Charge transfer fluctuations as a QGP probe

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Abstract. In this work, the charge transfer fluctuation (CTF) which was previously used for \( pp \) collisions is proposed for relativistic heavy-ion collisions as a QGP probe. We propose the appearance of a local minimum at midrapidity for the charge transfer fluctuation for a large acceptance experiment and the fast reduction of the CTF near midrapidity for a limited acceptance experiment as a signal for a QGP.

1. Introduction
In many-body systems, there are many instances where averages alone cannot distinguish different underlying systems. When two heavy nuclei collide, the created system may very well be a mixture of a deconfined matter (a quark-gluon plasma or QGP) and an ordinary confined matter. How can one detect the presence of the QGP? An ideal situation would be that single-particle averages show a clear difference between the systems with a QGP and the systems without it. For the systems created at RHIC, most of the proposed QGP signals so far seem to rely on two-particle correlations one way or another: The Hanbury-Brown-Twiss effect, the disappearance of the away-side jets and the elliptic flow \( v_2 \) can all be formulated in terms of 2-particle correlation functions and/or conditional probabilities. Certainly, there are single-particle observables that show a clear difference as one varies centrality of the collisions such as the suppression of high \( p_T \) particles. Yet, even in this case the disappearance of the away-side jets gives us an added confidence. Therefore obtaining as much information as possible about the correlation functions is an important part of the phenomenological study of heavy ion collisions.

Fluctuations, defined as the variance

\[
\langle \Delta X^2 \rangle = \langle X^2 \rangle - \langle X \rangle^2
\]
for any observable $X$, probe the strength of the self-correlation of $X$. The advantage of studying fluctuations in addition to averages lies in the fact that fluctuations can be very system dependent even when the averages are the same. For instance, recent studies [1, 2] have shown that the multiplicity fluctuations can be very different depending on whether a conserved charge is fixed strictly (Microcanonical) or only on average (Grandcanonical) while the average multiplicities remain the same.

In previous studies [3, 4], it has been shown that the net charge fluctuations per entropy $\langle \Delta Q^2 \rangle / \langle S \rangle$ can be very different in a QGP and in a resonance gas even when $\langle Q \rangle$ is the same. This is because quarks carry fractional charges and gluons are abundant in a QGP system. In terms of experimentally accessible observables, this means that $\langle \Delta Q^2 \rangle / \langle N_{\text{ch}} \rangle$ could be as much as 4 times smaller if the particles originate from a QGP rather than a resonance gas. Recent measurements by STAR[5] and PHENIX[6] do show a reduction when going from peripheral to central collisions. However, the magnitude of the reduction is much smaller than naive expectation from a pure QGP matter.

There could be many reasons why the reduction is not as big as expected even if there could have been a QGP in the system. For instance, if the hadronic phase is long, then the hadronized particles will re-equilibrate wiping out any signal from the early times. Another possibility is that the fraction of the entropy that came from the QGP phase is small compared to the total entropy. If this is indeed the case, then global observables such as the net charge fluctuations or the width of the balance function will not be very sensitive to the presence of the QGP component. For maximum sensitivity, one needs an observable that can detect the local concentration of the QGP component.

In this work, we propose the charge transfer fluctuations as an observable sensitive to the local concentration of the QGP component. We also provide a clear interpretation of what the experiments may see in terms of the local charge correlation length and the size of the QGP component.

