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Research Article

Investigation of Particle Distributions in Xe-Xe Collision at $\sqrt{s_{\mathrm{NN}}} = 5.44\,\mathrm{TeV}$ with the Tsallis Statistics

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The distribution characteristic of final-state particles is one of the significant parts in high-energy nuclear collisions. The transverse momentum distribution of charged particles carries essential evolution information about the collision system. The Tsallis statistics is used to investigate the transverse momentum distribution of charged particles produced in Xe-Xe collisions at $\sqrt{s_{\mathrm{NN}}} = 5.44\,\mathrm{TeV}$. On this basis, we reproduce the nuclear modification factor of the charged particles. The calculated results agree approximately with the experimental data measured by the ALICE Collaboration.

1. Introduction

One of the major goals of high-energy nucleus-nucleus (AA) collisions is to study quark-gluon plasma (QGP) at high energy density and high temperature. The Large Hadron Collider (LHC) has performed different species of collisions at one or more energies, such as lead-lead, proton-lead, and proton-proton collisions. The Xe-Xe ion collision [1, 2] at $\sqrt{s_{\mathrm{NN}}} = 5.44\,\mathrm{TeV}$ is a new collision experiment and is an intermediate-size collision system at the LHC. Since the mass number value of xenon is between proton and lead, it helps us to understand the system-scale effect of the final-state particle properties in ion collisions at high energy [3–6]. Compared with the sphere of the Pb nucleus, the deformation of the Xe nucleus is long and flattened in collisions. The deformed shape of Xe will provide us with different kinds of collision configurations. The deformed Xe nucleus will affect the initial condition of the reaction. How much impact does the deformation have on particle production and distribution? Many charged particles are produced and measured in the AA collisions. The investigation of the particle spectra is of great interest and is very helpful for comprehending the collision reaction mechanism and the particle production process in the different species of collision systems at different center-of-mass energies [7–13].

With respect to the final-state observations, the experimental transverse momentum p_T spectrum is of great significance in understanding the production process of the moving particles. In past years, theoretical efforts have been carried out in statistical models to analyze the particle spectra over a broad range of collision energies [14–18]. At RHIC and LHC energies, the p_T spectra have been investigated intensively in various collision systems like Au+Au, Pb+Pb, and pp at different energies. A statistical model can achieve some features in treating the multiparticle system in RHIC and LHC. Recently, the ALICE Collaboration reported the p_T spectra and nuclear modification factors of charged particles produced in Xe-Xe collisions at $\sqrt{s_{\mathrm{NN}}} = 5.44\,\mathrm{TeV}$ [1]. The nuclear modification factor R_{AA} is also an important observation and can provide information about the dynamics of QGP matter at extreme densities and temperatures [19–26].

In this paper, we discuss the p_T spectra and the nuclear modification factor R_{AA} in the Tsallis statistics. By the investigation of the p_T spectra, we extract the parameters, which provide the calculation foundation for the nuclear modification factor R_{AA}.

2. Description of the Particle Distribution in the Tsallis Statistics

The Tsallis statistics has been widely used to study the properties of final-state particles produced in nucleus-nucleus and proton-proton collisions at high energy [27–30]. In The Tsallis statistics, more than one version of the Tsallis distribution is used to investigate particle distributions. According to the Tsallis statistics, the number of the particles is

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

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

where g and μ are the degeneracy factor and the chemical potential of the multiparticle system, respectively. T and q are the Tsallis temperature and the degree parameter of deviation from equilibrium, respectively. The first equation and second equation are two versions. The second equation (equation (1b)) can naturally meet the thermodynamic consistency [31–33]. At $\mu = 0$, the transverse momentum distribution is

$$\begin{aligned} \frac{d^2N}{dy dp_T} = & \frac{gVp_T\sqrt{p_{p_T}^2 + m^2}\cosh y}{(2\pi)^2} \\ & \cdot \left[1 + (q-1)\frac{\sqrt{p_{p_T}^2 + m^2}\cosh y}{T}\right]^{-(q/q-1)}. \end{aligned} \tag{2}$$

The nuclear modification factor R_{AA} acts as a probe to understand the nuclear medium effect in the AA collision and is a measure of the particle production modification. It is typically expressed as a ratio of the particle p_T spectra in AA collisions to that in pp collisions:

