

## Detecting quark gluon plasma with charge transfer fluctuations

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We analyze the recently proposed charge transfer fluctuations within a finite pseudorapidity space. As the charge transfer fluctuation is a measure of the local charge correlation length, it is capable of detecting inhomogeneity in the hot and dense matter created by heavy-ion collisions. We predict that, going from peripheral to central collisions, the charge transfer fluctuations at mid-rapidity should decrease substantially while the charge transfer fluctuations at the edges of the observation window should decrease by a small amount. These are consequences of having a strongly inhomogeneous matter in which the quark gluon plasma component is concentrated around mid-rapidity. We also show how to constrain the values of the charge correlation lengths in both the hadronic phase and the quark gluon plasma phase by using the charge transfer fluctuations.

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### I. INTRODUCTION

More than 20 years ago, Bjorken in his seminal paper [1] considered the possibility that the central plateau around mid-rapidity could be due to a hot and dense matter undergoing a boost-invariant expansion. At high enough collision energies, the temperature and density would be high enough for the created matter to be composed of deconfined quarks and gluons (quark-gluon plasma or QGP).

Recent studies at Brookhaven National Laboratory's Relativistic Heavy Ion Collider (RHIC) have shown that extremely hot and dense matter has indeed been created around mid-rapidity with the energy density well above the expected transition density [2–6]. However, there is also evidence that the boost invariance may not be a feature of the created system, even within the apparent plateau region. For instance, the elliptic flow measured by the PHOBOS Collaboration [7] shows no discernible plateau around the central (pseudo)rapidity.

Taken together, the above evidence can be regarded as an indication that the spatial extent (in the pseudorapidity space) of the created QGP may be only a fraction of the size of the plateau region. For instance, the QGP component may be concentrated around the mid-rapidity as schematically shown in Fig. 1 whereas the rest of the system is mostly hadronic.

In view of such a possibility of having inhomogeneous matter, we should ask different questions about the produced matter at RHIC. Namely, instead of asking whether we have created a QGP, we should ask what fraction of the produced matter went through the deconfined phase and how big the size of the deconfined phase was. If inhomogeneity is strong, these questions should be answerable by some judicious choice of observables.

In a previous paper [8], we proposed a new observable, the charge transfer fluctuations, for measuring the *local* charge correlation length. Because the charge correlation lengths of a

QGP and a hadronic gas can be significantly different [9–13], the changes in charge transfer fluctuations should signal the presence and the extent of the inhomogeneity. In Ref. [8], we considered an ideal case, assuming a nearly  $4\pi$  detector with 100% efficiency. We argued that, with such an ideal detector, the charge transfer fluctuations should show a local minimum where the QGP was formed. In this follow-up paper, we concentrate on a more realistic case. The goal is to predict what experiments at RHIC, STAR in particular, should observe.

The charge transfer fluctuation is defined by [14,15]

$$D_u(\eta) \equiv \langle u(\eta)^2 \rangle - \langle u(\eta) \rangle^2. \quad (1)$$

The charge transfer  $u(\eta)$  is in turn defined by the forward-backward charge difference:

$$u(\eta) = [Q_F(\eta) - Q_B(\eta)]/2, \quad (2)$$

where  $Q_F(\eta)$  is the net charge in the forward pseudorapidity (or rapidity) region of  $\eta$  and  $Q_B(\eta)$  is the net charge in the backward pseudorapidity (or rapidity) region of  $\eta$ . The fluctuation  $D_u(\eta)$  is then a measure of the correlation between the charges in the forward and the backward regions that are separated by a cut located at  $\eta$ . As the net charge is experimentally easier to measure in the pseudorapidity space, from now on we use the pseudorapidity exclusively. However, all formalism can be directly translated to the rapidity.

In Ref. [8], we considered the case in which the experimental pseudorapidity coverage is much larger than the extent of the QGP region. Using single-component and two-component neutral-cluster models, we showed that the presence of a QGP component results in a local minimum for  $D_u(\eta)$  at the location of the highest concentration of the QGP because it has a shorter charge correlation length. The size of the dip can be then used to infer the size of the QGP region. Data from  $pp$  and  $K^-p$  collisions in the energy ranges of  $p_{\text{lab}} = 16$  GeV to  $p_{\text{lab}} = 205$  GeV show that the charge transfer fluctuations is independent of rapidity [15,16]. This is also true for HIJING [17–19] and URQMD [20,21] events for Au-Au collisions, as shown in Fig. 2.

