Is there hydrodynamic flow at RHIC?

Wang Meijuan,1 Liu Lianshou,1,2 and Wu Yuanfang1,2

1Institute of Particle Physics, Huazhong Normal University, Wuhan 430079, China
2Key Laboratory of Quark and Lepton Physics, Ministry of Education of China

It is argued that the observation of anisotropic azimuthal distribution of final state particles alone is insufficient to show whether the formed matter at RHIC behaves like hydrodynamic flow. Examining the intrinsic interaction (or correlation) of the formed matter should provide more definite judgement. To the end, a spatial-dependent azimuthal multiplicity-correlation pattern is suggested. It shows clearly in the pattern that there are two kinds of interactions at the early stage of Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV generated by RQMD with hadron re-scattering and AMPT with string melting. This is out of the expectation from the elliptic flow driven by anisotropic expansion.

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The data from current relativistic heavy ion experiments show that a new form of matter — quark-gluon plasma (QGP) has been produced at RHIC [1,2]. The second Fourier coefficient $v_2$ of the anisotropic transverse-momentum $p_T$ distribution of final state particles is believed to provide the anisotropic collective flow behavior at the early stage of collision. The successful hydrodynamic description [3] on the observed mass dependence of $v_2$ at $p_T < 2$ GeV shows that the observed dense matter behaves like a perfect fluid rather than an ideal gas, and is, therefore, referred to as sQGP.

However, hydrodynamics can still not quantitatively fit the observed mass dependence of $v_2$ [4]. The recently measured elliptic flow $v_2$ from Cu + Cu collisions at 200 GeV is unexpected as large as that from Au + Au collisions at the same energy [5,6]. Moreover, the resulting matter may be treated as hydrodynamic flow only if the initial interaction among the constituents are sufficiently strong to establish local thermal equilibrium rapidly, and then to maintain it over a significant evolution time. No known strong-interaction process could be thermalized on such a short timescale. A Liquid without viscosity is also hard to be understood theoretically [7]. So, there appear a number of alternative non-equilibrium treatments, which have also been compared to RHIC data [8,9,10].

To conclusively clarify the debate, a direct experimental examination on the intrinsic interaction of the formed matter is necessary. The hydrodynamic flow at RHIC is supposed to be driven by the so called anisotropic expansion. In non-central collisions, the initial participant zone of the two colliding nuclei is approximately an ellipse, and the density gradient along the short side of ellipse is larger than that along the long side. It is argued that the larger density, or pressure, gradient along the short side of ellipse makes collective expansion to be privileged in this direction, i.e., the anisotropic expansion, producing in-plane elliptic flow, or the transverse-momentum of final state particles distribute in an ellipse perpendicular to the one in coordinate space.

However, the main physical quantity which can be extracted from experimental data in exploiting relativistic hydrodynamic approach is the elliptic flow parameter $v_2$. It only indicates the possible preferential direction of expansion and contains no information on the intrinsic interaction of the formed matter. It therefore is insufficient to assure whether the formed matter behaves like hydrodynamic flow. If the anisotropic expansion is the only driver of the elliptic flow, the distribution of intrinsic interaction (or correlation) of flow should have the same anisotropy, i.e., in-plane like. Moreover, if it is really hydrodynamic flow, it should be well locally thermalized and reach thermal equilibrium. Then all other interaction history before anisotropic expansion should be forgotten. These characteristics can be examined in an experimentally measurable correlation pattern.

In this letter, we will first introduce the spatially-dependent correlation pattern, i.e., neighboring angular-bin multiplicity correlation pattern. Then, we demonstrate that at least two kind of interactions are revealed by the suggested correlation pattern in Au + Au collisions at 200 GeV, generated by RQMD [16] and AMPT [17]. Finally, how to experimentally measure the correlation pattern and anisotropic correlation coefficient is discussed.

To examine the intrinsic interaction of highly anisotropic system, a spatial-dependent bin-bin correlation is called for. Conventionally, the spatially averaged bin-bin correlation has been used in multiparticle production in exploring self-similar fractality [11], where the system is supposed to be homogeneous, and only scaling in the shrinking of phase space is concerned. Another intrinsic interaction related measure is the 2-particle azimuthal correlation [4,12]. It concerns the average correlation of two particles separated by a certain angle, no matter where the two particles are in the azimuthal space. It therefore can not tell us where the preferential direction of intrinsic interactions are.

The newly suggested spatial-dependent neighboring bin correlation pattern [16] provides a typical spatial distribution of two-bin correlation. The information on intrinsic correlation can be well presented by the measure, and it should give more direct and definite judgement on the propery of the formed matter at RHIC.

