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

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ABSTRACT

The transverse mass spectra of light mesons produced in Au–Au collisions at $\sqrt{s_{NN}} = 200$ 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.

1. 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 μ 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 η 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 mesons and obtain the temperature of emission sources directly.

2. 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

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(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 [10], the total number of the mesons is given by

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

where p, E, T, μ, 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 non-equilibrium. The corresponding momentum distribution is

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

We have the transverse mass m_T distribution,

$$\left.\frac{d^2N}{m_T\,dm_T\,dy}\right|_{y=0} = \frac{gVm_T\cosh y}{(2\pi)^2}\left[1+(q-1)\frac{m_T\cosh y}{T}\right]^{-1/(q-1)}. \quad (3)$$

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

$$\left.\frac{d^2N}{m_T\,dm_T\,dy}\right|_{y=0} = \frac{gVm_T}{(2\pi)^2}\left[1+(q-1)\frac{m_T}{T}\right]^{-1/(q-1)}, \quad (4)$$

which is only an 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

$$\frac{dN}{m_T\,dm_T} = C\int_{-Y}^{Y}\cosh y\,dy\,m_T\left[1+(q-1)\frac{m_T\cosh y}{T}\right]^{-1/(q-1)}, \quad (5)$$

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 rep-

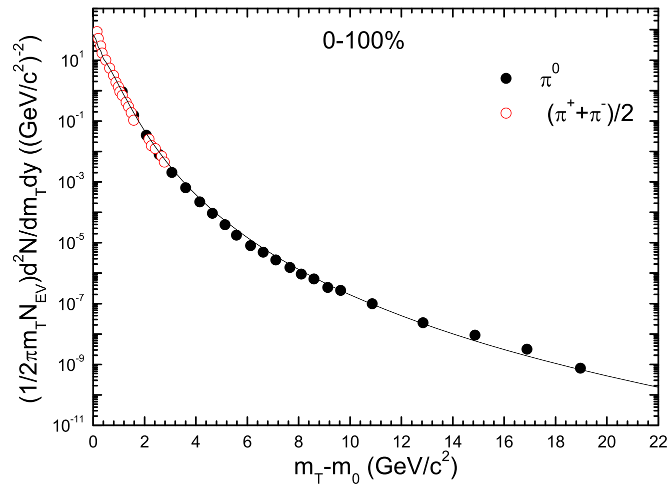

Fig. 1. Pion transverse mass spectra in $\sqrt{s_{NN}} = 200$ GeV/nucleon Au–Au collisions. Experimental data are taken from PHENIX Collaboration [15,16], and are shown with the scattered symbols. Our calculated results are shown with the curves.

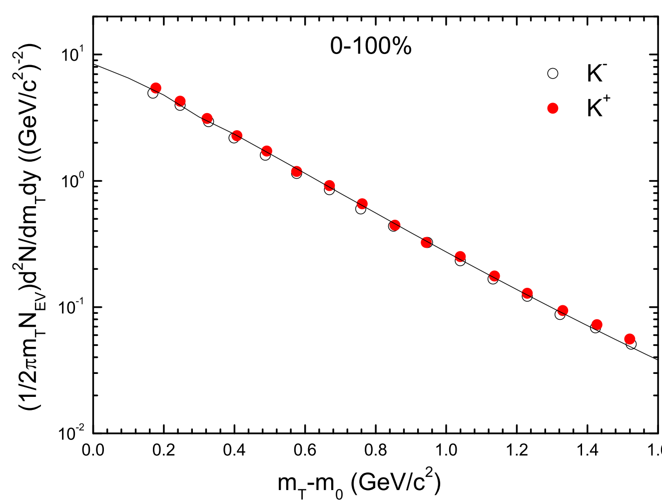

Fig. 2. K^- and K^+ transverse mass spectra in $\sqrt{s_{NN}} = 200$ GeV/nucleon Au–Au collisions. Experimental data are taken from PHENIX Collaboration [16], and are shown with the scattered symbols. Transverse mass scaled results are shown with the curves.

Table 1
Values of the parameters T and q for pions in our calculations.

Centrality	T (GeV)	q	χ^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 2
Values of χ^2/dof for Figs. 2–4, Fig. 6 and Fig. 7.

Mesons	0–100%	0–20%	20–60% (20–40% for J/ψ)	60–92% (40–92% for J/ψ)
K^+	0.42	0.44	0.35	0.55
K^-	0.51	0.55	0.57	0.65
J/ψ	0.57	0.70	0.61	0.58
ϕ	0.59	0.50	0.55	0.45
η	0.89	0.94	0.82	0.76
ω	0.70	–	–	–