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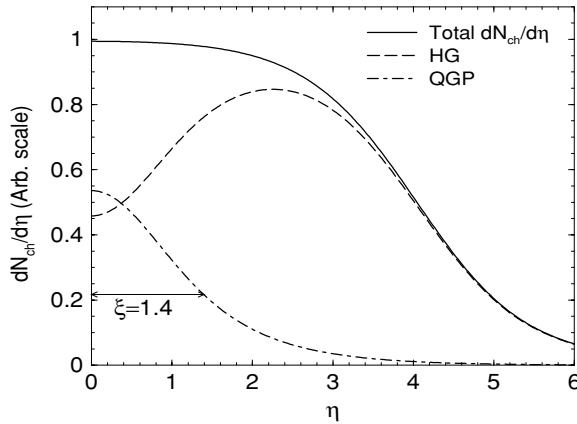


FIG. 1. Illustration of a possible spatial inhomogeneity of the matter produced in central heavy-ion reactions at RHIC. The solid curve represents all charged particles produced in the heavy-ion collisions. The dotted-dashed curve indicates the fraction of charged particles originating from a QGP, and the dashed curve is for the charged particles that never went through a deconfined phase. At mid-rapidity, the QGP concentration is high, whereas, in the forward direction, almost all particles come from the confined hadronic matter (hadronic gas or HG).

If the detector coverage is comparable with or smaller than the QGP size, then it is not likely that the local minimum can be observed. Among the four experiments currently operating at RHIC, only the STAR detector has enough coverage and charge identification capability to carry out the charge transfer fluctuation studies. Still, the STAR pseudorapidity coverage ( $|\eta| \leq 1$ ) is comparable with the extent of the QGP region we estimated in Ref. [8]. Hence a quantitative analysis is necessary to show the potential of the charge transfer fluctuation measurement.

The strength of the observed signal depends critically on the difference between the charge correlation lengths in the QGP and the hadronic phases. One way to estimate the difference is through the net charge fluctuations. In Refs. [22,23], two

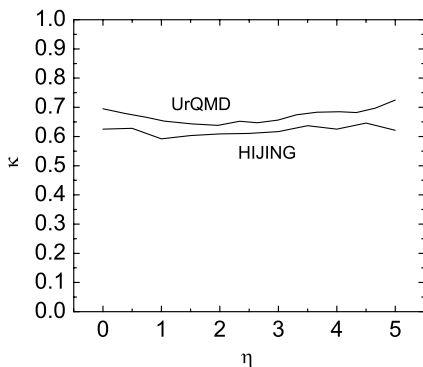


FIG. 2.  $\tilde{\kappa}(\eta) = [D_u(\eta) - \langle \Delta Q^2 \rangle_{4\pi} / 4] / (dN_{ch}/d\eta)$  generated by URQMD Au-Au central collisions and HIJING central collisions. The net charge fluctuation  $\langle \Delta Q^2 \rangle_{4\pi}$  of the produced particles is in general nonzero because the net charge of the spectators fluctuates. Hence it must be subtracted from  $D_u$  so that the ratio remains finite near the beam rapidities.

teams independently showed that the net charge fluctuations per charged degrees of freedom,  $\langle \Delta Q^2 \rangle / \langle N_{ch} \rangle$ , can be two to four times smaller if the hadrons came from a hadronizing QGP rather than from a hot resonance gas [13]. Using neutral-cluster models, one can show that this in turn implies that the charge correlation length is two to four times smaller in a QGP than in a hadronic system.

## II. THOMAS-CHAO-QUIGG RELATIONSHIP AND NON-QGP MODELS

Originally, Thomas and Quigg [14] applied the charge transfer fluctuations in the boost-invariant case and obtained

$$D_u = c\gamma \frac{N_{ch}}{Y}, \quad (3)$$

where  $N_{ch}/Y$  is the value of the boost-invariant  $dN_{ch}/dy$  and  $\gamma$  is the charge correlation length. The proportionality constant  $c$  depends on the properties of the underlying clusters. Later, Chao and Quigg generalized this to smooth  $dN_{ch}/dy$  cases and wrote the following Thomas-Chao-Quigg relationship [15]:

$$D_u(y) = \kappa \frac{dN_{ch}}{dy}, \quad (4)$$

where  $\kappa \propto \gamma$ . They also showed that  $\kappa$  is constant (independent of  $y$ ) for all available elementary particle collision data at the time.

