Centrality, system size and energy dependences of charged-particle pseudo-rapidity distribution

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Utilizing the three-fireball picture within the quark combination model, we study systematically the charged particle pseudorapidity distributions in both Au+Au and Cu+Cu collision systems as a function of collision centrality and energy, $\sqrt{s_{NN}} = 19.6, 62.4, 130$ and 200 GeV, in full pseudorapidity range. We find that: (i) the contribution from leading particles to $dN_{ch}/d\eta$ distributions increases with the decrease of the collision centrality and energy respectively; (ii) the number of the leading particles is almost independent of the collision energy, but it does depend on the nucleon participants $N_{part}$; (iii) if Cu+Cu and Au+Au collisions at the same collision energy are selected to have the same $N_{part}$, the resulting of charged particle $dN/d\eta$ distributions are nearly identical, both in the mid-rapidity particle density and the width of the distribution. This is true for both 62.4 GeV and 200 GeV data. (iv) the limiting fragmentation phenomenon is reproduced. (iv) we predict the total multiplicity and pseudorapidity distribution for the charged particles in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV. Finally, we give a qualitative analysis of the $N_{ch}/ < N_{part}/2 >$ and $dN_{ch}/d\eta/ < N_{part}/2 >$ $|\eta| \leq 0$ as function of $\sqrt{s_{NN}}$ and $N_{part}$ from RHIC to LHC.

Keywords: Relativistic Heavy-Ion Collider; Quark Combination Model(QCM), Pseudo-rapidity Distribution.

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1. Introduction

In relativistic heavy ion collisions at RHIC energies, the charged particles are produced copiously in vacuum. The number of charged particles per unit pseudorapidity $dN_{ch}/d\eta$, and in particular its dependence on some variables, such as rapidity, collision centrality and energy, are the important observables, from which a lot of information about the hot and dense matter created in collisions can be extracted.1-8 From the pseudo-rapidity density and the transverse energy per particle, one can determine via Bjorken method the initial energy density of the fireball which can provide one piece of evidence for the deconfinement phase transition. In the fragmentation region, the charged particle production, in general, is thought to be distinct from that at mid-rapidity, although there is no obvious evidence for two separate regions at any of the RHIC energies. The pseudo-rapidity density $dN_{ch}/d\eta$
in forward rapidity region carries some information of leading particles produced in collisions.\textsuperscript{[9]} The experimental data about the charged-particle pseudo-rapidity density in both Au+Au and Cu+Cu collision systems have been presented by the PHOBOS collaboration \textsuperscript{[10–13]}, the PHENIX collaboration \textsuperscript{[14]}, and the BRAHMS Collaboration \textsuperscript{[15–16]}. The data for the scaled and shifted pseudo-rapidity distribution \(dN_{ch}/d\eta'/\langle N_{part}/2\rangle\), exhibit the limiting fragmentation phenomenon in both Au+Au and Cu+Cu collisions at different energies and centralities.\textsuperscript{[17–18]}

Recombination of partons \textsuperscript{[19–24]}, Partonic coalescence \textsuperscript{[25–28]} and QCM \textsuperscript{[29–31]} have been made to described many observations. In our previous work \textsuperscript{[29]}, using a Gaussian-like shape rapidity distribution for constituent quarks as a result of the Landau hydrodynamic evolution \textsuperscript{[32–33]}, we have presented the pseudo-rapidity distributions of charged particles in Au+Au collisions as a function of collision centrality and energy. The calculation results are in good agrement with the data in central collisions. In peripheral collisions, our predictions are slightly lower than data in high rapidity range. The reason may be that we have not considered the contribution of leading particles. In present work, taking into account the leading particle influence, we apply a three-fireball picture \textsuperscript{[34–35]} to describe the evolution of the hot and dense quark matter produced in collisions, and obtain the rapidity distribution of the constituent quarks just before hadronization. Then let these constituent quarks combine into initial hadrons according to a quark combination rule, and allow the resonances in the initial hadrons to further decay into final hadrons with the help of the event generator PYTHIA 6.1 \textsuperscript{[36]}

2. Three-fireball picture and quark combination model

In this section, we introduce the three-fireball picture, which is used to describe the rapidity distribution of quark and antiquarks just before hadronization. In addition, we briefly introduce the QCM which describes the hadronization of these quarks and antiquarks produced in collisions.

