Formulation of transverse mass distributions in Au-Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV/nucleon

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The transverse mass spectra of light mesons produced in Au-Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV/nucleon are analyzed in Tsallis statistics. In high energy collisions, it has been found that the spectra follow a generalized scaling law. We applied Tsallis statistics to the description of different particles using the scaling properties. The calculated results are in agreement with experimental data of PHENIX Collaboration. And, the temperature of emission sources is extracted consistently.

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I. INTRODUCTION

Multiparticle production is an important experimental phenomenon at Relativistic Heavy Ion Collider (RHIC) in Brookhaven National Laboratory (BNL). In Au-Au collisions, identified particle yields per unity of rapidity integrated over transverse momentum $p_T$ ranges have provided information about temperature $T$ and chemical potential $\mu$ at the chemical freeze-out by using a statistical investigation [1]. It brings valuable insight into properties of quark-gluon plasma (QGP) created in the collisions. A much broader and deeper study of QGP will be done at Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN) and the Facility for Antiproton and Ion Research (FAIR) at the Gesellschaft für Schwerionenforschung mbH (GSI).

In order to estimate hadronic decay backgrounds in photon, single lepton and dilepton spectra which are penetrating probes of QGP, $m_T$ spectra of identified mesons have been studied in detail [2–6], where $m_T = \sqrt{m_0^2 + p_T^2}$ is transverse mass of a particle with rest mass $m_0$ at a given $p_T$. In Ref. [7], $m_T$ spectral shapes of pions and $\eta$ mesons in S-S and S-Au collisions are identical. Such behaviors are caused by $m_T$ scaling properties, which help us to predict new $m_T$ spectra and understand the mechanism of meson production. Statistical analysis of $m_T$ spectra is extremely useful to extract information of particle production process and interaction in hadronic and QGP phases. In the CGS (Color Glass Condensate) description, the total hadron multiplicity follows a scaling behavior motivated by the gluon saturation.

Different phenomenological models of initial coherent multiple interactions and particle transport have been introduced to describe the production of final-state particles [8,9] in Au-Au collisions. With Tsallis statistics’ development and success in dealing with non-equilibrated complex systems in condensed matter research [10], it has been utilized to understand the particle production in high-energy physics [11–13]. In our previous work [14], the temperature information of emission sources was understood indirectly by an excitation degree, which varies with location in a cylinder. We have obtained emission source location dependence of the exciting degree specifically. From central axis to side-surface of the cylinder, the excitation degree of the emission source decreases linearly with the direction of radius. In this work, we parametrize experimentally measured $m_T$ spectra of pions in Tsallis statistics. Using the $m_T$ scaling properties in the spectrum calculation, we reproduce $m_T$ spectra of other light

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mesons and obtain the temperature of emission sources directly.

II. THE FORMULATION AND COMPARISON WITH PHENIX RESULTS

At the initial stage of nucleus-nucleus collisions, plenty of primary nucleon-nucleon collisions happen. The primary nucleon-nucleon collision can be regarded as an emission source (a compound hadron fireball) at intermediate energy or a few sources (wounded partons and woundless partons) at high energy. The participant nucleons in primary collisions have probabilities to take part in cascade collisions with latter nucleons. Meanwhile, the particles produced in primary or cascade nucleon-nucleon collisions have probabilities to take part in secondary collisions with latter nucleons and other particles. Each cascade (or secondary) collision is also regarded as an emission source or a few sources. Many emission sources of final-state particles are expected to be formed in the collisions.

According to Tsallis statistics, the total number of the mesons is given by

$$N = gV \int \frac{d^3p}{(2\pi)^3} \left(1 + (q - 1) \frac{E - \mu}{T}\right)^{-1/(q-1)} ,$$

where $p$, $E$, $T$, $\mu$, $V$ and $g$ are the momentum, the energy, the temperature, the chemical potential, the volume and the degeneracy factor, respectively. A parameter $q$ is used to characterize the degree of nonequilibrium. The corresponding momentum distribution is

$$E \left(\frac{d^3N}{d^3p}\right) = gV \left(2\pi\right)^3 \left[1 + (q - 1) \frac{E - \mu}{T}\right]^{-1/(q-1)} .$$

We have the transverse mass $m_T$ distribution,

$$\left. \frac{d^2N}{m_T dm_T dy} \right|_{y=0} = \frac{gV m_T \cosh y}{(2\pi)^2} \left[1 + (q - 1) \frac{m_T \cosh y}{T}\right]^{-1/(q-1)} .$$

At midrapidity $y = 0$, for zero chemical potential, the transverse mass spectrum in terms of $y$ and $m_T$ is

$$\left. \frac{d^2N}{m_T dm_T dy} \right|_{y=0} = \frac{gV m_T}{(2\pi)^2} \left[1 + (q - 1) \frac{m_T}{T}\right]^{-1/(q-1)} ,$$

which is only a $m_T$ distribution of particles emitted in the emission source at midrapidity $y = 0$.