These original studies used a simple neutral-cluster model in which an underlying cluster with rapidity  $y$  decays into two charged particles and a single neutral particle. The rapidities of these three decay products are given by  $(y - \Delta, y, y + \Delta)$ , with  $\Delta \propto \gamma$ . In Ref. [8], we generalized this simple model so that the joint probability density for the charged decay products is given by (switching to pseudorapidity)

$$f(\eta^+, \eta^-) = R(r)F(Y), \quad (5)$$

where  $r = \eta^+ - \eta^-$  and  $Y = (\eta^+ + \eta^-)/2$ . Here the function  $F(Y)$  can be interpreted as the rapidity distribution of the clusters and  $R(r)$  can be interpreted as the rapidity distribution of the decay products given the cluster rapidity  $Y$ . We then showed that the above Thomas-Chao-Quigg relationship (4) with a constant  $\kappa$  is exactly satisfied if

$$R(r) = \frac{1}{2\gamma} \exp(-|r|/\gamma), \quad (6)$$

with  $\gamma = 2\kappa$ , and  $F(Y)$  is chosen so that the single-particle distribution  $g(\eta) = \int_{-\infty}^{\infty} d\eta' f(\eta', \eta)$  yields the normalized  $dN_{ch}/d\eta$  by use of the fact that the above  $R(r)$  is the Green's function of the operator  $d^2/dr^2 - 1/\gamma^2$ . The charged particle density  $dN_{ch}/d\eta$  is modeled with a Woods-Saxon form in this study. More sophisticated fittings are also possible [24].

As shown in Fig. 2, non-QGP models of heavy-ion collisions also satisfy the Thomas-Chao-Quigg relationship with a constant  $\kappa \approx 0.6-0.7$  or equivalently  $\gamma \approx 1.2-1.4$ .

One should emphasize here that the Thomas-Chao-Quigg relationship is for the case in which the *whole* (pseudo) rapidity space is observed. If the observational window is limited, then

the ratio

$$\bar{\kappa}(\eta) = \frac{\bar{D}_u(\eta)}{dN_{\text{ch}}/d\eta} \quad (7)$$

will no longer be independent of  $\eta$  even if  $\gamma$  is constant. The bar over  $\kappa$  and  $D_u$  indicates that they are measured within only a finite observation window. In Ref. [8] we showed that, when the observation window is confined to  $|\eta| \leq \eta_o$ , the charge transfer fluctuation is

$$\bar{D}_u(\eta) = \frac{\langle \Delta Q^2 \rangle}{4} + 2\langle M_0 \rangle \int_{-\eta_o}^{\eta} d\eta^- \int_{-\eta}^{\eta_o} d\eta^+ f(\eta^+, \eta^-), \quad (8)$$

where

$$\langle \Delta Q^2 \rangle = 4\langle M_0 \rangle \int_{-\infty}^{-\eta_o} d\eta^+ \int_{-\eta_o}^{\eta_o} d\eta^- f(\eta^+, \eta) \quad (9)$$

is the net charge fluctuation within  $|\eta| < \eta_o$  and  $M_0$  is the total number of the neutral clusters.

If  $dN_{\text{ch}}/d\eta$  is constant within the window, as is the case for the STAR Au-Au data at RHIC energies, it is clear that  $\bar{\kappa}(\eta)$  still varies with  $\eta$  even if  $\kappa$  itself is constant and such variation is entirely given by the second term in Eq. (8). In Fig. 3, we show HIJING, URQMD, and RQMD [25,26] results at various centralities together with a single-component model fit. The calculation is done with the STAR acceptance  $\eta_o = 1$  and  $p_T > 0.1$  GeV. Also, the STAR detection efficiency is taken into account in a simple way by either randomly taking out 10% of charged particles (for simulations) or by adding 10% of uncorrelated charged particles (for the neutral-cluster model). From these figures, it is clear that the non-QGP model results are very well described by a single-component neutral-cluster model with  $\gamma \approx 1.75$  independent of centralities. The discrepancy between this value of  $\gamma$  and the  $\gamma$  obtained in the full phase-space study is partly due to the acceptance cuts and partly due to the presence of large  $\langle \Delta Q^2 \rangle$  within  $|\eta| \leq \eta_o$ . In the present case of limited observational window, the net charge fluctuations should *not* be subtracted from  $\bar{D}_u$ .