2.1. Three-fireball picture

It is known that the nucleus-nucleus collisions at RHIC energies are neither fully stopped nor fully penetrated. As the incident nuclei penetrate through the target nuclei, the most of the collision energy is deposited in collision region to form a big central fireball, and the penetrating quark matter forms two small fireballs, i.e. target and projectile fireballs, in forward rapidity region. The charged hadron pseudorapidity distribution is the total contributions from the three fireballs.

The big central fireball which contains the main part of collision energy, controls the rough shape of charged particle pseudorapidity distribution (width and height). Relativistic hydrodynamics has successfully described the evolution of system before hadronization. Here we use a Gaussian-type rapidity distribution for constituent quarks as a result of the Landau hydrodynamic evolution.\textsuperscript{[37–40]}

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\[ f(y) = \frac{1}{\sqrt{2\pi}\sigma^2} \exp \left( -\frac{y^2}{2\sigma^2} \right), \]  

(1)

where

\[ \sigma^2 \approx \frac{2c_s^2}{1 - c_s^2} \ln \left( \frac{E\sqrt{s_{NN}}}{2m_p\epsilon_c} \right). \]  

(2)

Here, \( E \) is the effective energy offered by per participant pair, and it is used to produce the central fireball. \( m_p \) is the proton mass and \( c_s \) is the sound velocity. \( \epsilon_c \) is the energy in the volume of a free hadron at hadronization. All quarks and anti-quarks in the central fireball are within the rapidity range \([-y_{\text{max}}, y_{\text{max}}]\).

\[ y_{\text{max}} = \frac{c_s}{1 + c_s^2} \ln \left( \frac{E\sqrt{s_{NN}}}{2m_p\epsilon_c} \right). \]  

(3)

The average constituent quark number in the big central fireball can be obtained from a simple quark production model \(^{29,30}\)

\[ \langle N_q \rangle = 2[(\alpha^2 + \beta E)^{1/2} - \alpha]\langle N_{\text{part}}/2 \rangle, \]  

(4)

where the parameter \( \beta \approx 3.6 \) GeV, and the parameter \( \alpha = \beta m - \frac{1}{4} \), \( m \) is the averaged quark mass and it is taken to be 0.36 GeV, they are the same with Ref. \(^{29}\).

The two penetrating fireballs mainly consist of leading light quarks. We also adopt a Gaussian type rapidity distribution for leading quarks

\[ f'(y) = \frac{1}{(N_{q(T/P)})} \frac{dN_q(T/P)}{dy} = \frac{\exp\left(-\frac{(y+y_0)^2}{2\sigma'^2}\right)}{\sqrt{2\pi}\sigma'^2}, \]  

(5)

where \( N_{q(T/P)} \) is the total quark number in the penetrating target and projectile fireballs. \( y_0 = \pm \frac{y_{\text{beam}} + y_{\text{max}}}{2} \) is the rapidity center for target and projectile fireballs respectively. Rapidity distribution range of quarks in the center of mass frame is \( y \in [-y_{\text{beam}}, -y_{\text{max}}] \) for target fireball and \( y \in [y_{\text{max}}, y_{\text{beam}}] \) for projectile fireball, respectively. In this work, the spectrum width of penetrating fireballs is taken to be \( \sigma' = 0.18 \).

The total energy of the three fireballs in nucleus-nucleus collisions is \( \sqrt{s_{NN}} \langle N_{\text{part}}/2 \rangle \)

\[ E_{(T+P)} = (\sqrt{s_{NN}} - E)\langle N_{\text{part}}/2 \rangle, \]  

(6)

where \( E_{(T+P)} \) is total energy of the two penetrating fireballs. The average number of quarks in penetrating projectile and target fireballs \( \langle N_q(T+P) \rangle \) is determined by \( E_{(T+P)} \):

\[ \langle N_q(T+P) \rangle = \frac{E_{(T+P)}}{\langle E_q \rangle}. \]  

(7)
\( \langle E_q \rangle \) is the average energy of each quark in the penetrating projectile/target fire-balls, and it can be written as:

\[
\langle E_q \rangle = \frac{\int_{y_{\text{beam}}}^{y_{\text{max}}} m_T \cosh(y) f'(y) dy}{y_{\text{max}}},
\]

where \( m_T = \sqrt{m^2 + p_T^2} \) is the transverse mass of leading quarks. The transverse momentum \( p_T \) of leading quarks is approximately taken to be 0.25 GeV, one third of the value of net-proton at forward rapidity \( y \approx 341 \).

