PHYSICAL REVIEW C **79**, 054912 (2009)

Two-particle azimuthal angle correlations and azimuthal charge balance function in relativistic heavy ion collisions

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(Received 4 September 2008; published 27 May 2009)

The two-particle azimuthal angle correlation (TPAC) and azimuthal charge balance function (ACBF) are used to study the anisotropic expansion in relativistic heavy ion collisions. It is demonstrated by the relativistic quantum molecular dynamics (RQMD) model and a multi-phase transport (AMPT) model that the small-angle correlation in TPAC indeed presents anisotropic expansion, and the large-angle (or back-to-back) correlation is mainly due to global momentum conservations. The AMPT model reproduces the observed TPAC, but the RQMD model fails to reproduce the strong correlations in both small and large azimuthal angles. The width of ACBF from RQMD and AMPT models decreases from peripheral to central collisions, consistent with experimental data, but in contrast to the expectation from thermal model calculations. The ACBF is insensitive to anisotropic expansion. It is a probe for the mechanism of hadronization, similar to the charge balance function in rapidity.

DOI: 10.1103/PhysRevC.79.054912 PACS number(s): 25.75.Gz, 25.75.Ld, 24.10.Lx

I. INTRODUCTION

Current results from relativistic heavy ion collisions have shown that a system of strongly interacting quarks and gluons has been formed at RHIC [1]. One important piece of experimental evidence is from the measurement of collective anisotropic flow. The observed large elliptic flow and its mass dependence at low transverse momentum has been interpreted as due to a strongly interacting quark gluon plasma (sQGP) phase [2]. It has been proposed that the search for QGP may indeed be over and the study of properties of this new form of matter should begin [3]. A better understanding of elliptic flow is a step forward along this line.

Flow measures the anisotropic transverse momentum distribution [i.e., $v_2(p_t) = \langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \rangle$, where p_x and p_y are components of transverse momenta $\mathbf{p_t}$ of final state particles in x and y directions of the transverse plane]. Experimentally, it actually measures the correlations of particle emission with respect to the reaction plane [4], that is, $v_2(\phi) = \langle \cos 2(\phi - \Psi_R) \rangle$, where ϕ is the azimuthal angle of final state particles and Ψ_R is the azimuthal angle of the reaction plane, which is defined on an event-by-event basis and involves experimental uncertainties and complications. To reduce the uncertainties of the reaction plane, some reaction-plane-independent measurements have been recommended [5–8]. The two-particle azimuthal angle correlation (TPAC) has been studied in PHENIX experiments [8] with finite acceptance in azimuth $[0, \pi]$, where it has been reported that the small angle (around $\phi = 0$) correlation is as strong as that of the large angle ($\phi = \pi$) and that the strength of correlation increases with impact parameter and with transverse momentum of final state particles (as shown in the right of Fig. 2).

The TPAC measures the correlation between two particles that are separated by an azimuth $\delta\phi$ in the transverse plane. It is defined similarly to the well-known two-particle rapidity correlations [9]:

$$C^{ab}(\delta\phi) = \frac{\langle n_{ab}(\delta\phi) \rangle}{\langle n_{ab} \rangle}, \tag{1}$$

where $n_{ab}(\delta\phi)$ is the number of pairs of charged (and signed) a and b particles with relative azimuthal angle $\delta\phi$ and n_{ab} is the total number of pairs integrated over azimuthal angles 2π. $n_{ab} = n_a(n_a - 1)$ if a and b are the same charged particles; $n_{ab} = n_{\rm ch}(n_{\rm ch} - 1)$ for all charged pairs; and $n_{ab} = n_a n_b$ for opposite charged pairs. The average is over selected events. Here, the azimuthal angles of the two particles are relative and, therefore, do not depend on the event reaction plane.

The TPAC should also be sensitive to enhancement in small-angle correlation caused by an anisotropic distribution in transverse momentum and the effects of quantum statistics. The large-angle correlation from global momentum conservation can be easily isolated from the small-angle one.

