Net charge fluctuation and string fragmentation

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Abstract

We present simulation results of net charge fluctuation in Au + Au collisions at $\sqrt{s_{nn}}=130$ GeV from a dynamic model, JPCIAE. The calculations are done for the quark-gluon phase before hadronization, the pion gas, the resonance pion gas from $\rho$ and $\omega$ decays and so on. The simulations of the charge fluctuation show that the discrepancy exists between the dynamic model and the thermal model for a pion gas and a resonance pion gas from $\rho$ and $\omega$ decays while the simulated charge fluctuation of the quark-gluon phase is close to the thermal model prediction. JPCIAE results of net charge fluctuation in the hardonic phase are nearly 4 – 5 times larger than one for the quark-gluon phase, which implies that the charge fluctuation in the quark-gluon phase may not survive the hadronization (string fragmentation) as implemented in JPCIAE.

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I. INTRODUCTION

Study of Event-by-Event fluctuation reveals dynamics in relativistic heavy-ion collisions. With the increase of particle multiplicity statistically significant measurements of E-by-E fluctuations became possible for the first time in $Pb+Pb$ collisions at 158A GeV/c and recently in $Au+Au$ collisions at $\sqrt{s_{NN}}=130$ GeV. Many theoretical studies based on hadronic transport models and effective models were carried out trying to understand the effects of different dynamic processes on the E-by-E fluctuations. However, experimental data show that non-statistical contributions to the E-by-E fluctuation of average transverse momentum, $k/\pi$ ratio, and net charge multiplicity are small.

The charged particle ratio fluctuation was recently proposed as a signal of QGP formation. The thermal model predicts that the magnitude of net charge fluctuation is $\sim 4$ for a pion gas, $\sim 3$ for a resonance pion gas (pion from $\rho$ and $\omega$ decays), and $\sim 0.75$ for massless noninteracting quarks and gluons because the unit of charge in the QGP phase is 1/3 while it is 1 in the hadronic phase. Therefore, if the initial fluctuation survives hadronization, a measurement of the charge fluctuation would be able to tell whether a QGP phase is formed.
FIG. 2: Comparison between pion net charge fluctuation and hadron net charge fluctuation in Au + Au collisions at $\sqrt{s_{NN}}=130$ GeV: the left panel compares the results of "directly produced pions" with "directly produced hadrons", the right panel compares the results of "pions from $\rho$, $\omega$ decay" with "decay hadrons".

in the early stage of relativistic heavy-ion collisions. A review on E-by-E fluctuation can be found in [17].

A crucial question here is how hadronization affects the charge fluctuation. Hadronization belongs to the non-perturbative regime and can not be solved from a first principle theory. The best knowledge of our understanding about hadronization has been implemented into two phenomenological models, string fragmentation [18] and cluster model [19]. In the string fragmentation, the parton cascade processes cease when the transverse momenta of emitted partons (ordered by their $p_T$) become smaller than a given cut, $p_T^{\text{min}} \sim 1$ GeV/c. After that, a string is formed with a color triplet quark and a color anti-triplet antiquark (or diquark and anti-diquark) on each end of the string and gluons from the parton cascade distributed as ‘kinks’ along the string. The formed string fragments into hadrons through quark-antiquark pairs (diquark and anti-diquark pairs) production from the QCD vacuum. In the cluster model, at the end of the perturbative phase of parton cascade evolution, each gluon is forcibly split into a quark-antiquark pair. Color singlet clusters are formed from the final quark-antiquark pairs (distinct from those in the gluon splitting), which have a minimal separation in coordinate and momentum space. The clusters subsequently decay.
independently i:

\[ \text{FIG. 3: } 4D_Q \text{ (left panel) and } 4\tilde{D}_Q \text{ (right panel) as a function of } \Delta \eta \text{ from JPCIAE calculations for } Au + Au \text{ collisions at } \sqrt{s_{nn}} = 130 \text{ GeV. Open circles, open triangles and full squares are results of default JPCIAE, JPCIAE without rescattering and "quark-gluon phase", respectively.} \]

In elementary collisions, like in $e^+e^-$ and $pp$, the string is a well-established object due to confinement force between quarks. However, in AA collisions, if a deconfined state is formed in the early stage of a collision, it is conceivable that the concept of string may become irrelevant any more since quarks are no longer bound together by the string-like color force. In this case, a coalescence picture of hadronization in the cluster model seems more applicable.