3. The quark combination model

The QCM was first proposed for high energy \( e^+e^- \) and \( pp \) collisions and recently it was extended to ultra-relativistic heavy ion collisions \( [31, 12] \). The model describes the production of initially produced ground state mesons (36–plets) and baryons (56–plets). In principle the model can also be applied to the production of excited states \( [13] \). These hadrons through combination of constituent quarks are then allowed to decay into the final state hadrons. We take into account the decay contributions of all resonances of 56–plets baryons and 36–plets mesons, and cover all available decay channels by using the decay program of PYTHIA 6.1 \( [36] \). The main idea is to line up \( N_q \) quarks and anti-quarks in a one-dimensional order in phase space, e.g. in rapidity, and let them combine into initial hadrons one by one following a combination rule (see section 2 of Ref. \( [32] \) for a short description of such a rule). We note that it is very straightforward to define the combination in one dimensional phase space, but it is highly complicated to do it in two or three dimensional phase space \( [14] \). The flavor SU(3) symmetry with strangeness suppression in the yields of initially produced hadrons is fulfilled in the model \( [30, 13] \).

4. Centrality, system size and energy dependence of charged-particle pseudo-rapidity distribution

In this section, we will study the system size, energy and centrality dependence of pseudorapidity distribution of charged particles, and multiplicity distribution in mid and forward rapidity range respectively in relativistic heavy ion collisions. Moreover, if the particle production mechanisms in A+A collisions at RICH and LHC are the same, we predict the energy and centrality dependences of \( \frac{N_{ch}}{N_{\text{part}}/2} \) and \( \frac{dN_{ch}}{dy} \) at \( |y| \approx 0 \).

From Eq. \( (6) \), we can see that there is only one free variable, i.e. \( E \) or \( E_{(T+P)} \), which should be determined from the experimental data. In the present work, we determine the effective energy \( E \) for central fireball by fitting the pseudorapidity density \( \frac{dN_{ch}}{dy} \) in \( \text{Au+Au} \) collisions at \( \sqrt{s} = 130 \) GeV. Then the \( E_{(T+P)} \) and leading quark number \( \langle N_q(T+P) \rangle \) can be naturally obtained. Using this method, we get the leading quark number in different collision centralities and parameterize it.
Fig. 1. Charged hadron pseudo-rapidity distributions for different centralities in Au+Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \). The lines are our results and the points are data taken from PHOBOS.

as the function of nucleon participants \( N_{\text{part}} \)

\[
N_{q(T+P)} = -84.44 + 35.82 \times N_{\text{part}}^{0.4}.
\]

At other energies, basing on the relation between the number of leading quarks and the centrality, we can get \( E \), and the pseudorapidity distribution in different centralities within a quark combination model.

Applying Eq. (9) to other RHIC energies, we firstly calculate the charged particle pseudorapidity distributions for different centralities in Au+Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \). The data are taken from PHOBOS\textsuperscript{11,12}. The results are shown in Fig. 1. The dashed lines are the contribution from the central fireballs. The dotted lines in the forward pseudorapidity range show the contributions of penetrating target and projectile fireballs respectively. The solid lines are the total contribution of the three fireballs. One can see that our results are in good agreement with the data. In addition, we find that the contribution from leading particles to \( dN_{\text{ch}}/d\eta \) distributions increases with the decrease of the collision centralities. We also give the results of \( dN_{\text{ch}}/d\eta \) distribution at \( \sqrt{s_{NN}} = 19.6, 62.4 \text{ GeV} \), and they are shown in Fig. 2. The data are taken from PHOBOS\textsuperscript{11,12}. The agreement of calculated
results with the data is also satisfactory. The Fig. 2 shows the charged-particle pseudorapidity distributions in most central Au+Au collisions at $\sqrt{s_{NN}}=19.6, 62.4, 130$ and 200 GeV. The results indicate that the contribution from leading particles to $dN_{ch}/d\eta$ distributions increases with the decrease of collision energy.