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dydp_T}{\langle T_{AA}\rangle d^2\sigma^{pp}/dydp_T}, \tag{3}$$

where N^{AA} is the production yield in AA collisions and σ^{pp} is the production cross-section in pp collisions. The average nuclear overlap function $\langle T_{AA}\rangle$ is estimated via a Glauber model of nuclear collisions. The R_{AA} is also expressed as

$$R_{AA} = \frac{f_{fin}}{f_{in}}, \tag{4}$$

where f_{in} is the distribution of the initial particles produced at an early time of the hadronization. Then, these particles interact with the medium system. The function f_{fin} is the distribution of the final-state particles, which no longer interact with each other.

According to the Boltzmann transport equation, the distribution of the particles $f(x, p, t)$ is

$$\frac{df(x,p,t)}{dt} = \frac{\partial f}{\partial t} + v \cdot \nabla_x f + F \cdot \nabla_p f = C[f]. \tag{5}$$

The evolution of the particle distribution is attributed to its interaction with the medium particles. The terms v and F are the velocity and the external force, respectively. In relaxation time approximation, the collision term $C[f]$ is given by

$$C[f] = -\frac{f - f_{eq}}{\tau}, \tag{6}$$

where τ is the relaxation time. The Boltzmann local equilibrium distribution f_{eq} is

$$f_{eq} = \frac{gV}{(2\pi)^2} p_T m_T e^{-(m_T/T_{eq})}, \tag{7}$$

where T_{eq} is the equilibrium temperature of the QCD phase transition. Considering $\nabla_x f = 0$ and $F = 0$, the distribution of the particles $f(x, p, t)$ is

$$\frac{df(x,p,t)}{dt} = \frac{\partial f}{\partial t} = \frac{f - f_{eq}}{\tau}. \tag{8}$$

A solution of the equation is

$$f_{fin} = f_{eq} + \left(f_{in} - f_{eq}\right) e^{-(t_f/\tau)}, \tag{9}$$

where t_f is the freeze-out time. The initial distribution is taken as the Tsallis distribution, *i.e.*, equation (2). Therefore, the final-state distribution is

$$\begin{aligned} f_{fin} = & \frac{gV}{(2\pi)^2} p_T m_T e^{-(m_T/T_{eq})} \\ & + \frac{gV}{(2\pi)^2} p_T m_T \left\{ \left[1 + (q-1)\frac{m_T}{T}\right]^{-(q/q-1)} \right. \\ & \left. - e^{-(m_T/T_{eq})} \right\} \cdot e^{-(t_f/\tau)}. \end{aligned} \tag{10}$$

Then, the nuclear modification factor R_{AA} is obtained as

$$\begin{aligned} R_{AA} = & \frac{f_{eq}}{f_{in}} + \left(1 - \frac{f_{eq}}{f_{in}}\right) e^{-(t_f/\tau)} \\ = & \frac{e^{-(m_T/T_{eq})}}{(1 + (q-1)(m_T/T))^{-(q/q-1)}} \\ & + \left[1 - \frac{e^{-(m_T/T_{eq})}}{(1 + (q-1)(m_T/T))^{-(q/q-1)}}\right] e^{-(t_f/\tau)}. \end{aligned} \tag{11}$$