Considering a width of the corresponding rapidity distribution of final-state particles, the $m_T$ spectrum is rewritten as

$$\frac{dN}{m_T dm_T} = C \int_{-Y}^{Y} \cosh y dy \left[1 + (q - 1) \frac{m_T \cosh y}{T}\right]^{-1/(q-1)} ,$$

where $C = \frac{gV}{(2\pi)^2}$ is a normalization constant and $Y (-Y)$ is the maximum (minimum) value of the observed rapidity. Generally speaking, the temperature $T$ and $q$ can be fixed for different event centralities (or impact parameters) by fitting the experimental data of pions. The temperature $T$ of emission sources is calculated naturally and consistently in the current formulation.

Fig. 1 shows $m_T$ distributions of charged and neutral pions in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV/nucleon. The symbols represent experimental data of PHENIX Collaboration and the curves are fitting results by using Eq.(5). By fitting the experimental data, values of $T$ and $q$ are given in Table I with $\chi^2$/dof (degree of freedom). Fig. 2, Fig. 3 and Fig. 4 present invariant yields of $K^+$, $J/\psi$, $\phi$, $\omega$ and $\eta$ as a function of $m_T - m_0$. The symbols represent experimental data of PHENIX Collaboration. The curves are calculated results by using $m_T$ scaling properties. The corresponding $\chi^2$/dof is given in Table II. One can see that the transverse mass scaled results of different mesons are in agreement with the experimental data in the whole observed $m_T - m_0$ region.
The transverse momentum spectra of charged and neutral pions for 0 – 100%, 0 – 20%, 20 – 60% and 60 – 92% centralities in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV/nucleon are shown in Fig. 5. The different symbols are experimental data [15, 16] in different centrality cuts indicated in the figure. The curves are the results obtained by fitting the data. We fit the spectra using Tsallis distributions and obtain the values of $T$ and $q$ which are given in Table I with $\chi^2$/dof. It is found that the temperature $T$ increase with the increase of the centrality. Fig. 6 and Fig. 7 show invariant yields of $K^\pm$, $J/\psi$, $\phi$, $\omega$ and $\eta$ as a function of $m_T - m$ in corresponding centrality cuts. The symbols represent experimental data of PHENIX Collaboration [16, 18, 20, 21]. The curves are the results calculated by using $m_T$ scaling properties. The values of $\chi^2$/dof are shown in Table II. For different centralities, the $m_T$ scaled results are in agreement with the experimental data of different mesons.

TABLE I: Values of the parameters $T$ and $q$ for pions in our calculations.

| Centrality       | $T$(GeV) | $q$       | $\chi^2$/dof |
|------------------|----------|-----------|--------------|
| Minimum Bias     | 0.064 ± 0.02 | 1.094 ± 0.02 | 0.80         |
| 0-20%            | 0.078 ± 0.03 | 1.086 ± 0.02 | 0.56         |
| 20-60%           | 0.072 ± 0.02 | 1.091 ± 0.03 | 0.49         |
| 60-92%           | 0.059 ± 0.03 | 1.098 ± 0.02 | 0.38         |

TABLE II: Values of $\chi^2$/dof for Fig.2—Fig.4, Fig.6 and Fig.7.

| Mesons | 0 – 100% | 0 – 20% | 20 – 60% | 60 – 92% |
|--------|----------|----------|----------|----------|
| $K^+$  | 0.42     | 0.44     | 0.35     | 0.55     |
| $K^-$  | 0.51     | 0.55     | 0.57     | 0.65     |
| $J/\psi$ | 0.57  | 0.70     | 0.61     | 0.58     |
| $\phi$ | 0.59     | 0.50     | 0.55     | 0.45     |
| $\eta$ | 0.89     | 0.94     | 0.82     | 0.76     |
| $\omega$ | 0.70 | –        | –        | –        |

TABLE III: Meson-pion yield ratios.

| Centrality       | $K/\pi^0$ | $\eta/\pi^0$ | $\phi/\pi^0$ | $(J/\psi)/\pi^0$ |
|------------------|-----------|--------------|--------------|-------------------|
| Minimum Bias     | 0.531 ± 0.003 | 0.524 ± 0.038 | 0.342 ± 0.015 | 0.0034 ± 0.0004 |
| 0-20%            | 0.499 ± 0.004 | 0.538 ± 0.020 | 0.405 ± 0.012 | 0.0031 ± 0.0006 |
| 20 – 60% (20 – 40% for $J/\psi$) | 0.495 ± 0.003 | 0.577 ± 0.021 | 0.390 ± 0.010 | 0.0042 ± 0.0005 |
| 60 – 92% (40 – 92% for $J/\psi$) | 0.481 ± 0.005 | 0.545 ± 0.025 | 0.304 ± 0.017 | 0.0034 ± 0.0005 |