2. Charge Transfer Fluctuations

Originally, Quigg and Thomas[7] used a simple neutral cluster model to illustrate the relationship between the charge transfer fluctuations and the charge correlation length. The assumptions of this model are as follows: All particles come from neutral clusters. Each cluster decays into one positively charged particle, one negatively charged particle and one neutral particle (the “ω” model). The rapidities of each particle is randomly assigned from $(y − \Delta, y, y+\Delta)$ with $y$ distributed evenly across the rapidity space. Following Ref.[8], they then defined the charge transfer across the midrapidity

$$u(0) = (Q_F(0) − Q_B(0))/2$$

(2)

where $Q_F(0)$ is the net charge in the forward region of $y = 0$ and $Q_B(0)$ is the net charge in the backward region of $y = 0$. Using the above “ω” model then results in

$$D_u(0) = \langle u(0)^2 \rangle − \langle u(0) \rangle^2 = \frac{4\Delta}{3} \frac{M_0}{Y}$$

(3)

where $M_0$ is the number of clusters and $N_{\text{ch}}/Y = dN_{\text{ch}}/dy$.

This formula can be understood as follows. When a cluster decays within $±\Delta$ of $y = 0$ and the positively charged and the negatively charged particles are separated by $y = 0$, it changes the value of $u(0)$ by $±1$. If one has $N_{\text{cl}}$ number of clusters, then $u(0)$ takes $N_{\text{cl}}$ random-walk steps with a unit step-size. Therefore, we immediately get

$$D_u(0) = N_{\text{cl}}$$

(4)
The number of clusters that can potentially contribute to this random walk process is $2\Delta (M_0/Y)$. However, among them, $1/3$ will have the neutral particle crossing $y = 0$ and hence cannot contribute. Therefore, $N_{cl} = (2/3)(2\Delta)(M_0/Y)$ and we have Eq.(3) with $N_{ch} = 2M_0$. A schematic illustration of this picture is shown in Fig.1.

Realizing the essentially local nature of this argument, Chao and Quigg [9] later generalized this to smooth $dN_{ch}/dy$ cases and wrote down the following Thomas-Chao-Quigg relationship

$$D_u(y) = \kappa \frac{dN_{ch}}{dy}$$  (5)

where the charge transfer fluctuation

$$D_u(y) = \langle u(y)^2 \rangle - \langle u(y) \rangle^2$$  (6)

is now defined with

$$u(y) = (Q_F(y) - Q_B(y))/2$$  (7)

where $Q_F(y)$ ($Q_B(y)$) is the net charge in the forward (backward) region of $y$, which is not necessarily 0. Here $\kappa$ is linearly related to $\Delta$

$$\kappa = c \Delta$$  (8)

and the constant $c$ depends only on the properties of a single cluster such as the number of decay products per cluster. Hence if the same kind of clusters were distributed in the rapidity space, $\kappa$ will be constant. In $pp$ and $K^- p$ collisions up to the beam momentum of $p_{beam} = 205$ GeV/c, the data[9, 10] show that $\kappa$ is indeed independent of $y$ although there is a slight energy dependence.

The local nature of the above picture actually allows further generalization. Suppose the properties of clusters change along the rapidity axis, then the ratio

$$\kappa(y) = \frac{D_u(y)}{(dN_{ch}/dy)}$$  (9)

will be sensitive to the changes in the cluster properties.

How do we use this to detect the presence of a QGP? To answer that, we need to go back to the net charge fluctuations per entropy $\langle \Delta Q^2 \rangle /\langle S \rangle$ and ask what the reduction in $\langle \Delta Q^2 \rangle /\langle S \rangle$ can tell us about the nature of the clusters that results from a hadronizing QGP. To do so requires studying the relationship between correlation functions and the fluctuations. We come back to the question of detection later in section 4.
3. Correlations and Fluctuations

The “ω” model of Thomas-Chao-Quigg can be more generally formulated as follows. (i) All charged particles originate from neutral clusters. (ii) The neutral cluster rapidities are distributed according to a probability density function \( \mathcal{F}(Y) \). (iii) The conditional probability for the rapidities of the charged pair when the cluster is at \( Y \) is given by \( \rho(y_+, y_- | Y) \).