The net charge fluctuation was investigated using Monte-Carlo generators based on both string and cluster fragmentation in [20]. It was found that VNIb generator [21], which is based on cluster fragmentation, yields a net charge fluctuation close to that for a thermal QGP gas, a factor of 2 smaller than that from the generators based on string fragmentation. It was argued that the difference may be due to the higher gluon density in VNIb. However, another possibility is that the net charge fluctuation in the parton phase can not survive string fragmentation, but can survive coalescence type of hadronization. In order to test this possibility one needs to compare net charge fluctuations calculated before string fragmentation in the partonic phase and after string fragmentation in the hadronic phase. In addition, the net charge fluctuations may also be affected by the decays of resonances and
by rescatterings among hadrons produced during hadronization. These can be investigated in a dynamic model, JPCIAE.

In this paper a dynamic simulation based on the JPCIAE model was used to study the charge fluctuation in Au+Au collisions at \( \sqrt{s_{\text{NN}}}=130 \) GeV. In this calculation, the net charge fluctuations are calculated for the quark-gluon phase before parton fragmentation and for directly-produced pions and pions from \( \rho \) and \( \omega \) decays in the hadronic phase after string fragmentation. The results of this study are compared with the corresponding predictions of the thermal model. The simulations show that although the simulated net charge fluctuation of quark-gluon phase is close to that from the thermal model discrepancies are seen between the dynamic simulations and the thermal model predictions for pion gas and resonance pion gas from \( \rho \) and \( \omega \) decays. It is found that the net charge fluctuation in the hadronic phase from JPCIAE is nearly a factor of 4–5 larger than one for the quark-gluon phase. The results indicate that the charge fluctuation in the partonic phase may not survive the hadronization (string fragmentation) as implemented in JPCIAE.

II. CHARGE FLUCTUATIONS

The deviation of a physical variable \( x \) from its average value per event \( < x > \) and its variance are defined as [22]

\[
\delta x = x - < x >, \quad (1)
\]

and

\[
< (\delta x)^2 > = < x^2 > - < x >^2, \quad (2)
\]

respectively. Suppose \( x \equiv R = N_+/N_- \) to be the ratio of positively to negatively charged particle multiplicity, the corresponding variance is then

\[
< (\delta R)^2 > = < R^2 > - < R >^2 . \quad (3)
\]

Similarly, the variance of net charge multiplicity (\( Q = N_+ - N_- \)) reads,

\[
< (\delta Q)^2 > = < Q^2 > - < Q >^2, \quad (4)
\]

However, what are used to study charge fluctuation in literature is

\[
D_R \equiv < N_{\text{ch}} > < (\delta R)^2 >, \quad (5)
\]
or

\[ D_Q = \frac{\langle (\delta Q)^2 \rangle}{\langle N_{ch} \rangle}, \]  

(6)

In above equations \( N_{ch} = N_+ + N_- \) refers to the total charge multiplicity. When \( \langle N_{ch} \rangle \gg \langle Q \rangle \), a relation follows approximately \[ D_R \approx 4 D_Q. \]  

(7)

Two corrections have to be made in order to compare experimental data or dynamic simulations with the thermal model predictions. One correction, \( C_y \), is done for the finite rapidity bin size and another correction, \( C_\mu \), is for finite net charge. \( C_y \) and \( C_\mu \) are introduced in \[23\] as

\[ C_y = 1 - \frac{\langle N_{ch} \rangle_{\Delta y}}{\langle N_{ch} \rangle_{total}}, \]  

(8)

\[ C_\mu = \frac{\langle N_+ \rangle_{\Delta y}^2}{\langle N_- \rangle_{\Delta y}^2}. \]  

(9)

The corrected net charge fluctuation is denoted by

\[ \tilde{D}_Q = \frac{D_Q}{C_y C_\mu}, \]  

(10)

for instance.

