of energy, especially for high $\Delta n/\Delta y$. That is, in hadron-hadron collisions the width of balance function depends essentially *only* on multiplicity and is consistent with being independent of energy.

Let us now turn to discuss how does the width of balance function behave in nucleus-nucleus collisions.

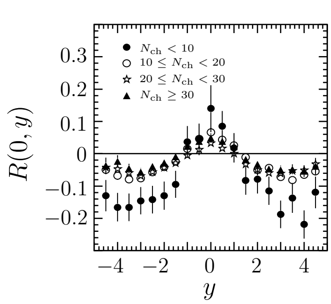

FIG. 2. The 2-particle correlation function $R(0, y)$ as function of y for different multiplicities in p-p collision at c.m. energy $\sqrt{s} = 200$ GeV.

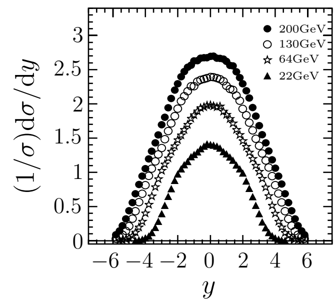

FIG. 3. The rapidity distribution of all charged particles in p-p collision at $\sqrt{s} = 22, 64, 130, 200$ GeV.

The Monte Carlo generator AMPT1.11 [11] is a multiphase transport model, which contains a quark-parton transport phase before hadronization. The initial spatial and momentum distributions of hard partons and soft string excitations are obtained from the HIJING [12] model. The parton cascade follows Zhang's parton-cascade (ZPC) model [13], which is based on two-body pQCD scattering with screening masses. When interaction ceases, the partons are hadronized [14] according to LUND string fragmentation mechanism [10]. Then the scatterings among the resulting hadrons are described by a relativistic transport (ART) model [15] that includes baryon-baryon, baryon-meson, and meson-meson elastic and inelastic scatterings.

AMPT is a nonequilibrium transport model. The partons are, by definition, hadronized after their last collisions. Therefore, there is no unique hadronization time for the whole system. Each parton has its own hadronization time, or freeze-out time $t_{\rm fr}$. To study the correlation, if any, between the width of balance function and hadronization time, we use the event mean of $t_{\rm fr}$

$$\overline{t_{\rm fr}} = \frac{1}{n_{\rm parton}} \sum_{i=1}^{n_{\rm parton}} t_{{\rm fr}i} \tag{4}$$

as the characteristic hadronization time for an event, where $n_{\rm parton}$ is the number of partons in the event, $t_{{\rm fr}i}$ is the freeze-out time of the ith parton.

The AMPT1.11 (default) generator is utilized to generate Au-Au collision events at $\sqrt{s_{NN}} = 200$ GeV. The default values of the parameters are used, in particular, the cross section is chosen to be 3 mb [11]. Two event samples with

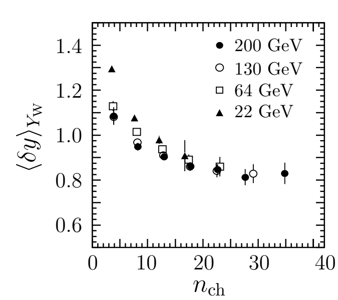

FIG. 4. The width of balance function in the rapidity region $[-3, 3]$ for different multiplicity in p-p collision at $\sqrt{s} = 22, 64, 130, 200$ GeV.

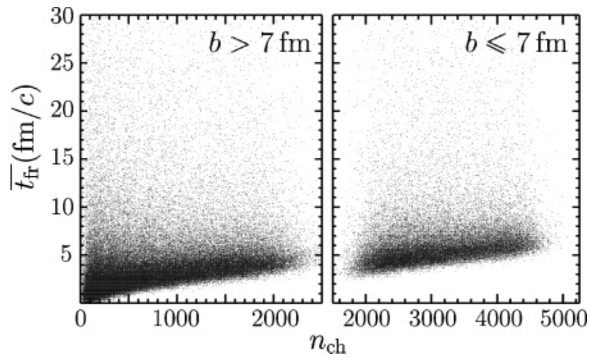

FIG. 5. Scattering plots of $\overline{t_{\rm fr}}$ vs. $n_{\rm ch}$ in Au-Au collision at $\sqrt{s_{NN}} = 200$ GeV for two different centralities.

250,000 and 770,000 events, respectively, are generated for two centralities $b \leqslant 7$ fm and $b > 7$ fm.

Fig. 5 shows the scattering plots of $\overline{t_{\rm fr}}$ vs. $n_{\rm ch}$ in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV for the two different centralities—$b \leqslant 7$ fm and $b > 7$ fm, respectively. It can be seen that in central collisions ($b \leqslant 7$ fm) $\overline{t_{\rm fr}}$ is larger than 3–4 fm, whereas in peripheral collisions ($b > 7$ fm) $\overline{t_{\rm fr}}$ is concentrated at $\overline{t_{\rm fr}} \sim$ 3–4 fm. That is, central collision events hadronize later than peripheral ones.

The distributions of event-mean freeze-out time $\overline{t_{\rm fr}}$ for the two different centralities in Au-Au collision at $\sqrt{s_{NN}} = 200$ GeV are shown in Fig. 6. For reference, in the same figure are also shown the distributions of single-particle freeze-out time $t_{\rm fr}$ for two fixed centralities $b = 2$ fm (dotted line) and 10 fm (dashed-dotted line), respectively.