Under these assumptions, if one collects events with \( M_0 \) neutral clusters where the cluster rapidities are \( \{Y_1, Y_2, \cdots, Y_{M_0}\} \), then the distribution of the charged particle rapidities is given by\(^1\)

\[
P(y_1^+, y_2^+, \cdots, y_{M_0}^+, y_1^-, y_2^-, \cdots, y_{M_0}^- | \{Y_i\}) = \prod_{i=1}^{M_0} \rho(y_i^+, y_i^- | Y_i)
\]  
(10)

Since the cluster rapidities are not directly observable, we need to integrate over \( \{Y_i\} \) with an appropriate distribution function. If we assume that the clusters are emitted independently so that the distribution of \( \{Y_i\} \) is just \( \prod_{i}^M \mathcal{F}(Y_i) \), then the final rapidity distribution of \( 2M_0 \) charged particles is

\[
P(y_1^+, y_2^+, \cdots, y_{M_0}^+, y_1^-, y_2^-, \cdots, y_{M_0}^-) = \prod_{i=1}^{M_0} f_0(y_i^+, y_i^-)
\]  
(11)

where

\[
f_0(y^+, y^-) = \int_{-\infty}^{\infty} dY \rho(y^+, y^- | Y) \mathcal{F}(Y)
\]  
(12)

This has to be then convoluted with the probability for the number of clusters \( P(M_0) \).

Given Eq.(11), the net charge fluctuation can be expressed as follows. First, we write

\[
Q = \sum_{i=1}^{M_0} \theta(-y_o < y_i^+ < y_o) - \sum_{i=1}^{M_0} \theta(-y_o < y_i^- < y_o)
\]  
(13)

where the interval \((-y_o, y_o)\) is the observation window and we defined \( \theta(\text{condition}) = 1 \) if the condition is fulfilled and \( \theta(\text{condition}) = 0 \) if the condition is not fulfilled. Using Eq.(11) to calculate averages yields\([11]\]

\[
\langle \Delta Q^2 \rangle_o = \langle N_{ch} \rangle_o - 2\langle M_0 \rangle \int_{-y_o}^{y_o} dy' \int_{-y_o}^{y_o} dy f_0(y, y')
\]

\[
= 4\langle M_0 \rangle \int_{-y_o}^{y_o} dy' \int_{-y_o}^{y_o} dy f_0(y, y')
\]  
(14)

where \( \langle N_{ch} \rangle_o \) is the average number of charged particles within the observation window. To get Eq.(14), we made a reasonable assumption that there is a symmetry between the different sign charges so that \( f(y_1, y_2) = f(y_2, y_1) = f(-y_1, -y_2) \). Since we assume neutral clusters, this should hold.

It is instructive to work out \( \langle \Delta Q^2 \rangle \) for the simple Thomas-Quigg-Chao “ω” model. In this case, \( \rho(y_+, y_- | Y) \) is a combination of 6 \( \delta \)-function products corresponding to the 6 different ways to assign the rapidities. It is a simple matter to integrate over these delta functions to get \( \langle \Delta Q^2 \rangle_o = 8\langle M_0 \rangle \Delta^2 \mathcal{F}(y_o)/3 \) when \( y_o > \Delta \). In Refs.[3, 4], the net charge fluctuation per entropy for a QGP was estimated to be 2 to 4 times smaller than that for a resonance gas. For this to be realized, the charge correlation length \( \Delta \) in a QGP must be also 2 to 4 times smaller than \( \Delta \) in a resonance gas.

\(^1\) For simplicity, we do not perform symmetrization here. The end formulae are not affected.
To get the expression for the charge transfer fluctuation $D_u(y)$, we first write

$$ Q_F(y) = \sum_{i=1}^{M_0} \theta(y_i^+ > y) - \sum_{i=1}^{M_0} \theta(y_i^- > y) \quad (15) $$

and

$$ Q_B(y) = \sum_{i=1}^{M_0} \theta(y_i^+ < y) - \sum_{i=1}^{M_0} \theta(y_i^- < y) \quad (16) $$