Another measurement is the newly introduced azimuthal charge balance function (ACBF) [10]. It is expected to be an independent constraint on the temperature and the amount of transverse flow at the freeze-out from thermal models (e.g., higher temperature and smaller v_2 will lead to a wider ACBF). The ACBF is defined similarly to the charge balance function in rapidity, that is,

$$B(\delta\phi) = \frac{1}{2}\left\{ \frac{\langle n_{+-}(\delta\phi)\rangle - \langle n_{++}(\delta\phi)\rangle}{\langle n_+ \rangle} + \frac{\langle n_{-+}(\delta\phi)\rangle - \langle n_{--}(\delta\phi)\rangle}{\langle n_- \rangle} \right\}, \tag{2}$$

where $n_{+-}(\delta\phi), n_{++}(\delta\phi)$, and $n_{--}(\delta\phi)$ are the numbers of opposite- and same-charged particle pairs satisfying the criteria that their relative azimuthal angle is equal to $\delta\phi$; n_+ and n_- are the numbers of positive and negative charged particles, respectively.

Neither the TPAC nor the ACBF depend on the reaction plane and both can be measured easily in experiments. Their dependence on elliptic flow and centrality in transport models, such as the relativistic quantum molecular dynamics (RQMD) model and a multi-phase transport (AMPT) model, will help us in understanding the nature of observed anisotropic flow. The RQMD model is based on hadron interaction [11], where without hadron rescattering the elliptic flow parameter $v_2 = 0$. In the RQMD model with hadron rescattering, $v_2 > 0$, but it is still much smaller than the observed data. Using the model, we can examine how anisotropic expansion contributes to the TPAC and the ACBF by simply switching on and off the hadron rescattering. The AMPT model takes both parton and hadron interactions into account [12]. In the AMPT model with string melting, the parton transportation, hadron re-scattering, and quark coalescence at hadronization are all implemented, well reproducing v_2 observed at RHIC. So we can further study how the TPAC and the ACBF change with anisotropic flow. In this paper, we will use samples of Au + Au collisions at 200 GeV generated by these two transport models.

II. RESULTS OF TWO-PARTICLE AZIMUTHAL ANGLE CORRELATIONS

We present in Fig. 1 the centrality dependence of elliptic flows v_2 for the RQMD model without and with hadron rescattering and for the AMPT model with string melting, respectively. The figure shows that v_2 values from the AMPT model for all centralities are larger than those from the RQMD model with hadron rescattering. The transverse momentum distribution from the RQMD model without hadron rescattering is isotropic and v_2 is zero for all centralities as expected.

In the same figure, the centrality dependence of v_2 for subsamples with positive and negative charged particles are also presented. They all coincide with corresponding samples of all charged particles. This indicates that identical particles have the same anisotropic transverse momentum distributions as all charged ones, and no additional contribution comes from the quantum correlations of identical particles, which is the default in these two models. If identical particle correlations

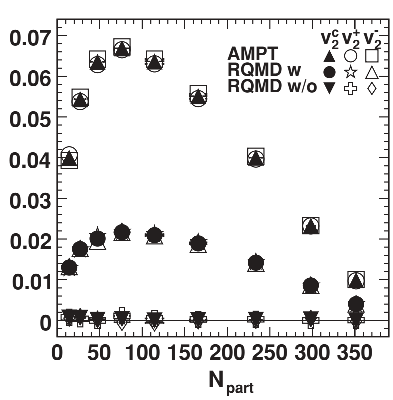

FIG. 1. Elliptic flow v_2 for all positive and negative charged particles produced by the AMPT model with string melting and for the RQMD model without and with hadronic rescattering.