Recently, PHOBOS Collaboration have presented the data on charged-particle pseudorapidity distributions in Cu+Cu collisions at $\sqrt{s_{NN}}=62.4, 200$ GeV. The other goal of this paper is to investigate the systematic dependence of particle production in nuclear collision at RHIC energies, in terms of overall $dN/d\eta$ distributions. We apply Eq. (9) to Cu+Cu collisions, and give the charged-particle pseudorapidity distributions as a function of centrality at $\sqrt{s_{NN}}=62.4, 200$ GeV. The results are shown in Fig. 3 and compared with the data. As we can see, our results are roughly consistent with the experimental data, but are slightly lower than the data in the mid-rapidity range, especially for the central Cu+Cu collisions. The reason may be that we did not consider the difference between the collision geometry in Cu+Cu and Au+Au, even at the same $N_{part}$ in Eq. (9), especially for the central Cu+Cu collisions. The two system have same shape, which indicate a similarity particle production mechanism between Au+Au and Cu+Cu, the results is the same as Ref. 45. Following that, we think the Au+Au and Pb+Pb collisions have the same particle production mechanism, so we predict the pseudorapidity distribution and charged particle multiplicity in Pb+Pb collisions at $\sqrt{s_{NN}}=5.5$ TeV in the followings.

The Large Hadron Collider (LHC) is scheduled to begin operation in May 2008. The most pressing issue for the early days at the LHC is to establish the global features of heavy ion collisions. This involves the estimation of the inclusive charged-
particle yield and the charged pseudorapidity distribution and so on. In this work, extending Eq. 9 to LHC energy, we can predict the charged particle pseudorapidity distribution as a function of centrality in Pb+Pb collisions. As an example, we calculate the most central Pb+Pb collisions at $\sqrt{s_{NN}} = 5500$ GeV in Fig. 3. The total charged-particle multiplicity is about 18170, and pseudorapidity density $dN_{ch}/d\eta_{|\eta|<0.5}$ is about 1630. Note that the sound velocity is taken be 1/3. To separate the trivial kinematic broadening of the $dN_{ch}/d\eta$ distribution from the more interesting dynamics, we also study the scaled, shifted pseudorapidity distribution $dN_{ch}/d\eta'/(N_{part}/2)$, where $\eta' = \eta - y_{beam}$, in most central Au+Au, Cu+Cu and Pb+Pb collisions at different energies. The calculation results are shown in Fig. 4.

We observe that the data at various energies and systems fall on a common limiting curve.

The centrality dependence of $N_{ch}/ < N_{part}/2 >$ and $dN_{ch}/d\eta/ < N_{part}/2 > \mid_{\eta\approx0}$ at $\sqrt{s_{NN}}=19.6, 62.4, 130, 200$ GeV in Au+Au collisions (open symbol) compared with the data (solid symbol) taken from PHOBOS[13] and the prediction at 5500 GeV in Pb+Pb collisions (the solid line) are shown in Fig. 4.

Fig. 3 shows the c.m. energy dependence of $N_{ch}/ < N_{part}/2 >$ and $dN_{ch}/d\eta/ < N_{part}/2 > \mid_{\eta\approx0}$ from RHIC to LHC predicted by the QCM (the lines). It shows that the $N_{ch}/ < N_{part}/2 >$ and $dN_{ch}/d\eta/ < N_{part}/2 > \mid_{\eta\approx0}$ from RHIC to LHC can grow at logarithmically with $\sqrt{s_{NN}}$.
Fig. 4. Particles pseudo-rapidity distributions for different centralities in Cu+Cu collisions at $\sqrt{s_{NN}}$=62.4, 200 GeV. The lines are our results, and the data are taken from PHOBOS.