We can then calculate $\langle u(y) \rangle$ and $\langle u(y)^2 \rangle$ using Eq.(11) and convolute them with $P(M_0)$ to yield

$$ D_u(y) = \frac{(\Delta Q^2)_{o}}{4} + 2\langle M_0 \rangle \int_{y_o}^{y} dy^- \int_{y}^{y_o} dy^+ f_0(y_+, y_-) \quad (17) $$

If we are able to observe the whole phase space, then the net charge is fixed by the charges of the initial particles. In this case, $\Delta Q = 0$ by definition and we have the following equation from the Thomas-Chao-Quigg relationship

$$ \int_{-\infty}^{y} dy' \int_{y}^{\infty} dy'' f_0(y', y'') = \kappa \int_{-\infty}^{\infty} dy' f_0(y', y) \quad (18) $$

where we used $dN_{ch}/dy = 2\langle M_0 \rangle \int_{-\infty}^{\infty} dy' f_0(y', y)$. In Refs.[12, 13], we solved Eq.(18) exactly for two cases. If $f_0(y, y') = R(y - y') F'((y + y')/2)$, then Eq.(18) is solved by

$$ R(y - y') = \frac{1}{2\gamma} e^{-|y-y'|/\gamma} \quad (19) $$

with

$$ F(y) = \frac{1}{\langle N_{ch} \rangle} \left( 1 - \frac{\gamma^2}{4} \frac{d^2}{dy^2} \right) \frac{dN_{ch}}{dy} \quad (20) $$

where $\gamma = 2\kappa$ and $\langle N_{ch} \rangle = 2\langle M_0 \rangle$ is the total number of charged particles. Suppose on the other hand that the particles are totally uncorrelated. In that case, $f_0(y, y') = g(y)g(y')$ and the solution is

$$ g(y) = \frac{1}{4\kappa \cosh^2(y/2\kappa)} \quad (21) $$

This is a sharply peaked function at $y = 0$ and is in conflict with the fact that we must also have $g(y) = (1/N_{ch}) dN_{ch}/dy$. The rapidity distribution in general is not described by $1/\cosh^2(y/2\kappa)$.

Turning the argument around, one can say that it is rather difficult to satisfy the Thomas-Chao-Quigg relationship with a constant $\kappa$ in a large rapidity range unless

(i) the underlying system is indeed made up of a single species of neutral clusters

(ii) the corresponding charge correlation function has the form

$$ f(y, y') \approx (1/2\gamma) e^{-|y-y'|/\gamma} F'((y + y')/2) $$

It is therefore quite remarkable that the Thomas-Chao-Quigg relationship is satisfied rather well in the elementary collisions ($pp$ and $K^- p$) at the beam energies ranging from 16 GeV to 205 GeV and also in models for heavy ion collisions that are based on the elementary collisions such as HIJING and UrQMD. Some results are shown in Fig.2.
4. Single vs. Two Component Systems

What kind of system do we expect to be created in heavy ion collisions? One extreme possibility is the Bjorken picture of a longitudinally expanding hot rod consisting purely of a QGP. More realistically, one may expect that a chunk of QGP is created near midrapidity with a finite extent. For this case, we can ask many questions. For instance, what is the size of the deconfined phase? Is midrapidity dominated by the QGP component? Why don’t we see a sizable reduction in the net charge fluctuations ($\langle \Delta Q^2 \rangle / \langle N_{ch} \rangle$) if there really was a chunk of QGP? We would like to answer some of these questions using charge transfer fluctuations.

There are already evidences that the Bjorken picture of an extended uniform system is not realized at RHIC energies. The rapidity distribution of pions, as opposed to the pseudo-rapidity distribution, does not show a plateau[14]. The BRAHMS collaboration asserts that this result is more consistent with the Landau picture of total stopping than the Bjorken picture. The Landau picture is also consistent with low energy data[15, 16] where a QGP is not expected to form. The elliptic flow measurements as a function of the pseudo-rapidity by the PHOBOS collaboration[17] show no discernible plateau either at $\sqrt{s} = 130$ GeV or at $\sqrt{s} = 200$ GeV. The fact that the pseudo-rapidity spectra for d-Au collisions and Au-Au collisions show a universal behavior outside of the plateau region[18] also limits the extent of the QGP component in the rapidity space.