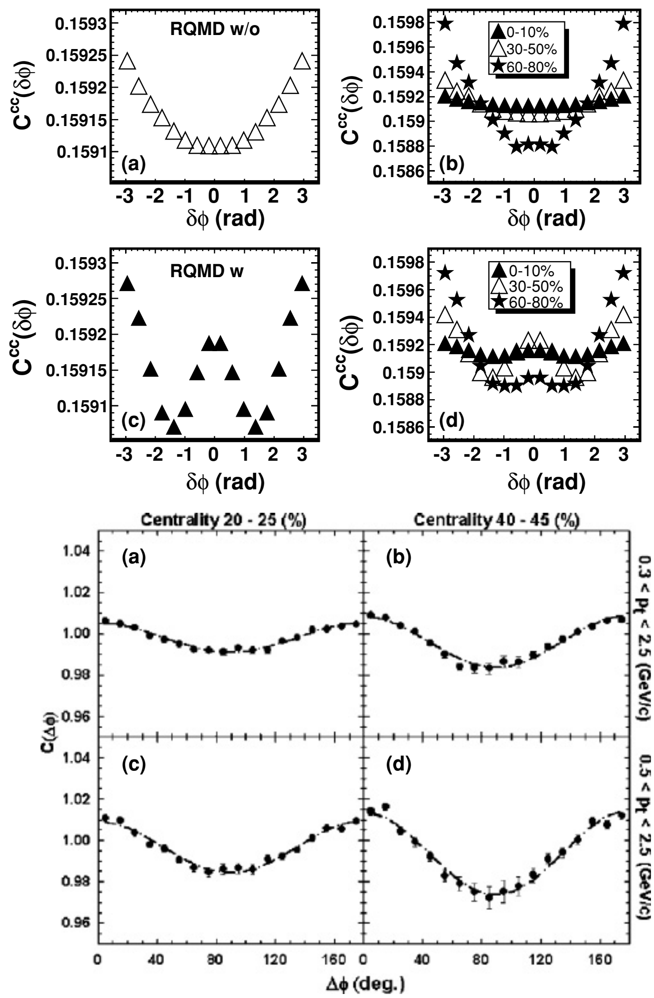

FIG. 2. (Top) The TPACs from the RQMD model without (upper panels) and with (lower panels) hadron rescattering for minimum bias samples, (a) and (c), and for three centralities, (b) and (d), as indicated in the legend. (Bottom) The centrality and p_T dependence of TPACs for charged hadrons from the PHENIX Collaboration [8].

contribute to the measurement, the differences between v_2^c of all charged particles and v_2^+ or v_2^- of identical particles could be observed.

In Fig. 2, the TPAC of all charged pairs from the RQMD model calculations without and with hadronic rescattering are presented in the upper and middle panels, respectively. For the result from the RQMD model without hadronic rescattering shown in Fig. 2(a), the small-angle correlation is the smallest whereas the large-angle correlation is the strongest. The strong large-angle correlation indicates that there are back-to-back correlations, which come from the constraint of momentum conservation. The centrality dependence of the correlation strength in Fig. 2(b) shows that, for more central collisions, the correlations become weaker. This is presumably because the larger the number of final state particles, the weaker the effect from the constraint of momentum conservation.

When hadron rescattering is switched on in the RQMD calculation, the small-angle correlations are enhanced, as shown in Fig. 2(c). But the magnitude is much smaller than

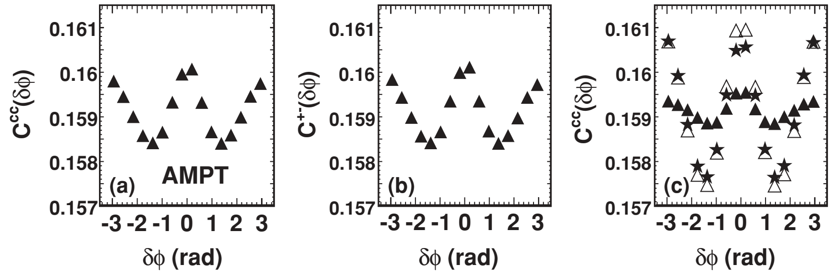

FIG. 3. Azimuthal angle correlations of all (a) and opposite (b) charged particles from the AMPT model with the string melting model, and centrality dependence of the correlation for all charged particles (c), where the centrality bins are 0%–10% (solid triangles), 30%–50% (open triangles), and 60%–80% (solid stars), respectively.