5. summery

Within a combination model, we study the charged particle pseudo-rapidity distributions in Au+Au and Cu+Cu collision systems as a function of collision centrality and energy ($\sqrt{s_{NN}}$ = 19.6, 62.4, 130 and 200 GeV), in full pseudo-rapidity range. We use a toy model, i.e. three fireballs, to describe the evolution of the hot and dense quark matter produced in collisions. The big central fireball which carries the main part of collision energy controls the rough shape of the charged particle pseudo-rapidity distribution. We apply the Landau relativistic hydrodynamic model to describe the the evolution of highly excited and possibly deconfined quark matter created in the big central fireball. As a result, we obtain a Gaussian-type rapidity spectra of constituent quarks before hadronization. The other two small fireballs in foreword rapidity carry the information of the leading particles. We also use a Gaussian-type rapidity spectra of constituent quarks before hadronization. Then we use our combination model to describe the hadronization of initially produced hadrons including resonances, whose decays are dealt with by the event generator PYTHIA 6.3 [36]. Firstly, by studying the contribution of leading particles to charged-particle pseudo-rapidity distribution in Au + Au collisions for different centralities at 130 GeV, we extract the centrality dependence of the average number of leading quarks from the data. Then we extend it to other RHIC energies. We calculate the charged particle pseudo-rapidity distributions in both Au+Au and Cu+Cu collision systems as a function of collision centrality, at $\sqrt{s_{NN}}$ = 19.6, 62.4 and 200 GeV, in full pseudo-rapidity range. The calculation results are in good agreement with
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Fig. 5. Charged particles pseudorapidity distributions calculated by QCM in most central Pb+Pb collisions at $\sqrt{s} = 5.5$ TeV. Data. To separate the trivial kinematic broadening of the distributions of the pseudo-rapidity density from more interesting dynamics, we compute the scaled and shifted pseudo-rapidity density distributions $dN_{ch}/d\eta'/\langle N_{part}/2 \rangle$ with $\eta' = \eta - y_{beam}$ at collision energies 19.6, 62.4, 130 and 200 GeV. The good agreement with data is found. Furthermore, we predict the total multiplicity and pseudo-rapidity distribution for the charged particles in most central Pb+Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV. Through investigating detailed $dN_{ch}/d\eta$ distributions, we find that: (i) The contribution from leading particles to $dN_{ch}/d\eta$ distributions increases with the decrease of the collision centrality and energy respectively; (ii) The number of leading particles is, independent of collision energy, only a function of nucleon participants $N_{part}$ for the same system; (iii) If Cu+Cu and Au+Au collisions at the same collision energy are selected to have the same $N_{part}$, the resulting of charged particle $dN/d\eta$ distributions are nearly identical, both in the mid-rapidity particle density and the width of the distribution. This is true for both 62.4 GeV and 200 GeV data. (iv) The limiting fragmentation phenomenon is reproduced. Furthermore, we predict the total multiplicity and pseudorapidity distribution for the charged parti-
Fig. 6. The scaled, shifted pseudorapidity density at $\sqrt{s_{NN}} = 19.6, 62.4, 130, 200$ GeV in most central Au+Au, Cu+Cu, and Pb+Pb collisions at $\sqrt{s} = 5.5$ TeV. The lines are our results, the symbols are data taken from PHOBOS.

In Pb+Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV, and find the $N_{ch}/ <N_{part}/2 >$ and $dN_{ch}/d\eta/ <N_{part}/2 > |_{\eta=0}$ from RHIC to LHC can grow at logarithmically with $\sqrt{s_{NN}}$.

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Fig. 7. The total number of charged particles (a) and mid-rapidity density (b) per participant pair shown as a function of $N_{\text{part}}$ for $\sqrt{s} = 19.6$, 62.4, 130 and 200 GeV in Au+Au collisions, and $\sqrt{s} = 5500$ GeV in Pb+Pb collisions. The solid symbols are data taken from PHOBOS, and the open symbols are our results in (a) and (b). The lines are our prediction at LHC in (a) and (b).

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Fig. 8. The charged particles mean multiplicity $<N_{ch}>$ and pseudorapidity density of charged particle per participant pair ($N_{part}/2$) as a function of the c.m. energy of collision. The lines are our results and the symbols are data taken from PHOBOS.

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