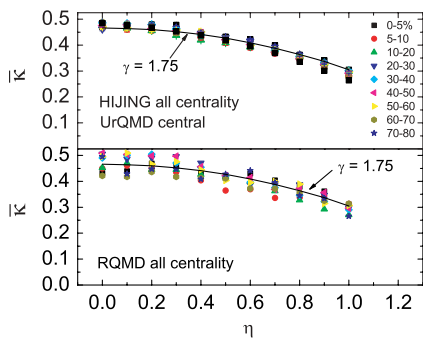


FIG. 3. (Color online) The charge transfer fluctuation is shown as a function of pseudorapidity  $\eta$ . Different symbols represent standard centralities as shown in the symbol legend. These results are from 8400 RQMD events for  $\sqrt{s} = 130$  GeV Au-Au collisions and 50000 HIJING events at  $\sqrt{s} = 200$  GeV. STAR acceptance and efficiency are taken into account in a simple way by restricting  $p_T > 0.1$  GeV and also randomly taking out 10% of the charged particles.

### III. A QGP MODEL—CENTRAL COLLISIONS

In RHIC energy heavy-ion reactions, the energy density of the created systems vary with the centrality of the collisions. The results of HIJING simulations and its single-component fit should correspond to the peripheral collision results. In central collisions, one expects that a QGP is formed and is concentrated around mid-rapidity. Hence the final-state particles can have two different origins in central collisions: Some particles will come from the hadronized QGP and others will come from the non-QGP hadronic component of the system.

In Ref. [8] we used a two-component neutral-cluster model and showed that even for such an inhomogeneous matter Eq. (8) still holds if one substitutes the  $f(\eta^+, \eta^-)$  with the following combination of the QGP correlation function  $f_{\text{QGP}}$  and the hadronic gas correlation function  $f_{\text{HG}}$ :

$$f(\eta^+, \eta^-) = (1 - p)f_{\text{HG}}(\eta^+, \eta^-) + pf_{\text{QGP}}(\eta^+, \eta^-). \quad (10)$$

Here  $p$  is the fraction of the charged particles originating from the QGP component in the whole phase space.

Each charge correlation function is assumed to have a separable form as in Eqs. (5) and (6). In the rest of this manuscript, we denote the hadronic correlation length by  $\gamma_1$  and the QGP correlation length by  $\gamma_2$ . The charge correlation length is expected to be a factor of 2–4 times smaller in the QGP than in the hadronic matter [13]; hence,  $\gamma_2 < \gamma_1$ . Details of determining  $f_{\text{HG}}$  and  $f_{\text{QGP}}$  can be found in Ref. [8]. The resulting charged particle distribution typically looks like Fig. 1. Here  $\xi$  denotes the rms width of the QGP component.

The results of the charge transfer fluctuation calculations in the two-component model are shown Fig. 4. For comparison, we have also plotted results of the single-component model calculations in Fig. 5. The results of the single-component and two-component model calculations are distinctive enough that the measurement of  $\bar{\kappa}(\eta)$  can clearly differentiate the two model cases, hence providing a way to show the existence of the QGP.

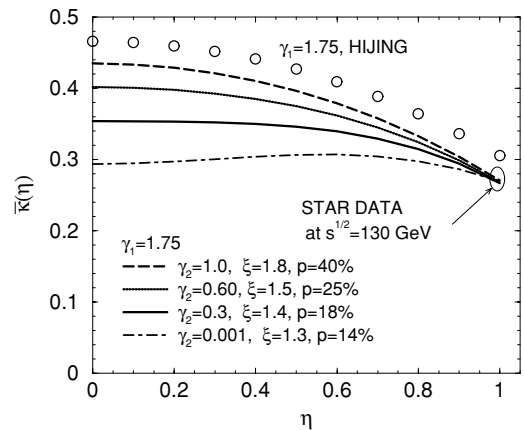


FIG. 4. The results of two-component model calculations together with the single-component result that describes the HIJING data. Also shown is the position of the data point deduced from the STAR net charge fluctuations measurement.