that for the large-angle ones, in contrast to the equally strong correlations in small and large angles observed by the PHENIX experiment [8] (cf. the bottom panel of Fig. 2). The magnitudes of the correlations from the models and data are quite different, as the latter is normalized to the number of uncorrelated pairs with the same relative angle, instead of the total number of pairs in Eq. (1).

The centrality dependence of the correlations from the same model is shown in Fig. 2(d), where the three centrality bins are 0%–10% (most central), 30%–50%, and 60%–80% (most peripheral). The small-angle correlations are the strongest for 30%–50% collisions and decrease for the most central collisions and the most peripheral ones. Such centrality dependence is similar to that for elliptic flow v_2 as shown in Fig. 1. Global momentum conservation contributes to large-angle correlations, which are very similar to those of the RQMD model without rescattering. These results are consistent with small-angle correlations being mainly caused by anisotropic expansion or elliptic flow.

We turn now to results from the AMPT calculations with string melting. The TPAC for all final state charged particles and for opposite charged particles are presented in Fig. 3(a) and 3(b), respectively. We observe from Fig. 3(a) that the small-angle correlation in the AMPT model with string melting is almost as strong as the large-angle one, consistent with the observed results from the PHENIX experiment [8] (cf. the bottom panel of Fig. 2). This is because the small-angle correlation resulting from anisotropic expansion in the AMPT model is considerably larger than that from the RQMD model with hadronic rescattering, as shown in Fig. 1.

The small-angle correlations for opposite charged pairs shown in Fig. 3(b) are almost the same as that for all charged pairs. So the oppositely charged pairs do not make any additional contributions to the small-angle correlations. The centrality dependence of the correlation for all charged particles is shown in Fig. 3(c). We can see again that the largest small-angle correlations are in peripheral collisions (30%–50%), the smallest ones in central collisions, and the middle ones is in the most peripheral collisions. These are exactly the same centrality dependencies of elliptic flow. Therefore, the small-angle correlation is indeed caused by anisotropic expansion.

III. THE AZIMUTHAL CHARGE BALANCE FUNCTION

It is interesting to study whether the azimuthal balance function has features similar to the TPAC in these two transport models. The centrality dependence of the ACBF from the RQMD model without and with hadron rescattering is presented in Fig. 4(a) and 4(b), respectively. The shapes of the ACBF from the RQMD model without rescattering are downward bending, similar to the corresponding TPAC, but they are centrality independent, in contrast to the TPAC shown in Fig. 2(a). This shows that the momentum conservation effect is not manifested in the ACBF. Although the ACBF from the RQMD model with rescattering at three centrality bins are upward bending, similar to the small-angle correlations, the large-angle correlations are absent, which confirms that the momentum conservation effect is well eliminated from the measurement.

The width of the ACBF becomes narrower with increasing centrality. The narrowest ACBF corresponds to the most central collisions. The width of the ACBF decreases monotonically with increasing centrality, consistent with the observed data from STAR experiments [14]. However, these trends are different from the centrality dependence of elliptic flow shown in Fig. 1, where the elliptic flow values are small for the most central and peripheral collisions. It also contrasts with the expectations from thermal models, where the lower freeze-out temperature and the larger transverse flow (or elliptic flow) are expected to produce a narrower ACBF [10].