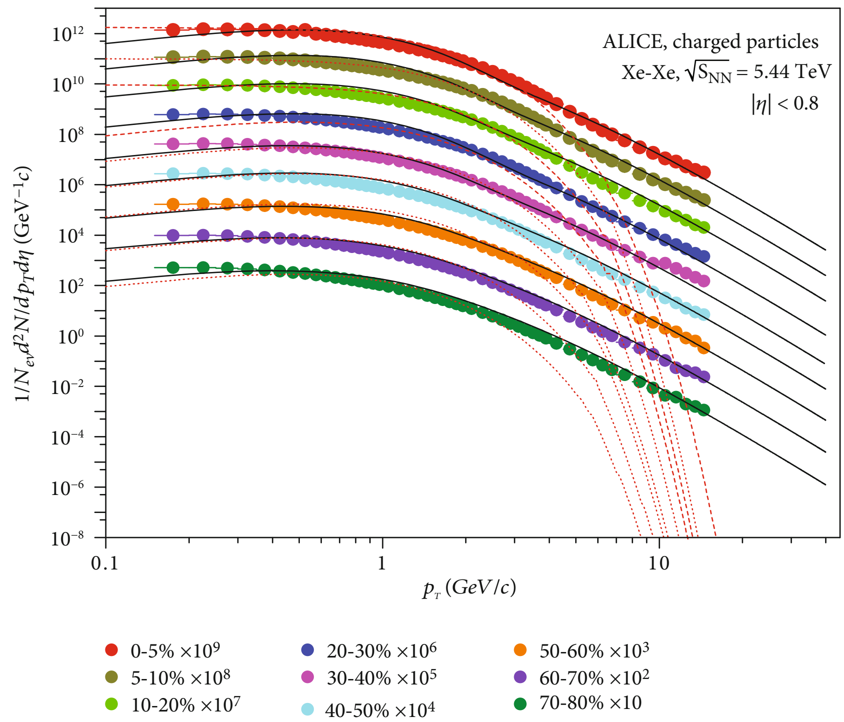

Figure 1: Transverse momentum distributions of charged particles produced in the Xe-Xe collision at $\sqrt{s_{NN}} = 5.44$ TeV. The filled circles indicate the experimental data in 0-5%, 5-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-60%, 60-70%, and 70-80% centrality classes [1]. The solid lines are the results of equation (2), and the dotted lines are the results of the Boltzmann statistics.

The equation is the calculation basis of the nuclear modification factor. In the relaxation time approximation, the R_{AA} is derived in the Tsallis statistics.

3. Discussions and Conclusions

In this section, we discuss the transverse momentum spectra and the nuclear modification factor of the charged particles produced in Xe-Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV. The transverse momentum contributes significantly to the characterization of the matter formed in high energy collisions because p_T is sensitive to the matter properties at an early time. The transverse momentum spectra in the kinematic range $0.15 < p_T < 50$ GeV/c and $|\eta| < 0.8$ are presented for nine centrality classes in Figure 1. The filled circles indicate the experimental data measured by the ALICE Collaboration [1]. The lines are the results of equation (2). The value of T_{eq} is 0.24 GeV. The model results are in agreement with the experimental data. The maximum value of χ^2 is 0.942 and the minimum is 0.205. The other parameters used in the calculation are listed in Table 1. The nonequilibrium degree q is a constant value. The freeze-out time t increases with increasing collision centrality. The final-state transverse momentum spectra for different centralities are determined by the temperature T, at which there are no interactions between the final-state particles. By the analysis of the p_T spectra, the thermodynamics parameters are extracted.

Table 1: Values of q, T, and t taken in Figure 1.

Centrality	q	T	t_f/τ
0-5%	1.125	0.196	1.581
5-10%	1.125	0.191	1.381
10-20%	1.125	0.187	1.005
20-30%	1.125	0.185	1.252
30-40%	1.125	0.180	0.788
40-50%	1.125	0.178	0.586
50-60%	1.125	0.175	0.360
60-70%	1.125	0.169	0.226
70-80%	1.125	0.165	0.115

The dotted lines are the results of the Boltzmann statistics, which can agree with the experimental data in the low p_T range.

The nuclear modification factor is also an important observation and is a measure of the particle-production modification. In Figure 1, we compare the p_T spectra of the model results and the experiment data, and can extract the parameters, which are required in the calculation of the nuclear modification factor R_{AA}. Figure 2 presents the nuclear modification factor R_{AA} of charged particles as a function of p_T in Xe-Xe at $\sqrt{s_{NN}} = 5.44$ TeV collisions. The filled circles indicate the experimental data measured by the ALICE Collaboration [1]. The lines are the results