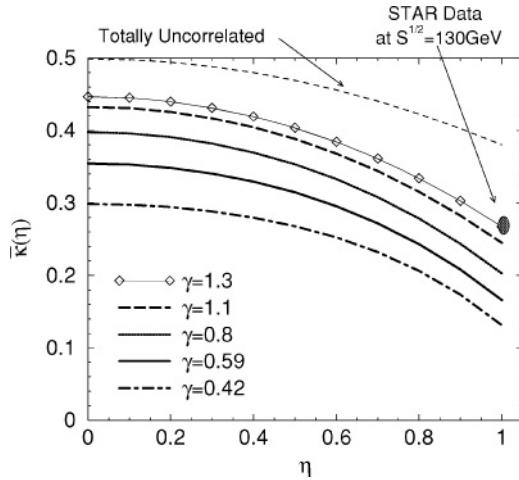


FIG. 5. Single-component results. The lower four curves have the same  $\bar{\kappa}(1)$  values as those of the four two-component model results in Fig. 4. Also shown are the results for the totally uncorrelated case (uppermost curve) and the single-component model result that has  $\bar{\kappa}(1) = 0.27$  (thin curve connecting the diamond symbols).

For the two-component model, we find that the single data point at  $\eta = 1.0$  does not constrain the overall shape of  $\bar{\kappa}(\eta)$  that much. We can find a range of possible parameter sets that give the same  $\bar{\kappa}(1.0) = 0.27$  while the corresponding shapes of  $\bar{\kappa}(\eta)$  are all very different. The biggest difference among these parameter sets is the value of  $\bar{\kappa}(\eta)$  at  $\eta = 0.0$ , where the concentration of the QGP component is strongest. The four lines with  $0.001 \leq \gamma_2 \leq 1.0$  in Fig. 4 represent typical results in two-component model calculations.

In clear contrast, in the single-component model the value of  $\bar{\kappa}(1.0)$  completely fixes the shape of  $\bar{\kappa}(\eta)$  in the entire interval  $0.0 \leq \eta \leq 1.0$ . To have  $\bar{\kappa}(1.0) = 0.27$ , the correlation length must be  $\gamma = 1.3$ . As shown in Ref. [8],  $\bar{\kappa}(\eta)$  is proportional to  $\gamma$  in the limit  $\gamma/\eta_0 \ll 1$ . Hence a reduction in  $\gamma$  results in the overall reduction of the  $\bar{\kappa}(\eta)$  in the whole range.

From these considerations, we can say that the measurement of the charge transfer fluctuations in the entire range  $0.0 < \eta < 1.0$  for various centralities will be a critical test for the existence of QGP. If the central collision data show a clear reduction from the  $\gamma = 1.3$  line in Fig. 5, it can be explained only by the presence of the second component. We also expect the amount of QGP would grow as one goes from peripheral to central collisions. Therefore the most peripheral collision data for  $\bar{\kappa}(\eta)$  will behave more like the single-component results whereas the most central collision data for  $\bar{\kappa}(\eta)$  will behave more like the two-component results. We predict that the most central collision data should lie between the two solid lines with  $\gamma_2 = 0.6$  and  $0.3$  in Fig. 4. For comparison, we have also shown two extreme cases with very large and very small QGP charge correlation lengths, where  $\gamma_2 = 1.0$  and  $0.001$ .

Before leaving this section, we would like to discuss two possible caveats here. There is a possibility that more than one QGP droplet may form in a typical central collision event in which these droplets are distributed in some rapidity interval. Averaged over many events, this would be very much like

lowering the charge correlation length of the entire rapidity interval. In this case, the central  $\bar{\kappa}$  should behave like the  $\gamma_2 = 1.0$  curve in Fig. 4 whereas the peripheral  $\bar{\kappa}$  should still follow the HIJING points. If this turns out to be indeed how the data behave, it would be much desirable to have a larger rapidity window.

There is also a possibility that baryon pairs in the hadronic phase are produced predominantly in the larger rapidity regions with shorter charge correlation lengths. If the number of such pairs is comparable with the lighter meson pairs, then they can mimic the concentrated QGP. However, as the number of  $\bar{p}$  is only about 7% of  $\pi^-$  in the central rapidity region [27], this should not be a problem for this study. In the same context, it will be interesting if baryon-number transfer fluctuations and strangeness transfer fluctuations can be measured at the same time as charge transfer fluctuations.

#### IV. UNCORRELATED CHARGES

The detection efficiency for charged particles is typically less than 100% in real experiments. This has been a concern in the measurement of the net charge fluctuations. In the previous paper, we argued that this effect is small and will not affect the qualitative arguments we had [8]. However, with a limited observation window, the difference between the one- and the two-component model is more quantitative, and the detector efficiency deserves some attention.