It is well-known that the general 2-bin correlation is
defined as
\[ C_{m_1,m_2} = \frac{\langle n_{m_1} n_{m_2} \rangle}{\langle n_{m_1} \rangle \langle n_{m_2} \rangle} - 1, \tag{1} \]
where \( m_1 \) and \( m_2 \) are the positions of the two bins in phase space and \( n_m \) is the measured content in the \( m \)th bin.

We divide the \( 2\pi \) azimuthal angle equally into \( M \) bins and specify \( n_m \) as the multiplicity in the \( m \)th angular bin. If we let \( m_1 = m \) and \( m_2 = m + 1 \), \( C_{m_1,m_2} \) is reduced to the neighboring angular-bin multiplicity correlation pattern,
\[ C_{m,m+1} = \frac{\langle n_m n_{m+1} \rangle}{\langle n_m \rangle \langle n_{m+1} \rangle} - 1. \tag{2} \]

It is clear that the correlation pattern measures how the nearby particles correlate with each other in different directions of azimuthal space. If the particles are produced independently in the whole phase space, then \( \langle n_m n_{m+1} \rangle = \langle n_m \rangle \langle n_{m+1} \rangle \), and \( C_{m_1,m_2} \) vanishes.

In order to apply this correlation pattern to current relativistic heavy ion collision, we choose the RQMD and AMPT models as examples. The RQMD (relativistic quantum molecular dynamics) with re-scattering is a hadron-based transport model [13]. The final hadron interactions are implemented in the model by hadron re-scattering. The anisotropic collective flow produced by the model is much smaller than the observed data at RHIC. In contrary to the RQMD model, the AMPT is a multi-phase transport model, where both hadron and parton interactions are taken into account. In the AMPT with string melting, the parton level transport is fully taken into account, and the observed anisotropic collective flow at RHIC is well reproduced [16].

For Au + Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV, we generate 249,824 and 204,004 events using RQMD with hadron re-scattering and AMPT with string melting, respectively. Their neighboring angular-bin multiplicity correlation patterns are shown in Fig. 1(a) by open and solid circles, respectively. Here we partition the whole azimuthal range \( 2\pi \) uniformly into 50 equal size angular bins. \( \phi = 0 \) refers to the direction of the reaction plane in nuclear collision. The errors are statistical only and most of them are smaller than the symbol size in this and following figures. It is clearly shown in Fig. 1(a) that correlation patterns from these two models are \( -\cos 2\phi \) (out-of-plane) like, opposite to the well-known \( \cos 2\phi \) (in-plane) liked azimuthal distribution. This is in contrary to the expectation that the formed matter expands collectively toward in-plane direction. Some unexpected interactions should be responsible for such a result.

In order to see how the results come, the centrality dependence of neighboring angular-bin multiplicity correlation patterns from these two models are presented in Fig. 1(b) and (c), respectively, where three typical centralities are specified in the legends. One can observe that the two models give qualitatively the same centrality dependence of azimuthal correlation pattern. The correlation patterns are \( \cos 2\phi \) like in peripheral collisions, then turn to flat in mid-central collisions, and become \( -\cos 2\phi \) like in near-central collisions. Here, we present only three centrality ranges to show their typical behavior. In fact, the correlation pattern changes gradually from \( \cos 2\phi \) to \( -\cos 2\phi \) with centrality. It is clear that two opposite trends dominate in peripheral and near-central collisions, respectively. In the mid-central collisions, the two trends turn to balance and the correlations become equal in all directions. Moreover, these characteristics are independent of the specific assumptions implemented in the two models, in particular independent of the hadronization schemes assumed in the models.

The characteristics of correlation pattern reveal that there are two opposite intrinsic interactions in the formed matter in these two transport models. One has the same preferential direction as the anisotropic expansion. The other one is opposite to it. This also shows that the anisotropic azimuthal distribution is not only driven by anisotropic expansion. It is resulted from the combination of these two opposite interactions.

The anisotropic expansion and the late hadronization are impossible to produce strong correlations in out-of-plane direction. Only the initial source eccentricity in non-central collisions is preferential in the direction. It results in a larger initial number of participant nucleons in the out-of-plane direction, which in turn could generate stronger interaction in the direction. As long as the system is not fully thermalized, this initial interaction will compete with the subsequent anisotropic expansion.

In peripheral collisions, the overlap zone is small and so is the number of participant nucleons, but the difference between the minor and major axes of overlap ellipse is large, and so is the difference of pressure gradients. In this case the anisotropic expansion dominates the final observables, and the effects of initial interaction in correlation patterns are hidden. In near-central collisions, the overlap zone becomes large and the difference between minor and major axes of ellipse is small, so that the initial interactions are strong enough to show themselves up in final observable. This is why the out-of-plane correla-
tion patterns appear at near-central collisions.