In view of these points, if indeed a QGP was created in heavy ion collisions, it is very likely to be distributed inhomogeneously. The QGP component would be mostly concentrated around midrapidity but fall off rapidly in either side. If this is the case, global observables that are only sensitive to the averaged effect will not generate a large signal as the QGP fraction is likely to be small. On the other hand, local observables that are sensitive to the different local concentration of the QGP component can show a sizable effect especially when the elementary particle collisions and purely hadronic models are featureless in this regard, for instance, Fig.2.

The charge transfer fluctuation is such a local observable. If the QGP component increases from peripheral collisions to central collisions, then one should see a structure in $\kappa(y)$ developing gradually as one goes from peripheral to central collisions. In contrast, in hadronic models such as the HIJING and RQMD, there is no dependence on centrality[13].

To test the sensitivity of this observable to the local presence of a QGP, we should consider...
systems with two quite different species of clusters and ask how sensitive $\kappa(y)$ is to the concentration of the second component. Specifically, we consider two kinds of neutral clusters with different charge correlation lengths: $\gamma_1 > \gamma_2$. In this case $\gamma_1$ would correspond to the hadronic component and $\gamma_2$ would correspond to the QGP component. The two components should be distributed in such a way that the fact that we have 2 distinct components is not readily visible in single particle distributions. We do this by having

$$\langle M_0 \rangle f_0(y, y') = \langle M_1 \rangle R_1(y_c) F_1(y_c) + \langle M_2 \rangle R_2(y_r) F_2(y_c)$$

(22)

where $y_r = y - y'$ and $y_c = (y + y')/2$. Here $M_1$ and $M_2$ are the number of the cluster species 1 and 2, respectively, and $R_i(y_r) = (1/2\gamma_i) e^{-|y_r|/\gamma_i}$. The center distribution functions are chosen to be

$$\langle M_1 \rangle F_1(y) = \frac{c_1}{1 + \exp((|y| - \sigma_0)/a_0)} - c_2 g_1(y)$$

(23)

and

$$\langle M_2 \rangle F_2(y) = c_2 g_2(y)$$

(24)

The Woods-Saxon function in Eq.(23) is there to approximately reproduce the experimental $dN_{ch}/dy$ with appropriate $c_1$, $\sigma_0$ and $a_0$. For convenience, we choose $g_1(y)$ to be a normalized gaussian with a width $\sigma_1$ and require

$$\int_{-\infty}^{\infty} dy' g_1(y_c) R_1(y_r) = \int_{-\infty}^{\infty} dy' g_2(y_c) R_2(y_r)$$

(25)

so that the shape of $dN_{ch}/dy$ is totally determined by the convolution of the Woods-Saxon term and $R_1(y_r) = e^{-|y_r|/\gamma_1}/2\gamma_1$. The parameter $c_2$ is chosen so that the minimum value of $F_1(y)$ is 0. An illustration of a typical situation is given in Fig.3.

Let us first consider the ideal case where whole phase space is covered by an experiment. Using Eqs.(17) and (22) we get

$$\kappa(y) = \frac{\gamma_1}{2} - \frac{\gamma_2}{2} \left( \frac{\gamma_1}{\gamma_2} - 1 \right) \frac{dN_{QGP}/dy}{dN_{ch}/dy}$$

(26)
Figure 4. The behavior of the charge transfer fluctuation in a large rapidity window. Here $\xi$ is the width of the QGP part of the $dN_{ch}/dy$. Results for two different values of $\xi$ are shown. Also shown are the hadronic part of $dN_{ch}/dy$.