To study the correlation between the width of balance function and the characteristics of single event-event-mean freeze-out time $\overline{t_{\rm fr}}$ and/or multiplicity $n_{\rm ch}$, each centrality sample is divided into subsamples according to the intervals of mean freeze-out time $\overline{t_{\rm fr}}$ and the resulting subsamples are further divided into subsamples by different multiplicity intervals.

The width of balance function in the rapidity region $Y_{\rm W} = [-3, 3]$ for different mean freeze-out time $\overline{t_{\rm fr}}$ intervals versus

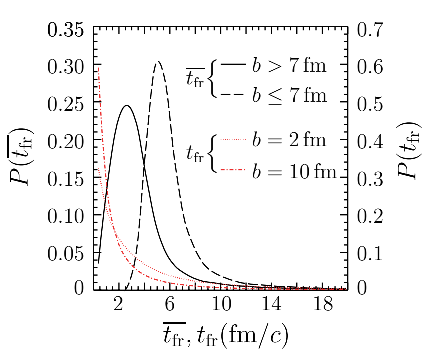

FIG. 6. (Color online) The distributions of event-mean freeze-out time $\overline{t_{\rm fr}}$ for two different centralities in Au-Au collision at $\sqrt{s_{NN}} = 200$ GeV. The dotted and dashed-dotted lines are the distributions of single-particle freeze-out time $t_{\rm fr}$ for two fixed centralities $b = 2$ and 10 fm, respectively.

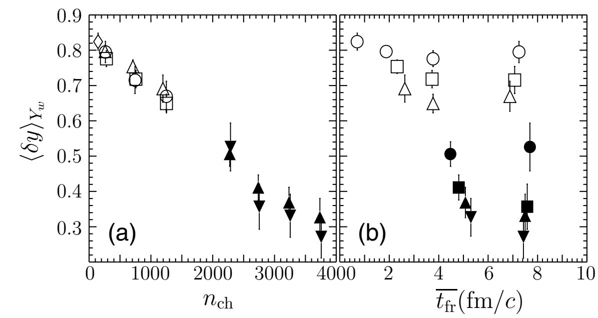

FIG. 7. The width of balance function in the rapidity region $Y_W = [-3, 3]$ in Au-Au collision at $\sqrt{s_{NN}} = 200$ GeV. (*a*) for different mean freeze-out time $\overline{t_{\rm fr}}$ intervals versus multiplicity $n_{\rm ch}$, where the freeze-out time intervals are $\overline{t_{\rm fr}} \in [0, 1]$ (◇), [1, 3] (△), [3, 5] (□), [5, 12] (○), [3, 6] (▲), [6, 12] (▼) fm; and (*b*) for different multiplicity $n_{\rm ch}$ intervals versus mean freeze-out time $\overline{t_{\rm fr}}$, where the multiplicity intervals are $n_{\rm ch} \in$ [0, 500] (○), [500, 1000] (□), [1000, 1500] (△), [2000, 2500] (●), [2500, 3000] (■), [3000, 3500] (▲), [3500, 4000] (▼).

multiplicity $n_{\rm ch}$ and for different multiplicity $n_{\rm ch}$ intervals versus mean freeze-out time $\overline{t_{\rm fr}}$ in Au-Au collision at $\sqrt{s_{NN}} = 200$ GeV are shown in Figs. 7(a) and 7(b), respectively.

It can be seen from Fig. 7(a) that the width of balance function decreases with the increasing of multiplicity, whereas in the same multiplicity interval, the width of balance function is consistent of being constant, independent of the hadronization time. However, it can be seen from Fig. 7(b) that although there is a weak anticorrelation between the width of balance function and the hadronization time $\overline{t_{\rm fr}}$, the former varies a lot with the varying of multiplicity even for the same hadronization time $\overline{t_{\rm fr}}$.

It is found using PYTHIA Monte Carlo that the width of charge balance function decreases with the increasing of multiplicity in high-energy hadron-hadron collisions, where the hadronization is almost instantaneous.

The relation between the hadronization time and the width of charge balance function in relativistic heavy ion collisions is examined using the default AMPT1.11 Monte Carlo generator. The mean freeze-out time of an event is used as the characteristic hadronization time of the event. The narrowing of balance function as the increase of multiplicity is observed also for relativistic heavy-ion collisions, whereas for a fixed multiplicity interval the width of balance function is consistent with being independent of hadronization time.

However, it is still hard to conclude whether the width of balance function is dependent on or independent of the hadronization time. Due to the correlation between hadronization time and multiplicity, *cf.* Fig. 5, the dependence of the width of balance function on hadronization time, even if it exists, will be submerged in the strong dependence of the width of balance function on multiplicity and is unobservable. Therefore, to use the narrowing of balance function in relativistic heavy-ion collisions as a measure of hadronization time and as a signal of QGP is unrealistic.

It should be noticed that the AMPT model is a multiphase transport model. In this model there is no unique hadronization time for an event. To use the average of parton freeze-out time in an event as the characteristic hadronization time of the event is a crude approximation. Further investigation along this line is needed.

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