In terms of the pair correlations, the nonideal detector efficiency renders some of the correlated pairs uncorrelated. The relevant formulas are already worked out in the previous paper [8].

If the detector efficiency is  $\epsilon$  and all the charged particles are correlated, then  $1 - \epsilon$  of detected particles will become uncorrelated because their partners are not detected. The corresponding charge transfer fluctuations are  $\bar{\kappa} = \epsilon \bar{\kappa}_{\text{corr}} + (1 - \epsilon) \bar{\kappa}_{\text{uncorr}}$ , where  $\bar{\kappa}_{\text{corr}}$  indicates the fully correlated charged particles and  $\bar{\kappa}_{\text{uncorr}}$  indicates the uncorrelated charged particles.

The shape of  $\bar{\kappa}_{\text{uncorr}}$  is shown in Fig. 5. The shape is flatter than the correlated cases and it is always above  $\bar{\kappa}_{\text{corr}}$ . The detector efficiency in STAR experiment is about 85%–90%. Having 10% of uncorrelated charges will slightly increase  $\bar{\kappa}(\eta)$  and make the overall shape a little bit flatter. This, however, will not change much of the results for  $\kappa(\eta)$ . The signature for the appearance of the second QGP-like component is still present, and we can still put an upper limit on the  $\gamma_{\text{QGP}}$  if a significant reduction of  $\kappa(0.0)$  is observed. All the results presented in this paper already considered the effect of uncorrelated charged particles.

#### V. SUMMARY

In this paper, we proposed the charge transfer fluctuation as a good observable capable of detecting the *local* presence of a QGP in a limited pseudorapidity space. In contrast, the net charge fluctuations [22,23] and the width of the balance function [9] are sensitive to the presence of a QGP only when

the fraction of the QGP component is substantial in the whole observational window. Because longitudinal inhomogeneity is expected from both theoretical considerations and experimental observations, it is important to have an observable that is sensitive to it. Furthermore, such inhomogeneity may explain why the net charge fluctuations did not show a strong signal even though the underlying net charge fluctuations could be strongly reduced in the QGP phase.

In this study, we showed that the three hadronic models, HIJING, RQMD, and URQMD are consistent with a single-component model with a fixed charge correlation length of about  $\gamma = 1.75$ . If a QGP is created in central heavy-ion collisions, a significant deviation from this behavior is expected in the data. Specifically, if the QGP component is concentrated around mid-rapidity and tapers off going away from mid-rapidity, then one should see the following trends in the data:

- (i) The overall values of  $\bar{\kappa}(\eta)$  must decrease going from peripheral collisions to central collisions. This indicates that more QGP is being created.
- (ii) The value of  $\bar{\kappa}(1.0)$  should change moderately from around 0.30 to 0.27 from peripheral to central collisions. These values correspond to the HIJING, URQMD and RQMD value for peripheral Au-Au collisions and the measured value of  $\langle \Delta Q^2 \rangle / \langle N_{\text{ch}} \rangle$  for central Au-Au collision from STAR. This small reduction indicates that, near  $\eta = \pm 1$ , the contribution from the QGP component is already much reduced.
- (iii) The reduction in the value of  $\bar{\kappa}(0.0)$  should be larger than the reduction in the value of  $\bar{\kappa}(1.0)$  as the QGP component is more concentrated around mid-rapidity. Going from

peripheral to central events, the value of  $\bar{\kappa}(0.0)$  should vary from around 0.45 (HIJING, URQMD, RQMD) down to 0.35. The value of  $\bar{\kappa}(0.0)$  puts a severe constraint on the value of the charge correlation length for the QGP component.

The change in the value of  $\bar{\kappa}(0.0)$  may not seem large. However, keep in mind that the value of  $\bar{\kappa}(1.0)$  cannot be lower than the already measured value of 0.27. Hence  $\bar{\kappa}(0.0)$ , too, cannot go lower than that. If  $\bar{\kappa}(0.0)$  is measured to be close to 0.35, it is impossible to explain this without the presence of the second phase with a very short charge correlation length.

In summary, we propose that the charge transfer fluctuation is a sensitive observable to find the presence and extent of the QGP created in high-energy heavy-ion collisions. In addition, this observable is relatively easy to measure and does not require the net charge conservation correction. We strongly suggest that the experimental group measure the charge transfer fluctuations.

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