So the behavior of the formed matter in these two transport models are far from the flow in relativistic hydrodynamics sense. This is out of the current expectation for the formed matter at RHIC. Measuring the correlation pattern by the data of relativistic heavy ion collisions at RHIC and LHC is therefore looking forward. As long as the observed preferential direction of correlation pattern are different from that of its azimuthal distribution, such as what we show by transport models, then there should be no hydrodynamic flow at RHIC. On the other hand, if the experimentally measured correlation pattern has the same anisotropy as its azimuthal distribution, it will be a strong support to the current expectation at intrinsic interaction level that the formed matter at RHIC indeed behaves like hydrodynamic flow.

The correlation patterns are typical periodic functions of azimuthal angle in peripheral and central collisions, as shown in Fig. 1. So they can be well expanded by Fourier series,

$$C_{\phi,\phi+\delta\phi} = C \left[ 1 + \sum_{i=1}^{2} 2u_i \cos(i(\phi - \psi_r)) \right] ,$$

where the $\psi_r$ is the direction of reaction plane, and is zero in the model analysis. But in real experimental data analysis, it has to be determined event-by-event, and thereby refers to event-plane. It has been carefully estimated in the measurement of anisotropic elliptic flow $v_2$ in current relativistic heavy experiments \[15\]. The main contribution in the expansion series comes from $\cos(2(\phi - \psi_r))$. Its coefficient $u_2$ provides the preferential direction and strength of anisotropic correlation pattern. We specify it as anisotropic correlation coefficient (ACC). It will make the systematic study of the correlation pattern easy.

It is interesting to see how ACC, $u_2$, depends on the transverse-momentum $p_t$ of final state particles, in comparison to the corresponding $p_t$ dependence of $v_2$. It is known that the evolution schemes of RQMD with re-scattering and AMPT with string are different. In the former, the $p_t$ spectrum is determined by the temperature of thermal source. High $p_t$ particles are emitted early at high temperature and low $p_t$ ones are emitted later on at low temperature. The range of $p_t$ of final state particles is related to its emitting proper-time \[12\]. So the $p_t$ dependence of $u_2$ in RQMD with re-scattering will present how the correlation pattern changes with evolution.

The results are presented in Fig. 2(a). We can see that in each $p_t$ interval, $u_2$ keeps positive in peripheral collisions, becomes negative for mid-central collisions, and becomes even more negative for central collisions. They are similar to that for all $p_t$ particles shown in Fig. 1(b). It should also be noticed in Fig. 2(a) that $u_2$ is almost independent of the choice of $p_t$ ranges of final state particles in peripheral and mid-central collisions, but decrease rapidly with the increase of $p_t$ in central collision. This is understandable since high $p_t$ particles are emitted earlier, and less influenced by the later anisotropic expansion in central collisions.

On the contrary, each parton in the AMPT with string melting has its own freeze-out time, which span a long period after the initial interaction of the two nuclei, and are unrelated to each parton’s transverse momentum \[16\]. So similar $p_t$ dependence of $u_2$ can be observed in this model only when the chosen interval of $p_t$ is very large.

The rapidity dependence of ACC, $u_2$, is further studied by these two transport models. They give qualitatively the same dependency. The results from RQMD are presented in Fig. 2(b), where three typical rapidity ranges, i.e., forward, backward and central rapidity ranges, are chosen. It shows that the correlation pattern is independent of the choice of rapidity range, and similar to that in the whole rapidity space. So in finite rapidity range of current relativistic heavy ion experiments \[19\], studying the correlation pattern and anisotropic correlation coefficient is expectable, and will provide more definite evidence on whether or not the formed matter behaves like hydrodynamic flow.

To the summary, it is argued that the observation of anisotropic azimuthal distribution of final state particles alone is insufficient to assure whether the formed matter at RHIC behaves like hydrodynamic flow. Examining the intrinsic interaction (or correlation) of the formed matter should provide more definite judgement. To the end, a spatially-dependent azimuthal multiplicity-correlation pattern is suggested. It shows clearly that there are two kinds of interactions at early stage of Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV, generated by RQMD with hadron re-scattering and AMPT with string melting. One is in-plane preferential as expected from anisotropic expansion due to initial eccentricity in non-central collisions. Another new one is out-of-plane preferential, which may be resulted from the larger initial number of participant nucleons in these direction. These characters of correlation pattern show at least in two transport models that the formed matter does not behave like hydrodynamic flow, in contrary to current expectation. Finally, how to experimentally measure the correlation pattern and
anisotropic correlation coefficient is discussed. The authors would thank Dr. Nu Xu, Aihong Tang and Huangzhong Huan for their stimulating comments. We are grateful for the financial supports from the NSFC of China under projects: No. 90503001, 10610285, 10775056.





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