Here

$$\frac{dN_{QGP}}{dy} = \frac{2\langle M_2 \rangle}{\gamma^2} \int dy_c F_2(y_c) e^{-2|y-y_c|/\gamma^2}$$  \hspace{1cm} (27)$$

is the rapidity distribution of charged particles coming from the QGP component. Since this distribution is peaked at $y = 0$ and $dN_{ch}/dy$ is flat around $y = 0$, $\kappa(y)$ has a local minimum at $y = 0$ as shown in Fig.4. Also, as long as $dN_{ch}/dy$ stays flat around midrapidity, the width of the dip is also the width of the QGP rapidity distribution. Hence, the appearance of the local minimum for $\kappa(y)$ indicates the presence of a QGP with a shorter charge correlation length. Furthermore, the shape of the depression is a direct reflection of the rapidity distribution of the QGP component. As the collisions become more central, we expect that $\langle M_2 \rangle/\langle M_1 \rangle$ will grow. Hence, the minimum at $y = 0$ will become more prominent as the collisions become more central.

Now consider a limited observation window within the rapidity interval $(-y_o, y_o)$. Specifically, consider the case where the width of $dN_{QGP}/dy$ is comparable to $y_o$. The function $\kappa(y)$ as a whole will still decrease as the amount of the QGP component increases. However, we can no longer expect that there will appear a local minimum which deepens in more central collisions. Instead, one must look at the rate of decrease at different $y$. Since the QGP component should be mostly concentrated around midrapidity, the rate of decrease at $y = 0$ will be faster than the rate of decrease at the edge of the detector window $y = y_o$. Hence, if more QGP is formed as the collisions become more central, $\kappa(0)$ should decrease substantially while $\kappa(y_o)$ should change relatively little. Again, the hadronic models in Fig.5 offer clear baseline: There is no centrality dependence in these models. In the same figure, the results for single component systems with varying $\gamma$ are shown: The whole curve moves up and down as $\gamma$ changes in homogeneous systems.

On the other hand, two component calculations with the total QGP fraction up to 26% (up to 51% within $|y| < 1$) shown in Fig.6 exhibit quite different behavior. In this figure, it can be
Figure 5. The behavior of the charge transfer fluctuation within $|y| < 1$ from HIJING and RQMD. Also shown are single component ($M_2 = 0$) results with various charge correlation lengths.

Figure 6. The behavior of the charge transfer fluctuation within $|y| < 1$ in the presence of a QGP component. Schematically, the upper line correspond to the very peripheral collisions, the middle line to semi-peripheral collisions and the lower line to very central collisions.

clearly seen that $D_u(y_o)$ changes relatively small amount while $D_u(0)$ changes substantially as the concentration of a QGP at $y = 0$ changes. As expected, the local minimum structure is not visible any more. However, the higher concentration of short correlation length component does cause $\kappa$ to be flatter.

5. Summary
In summary, we propose the charge transfer fluctuations as a sensitive probe of the local presence of a QGP. We have argued that the current evidences indicate the created QGP component will be mostly concentrated near midrapidity. Also we expect that the relative amount of the QGP should grow as the collisions become more central. Combining these ingredients, the following picture emerges for the signal of the presence of a QGP. In a large-acceptance experiment, the appearance of local minimum for $\kappa(y) = D_u(y)/(dN_{ch}/dy)$ signals the presence of a QGP. The depth of this minimum should grow as the collisions become more central producing more QGP.
The width of the local minimum can be then related to the extent of the QGP component in the rapidity space.

In a limited-acceptance experiment within $(-y_0, y_0)$, the faster drop of $\kappa(0)$ compared to $\kappa(y_0)$ from peripheral to central collisions signals the presence of a QGP. In available hadronic models, $\kappa(y)$ is independent of the centrality. Hence, if this variation is seen in experiments, it is a strong indication of having a QGP concentrated around midrapidity.

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