III. DISCUSSIONS AND CONCLUSIONS

The transverse mass spectra of mesons produced in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV/nucleon have been investigated in the framework of Tsallis statistics. We propose a formula for describing the distributions and fit experimental data of pions to estimate $q$ and the temperature $T$. Using the $m_T$ scaling properties, other meson
spectra are obtained and compared with experimental data at different collision centralities. The maximum value of \( \chi^2_{/\text{dof}} \) is 0.96, and the minimum value of \( \chi^2_{/\text{dof}} \) is 0.38. It is demonstrated that our results agree well with the available experimental data. The normalization parameters in the fits give the values of meson-pion yield ratio in Table III. The ratios are helpful to understand the contribution of hadronic decay in photonic and leptonic channels.

Final-state particles produced in high-energy nuclear collisions have attracted much attention, since attempt have been made to understand the properties of strongly coupled QGP by studying the possible production mechanisms \[22\,23\]. Thermal-statistical models have been successful in describing particle yields in various systems at different energies \[14\,24\,26\]. The temperature \( T \) of emission sources is very important for understanding the matter evolution in Au-Au collisions at RHIC. In the rapidity space, different sources of final-state particles stay at different positions due to stronger longitudinal flow \[27\,29\]. In our previous work, we have studied the transverse momentum spectra of strange particles produced in Cu+Cu and Au+Au collisions at \( \sqrt{s_{_{NN}}} = 62.4 \) and 200 GeV/nucleon in the framework of the cylinder model, which is developed from the fireball model. The temperature \( T \) of emission sources was characterized indirectly by the excitation degree, which varies with location in the cylinder. From central axis to side-surface of the cylinder, the excitation degree of the emission source decreases linearly with the direction of radius. In the present work, we can directly extract the temperature by using the \( m_T \) scaling law in Tsallis statistics. The temperature \( T \) increase with the increase of the centrality. It is consistent with results obtained in our previous work. But, the values of \( T \) is given specifically in the formulation.

Summarizing up, the transverse mass distributions of mesons produced in Au-Au at RHIC energies have been studied in Tsallis statistics, which reproduces \( m_T \) spectra of mesons by using \( m_T \) scaling properties. The \( m_T \) scaled spectra for each meson are compared with experimental data of PHENIX Collaboration. The formulation is successful in the description of meson production. At the same time, it can offer information about \( m_T \)-scaling properties and the temperature of emission sources in the collisions.

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FIG. 1: Pion transverse mass spectra in $\sqrt{s_{NN}} = 200$ GeV/nucleon Au-Au collisions. Experimental data are taken from PHENIX Collaboration [15, 16], and are shown with the scattered symbols. Our calculated results are shown with the curves.

FIG. 2: $K^-$ and $K^+$ transverse mass spectra in $\sqrt{s_{NN}} = 200$ GeV/nucleon Au-Au collisions. Experimental data are taken from PHENIX Collaboration [16], and are shown with the scattered symbols. Transverse mass scaled results are shown with the curves.
FIG. 3: $J/\psi$ and $\phi$ transverse mass spectra in $\sqrt{s_{NN}} = 200$ GeV/nucleon Au-Au collisions. The symbols represent experimental data from the PHENIX Collaboration [15, 16] in different $P_T$ ranges. The curves are transverse mass scaled results.

FIG. 4: $\omega$ and $\eta$ transverse mass spectra in $\sqrt{s_{NN}} = 200$ GeV/nucleon Au-Au collisions. The symbols represent the experimental data from the STAR Collaboration [17–21]. The curves are transverse mass scaled results.

FIG. 5: Pion transverse mass spectra for different centrality bins in $\sqrt{s_{NN}} = 200$ GeV/nucleon Au-Au collisions. The symbols represent the experimental data from PHENIX Collaboration [13, 16]. Our calculated results are shown with the curves.
FIG. 6: $K^-$, $K^+$ and $J/\psi$ transverse mass spectra for different centrality bins in $\sqrt{s_{NN}} = 200$ GeV/nucleon Au-Au collisions. The symbols represent the experimental data from PHENIX Collaboration [16, 17]. The curves are transverse mass scaled results.

FIG. 7: $\phi$ and $\eta$ transverse mass spectra for different centrality bins in $\sqrt{s_{NN}} = 200$ GeV/nucleon Au-Au collisions. The symbols represent the experimental data from PHENIX Collaboration [18, 20, 21]. Transverse mass scaled results are shown with the curves.