However, the values of the ACBF for the most peripheral collisions are negative. From the definition of the ACBF of Eq. (2), this happens when the number of same charged pairs are larger than that of opposite charged ones. This implies

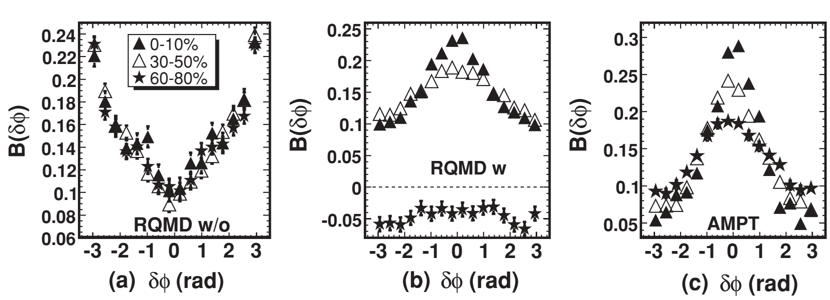

FIG. 4. Centrality dependence of the ACBF in the RQMD model without (a) and with (b) rescattering and in the AMPT model with string melting (c) at three centralities as indicated in the legend.

that charge balance is not well preserved in the case of the subsample from the model.

The centrality dependence of the ACBF from the AMPT model with string melting is presented in Fig. 4(c) for comparison. The balance functions at three centrality bins are all upward bending, similar to those from the RQMD model with hadron rescattering, and are all positive, in contrast to that of the most peripheral collisions from the RQMD calculation with hadron rescattering. The centrality dependence of the width of the ACBF is qualitatively the same as that from the RQMD model with hadron rescattering, but the width of the ACBF changes smoothly with centrality, in contrast to the case of the RQMD model with hadron rescattering. Therefore, it is in better agreement with the data from STAR experiments [14].

The ACBF measures the charge balance or compensation in the azimuthal angle resulting from the constraint of global charge conservation, which is related to the hadronization mechanism. The elliptic flow presents the azimuthal angular anisotropic expansion in the transverse momentum caused by noncentral collisions. The values of elliptic flow should be zero for head-on collisions and smaller for the most peripheral collisions. Elliptic flow is a nonmonotonic function of centrality. So the ACBF cannot be used as a probe of momentum asymmetry, but it may be useful in identifying the mechanism of hadronization, as it was originally supposed to be in rapidity [13].

The pictures of evolution and hadronization in the thermal model [10,15] and transport model, in particular in the AMPT model with string melting, are rather different and therefore results in different descriptions in the behavior of the ACBF. Our results show that quark coalescence at hadronization in the AMPT model with string melting successfully reproduces the observed centrality dependence of the ACBF [14]. Although the thermal model reproduces the observed centrality dependence of the charge balance function in rapidity [14,16], it fails to describe the observed centrality dependence of the charge balance function in azimuthal angle [10,14].

IV. SUMMARY

The two-particle azimuthal correlation and the azimuthal charge balance function are studied in Au + Au collisions at 200 GeV using two transport models, the RQMD model and the AMPT model. It is demonstrated that small-angle correlations in the TPAC are indeed related to the azimuthal angular anisotropic expansion of the collisions, and the large-angle (or back-to-back) correlations come mainly from global momentum conservation. The AMPT model reproduces the observed equally strong correlations in large and small angles, but in the RQMD model the stronger correlations appear in larger angles. The width of the ACBF in both RQMD and AMPT models decreases monotonically with increasing centrality. This is consistent with the observed data in STAR experiments, but contrasts with what is expected from thermal models, where the cooler freeze-out temperature and the larger elliptic flow will lead to a narrower ACBF. The ACBF is insensitive to anisotropic expansion, but it is a good probe for the mechanism of hadronization, similar to the charge balance function in rapidity.

ACKNOWLEDGMENTS

The authors are grateful to Dr. Huanzhong Huang for reading the manuscript critically and to Dr. Zhixu Liu, who generously offered samples of the RQMD model. This work is supported in part by the NSFC of China (Project Nos. 10835005, 90503001, and 90103019) and the Programme of Introducing Talents of Discipline to Universities under Grant No. B08033.

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