III. MODEL CALCULATIONS AND DISCUSSION

The JPCIAE model is a transport model for AA collisions in which each hadron- hadron collision, when its center-of-mass energy is larger than a given cut, is carried out by PYTHIA \[24\], otherwise by conventional two-body interactions \[25, 26, 27\]. In PYTHIA, a string is stretched out after a collision with quarks and gluons being distributed alone the string, and the string later fragments into hadrons based on the Lund string fragmentation scheme. The gluons are produced through hard QCD scattering and bremsstrahlung radiation. After one hadron-hadron collision, a formation time is given to produced hadrons. A hadron is only allowed to collide with other hadrons after it is formed. The hadron-hadron collisions will go on until no more collision would take place in the system. In the current version of PYTHIA produced partons do not rescatter with each other, unlike produced hadrons. Because both the partonic and hadronic phase are included in PYTHIA, it provides us a good dynamic
tool to study the charge fluctuation for quark-gluon phase, pion gas and resonance pion gas from ρ and ω decays. More importantly, we could use JPCIAE to investigate whether the charge fluctuation in the partonic phase can survive the hadronization (string fragmentation) processes. We refer to [28] for more details about the JPCIAE model.

In line with the thermal model calculations, several dynamic simulations were performed first for 10% most central Au + Au collisions at \( \sqrt{s_{\text{nn}}} = 130 \) GeV based on the JPCIAE model for quark-gluon phase, the pion gas, and the resonance pion gas from ρ and ω decays. The calculation of charge fluctuation for the quark-gluon phase is done before hadronization (string fragmentation), in which diquarks (anti-diquarks) are split into quarks (antiquarks) randomly, and the fractional charge of a quark (antiquark) is counted in its multiplicity and the gluon contribution in charge multiplicity is assumed to be 2/3 [15]. For the pion gas, only directly produced pions from string fragmentation are counted in the calculation of charge fluctuation, in contrast to the pion gas from ρ, ω decays.

Fig. 1 gives the simulated net charge fluctuation in Au+Au collisions at \( \sqrt{s_{\text{nn}}} = 130 \) GeV as a function of \( \Delta \eta \) for \( 4D_Q \) (left panel) and for \( 4\bar{D}_Q \) (right panel). The squares, circles, and triangles in this figure are the results for quark-gluon phase, pion gas (denoted by ”directly produced pions”), and the pion gas from ρ, ω decays, respectively. One sees in this figure that the charge fluctuation from the dynamic simulation is very close to the thermal model prediction for the quark-gluon phase, but our result for the pion gas from ρ, ω decays is higher than the thermal model calculation. The JPCIAE result for the directly produced pions is consistent with the thermal model calculation only in the region of small \( \Delta \eta \) and it increases rapidly with increasing \( \Delta \eta \).

In the left panel of Fig. 2 the net charge fluctuation of ”directly produced pions” are compared with the result of ”directly produced hadrons” from JPCIAE. One sees that the charge fluctuation for ”directly produced hadrons” is smaller than that for ”directly produced pions”, which is due to the constraint of charge conservation in string fragmentation when all hadrons are included. The result of ”pions from ρ, ω decay” is compared, in the right panel of Fig. 2, with the result of ”decay hadrons” (decay products from all unstable hadrons). One observes here that both results are close to each other, indicating that the correlation between positively and negatively charged hadrons from all unstable hadrons is similar.

The net charge fluctuation as a function of \( \Delta \eta \) from the JPCIAE simulations with (open circles) and without rescattering (open triangles) for Au + Au collisions at \( \sqrt{s_{\text{nn}}} = 130 \) GeV
is compared with each other in Fig. (3). The JPCIAE result for the quark-gluon phase (solid squares) is also plotted for comparison. The results show that the rescattering effect on charge fluctuation is small. It is also shown in the right panel of Fig. (3) that the default JPCIAE results are nearly a factor of 4–5 larger than that for the quark-gluon phase.

In summary, we have performed dynamic simulations based on JPCIAE model for the quark-gluon phase, the pion gas, and the resonance pion gas from $\rho$ and $\omega$ decays for 10% most central $Au + Au$ collisions at $\sqrt{s_{nn}} = 130$ GeV. Our results indicate that although the simulated net charge fluctuation of the quark-gluon phase is close to the thermal model prediction discrepancies are found between the dynamic simulation and the thermal model for the pion gas and resonance pion gas from $\rho$ and $\omega$ decays. It is also found that JPCIAE results of net charge fluctuation are nearly a factor of 4 – 5 larger than that from the simulation for the quark-gluon phase. Our results thus indicate the charge fluctuation does not survive hadronization (string fragmentation) as implemented in JPCIAE.

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