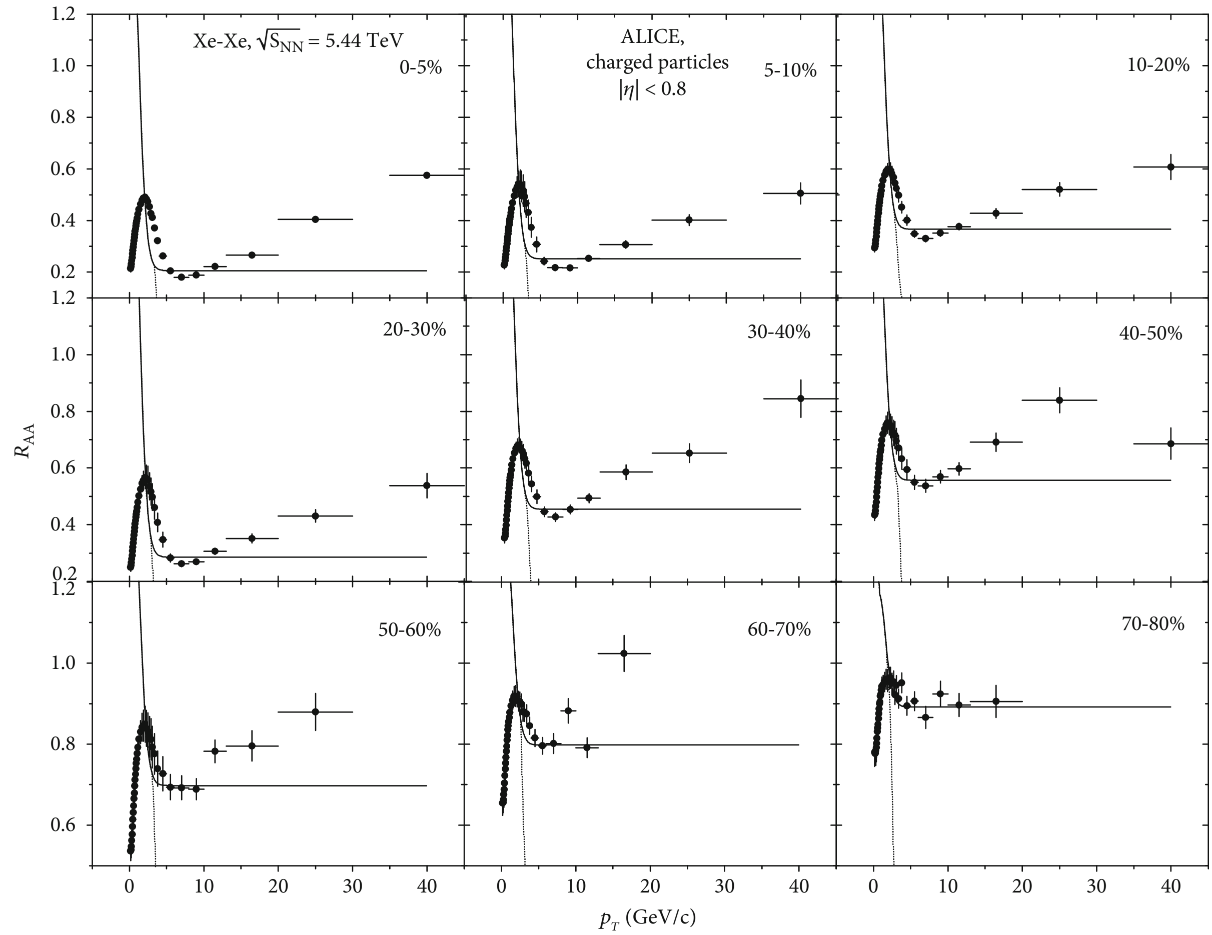

Figure 2: Nuclear modification factor R_{AA} as a function of p_T in the Xe-Xe collision at $\sqrt{s_{NN}} = 5.44$ TeV. The filled circles indicate the experimental data in 0-5%, 5-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-60%, 60-70%, and 70-80% centrality classes [1]. The lines are the results of equation (11) and the dotted lines are the results of the Boltzmann statistics.

of equation (11). The parameters used in the calculation are determined by the model results in Figure 1. The nuclear modification factor R_{AA} depends strongly on the collision centrality. The R_{AA} rises linearly at low p_T (about below 2.2 GeV). At high p_T, the R_{AA} first declines linearly and then rises slowly. The model can approximately describe the nuclear modification factor at the high p_T region, as shown in Figure 3. The dotted lines are the results of the Boltzmann statistics. Same as the above description of the transverse momentum spectra, they agree with the experimental data at low p_T.

Both experimentally and theoretically, the study of the particle spectra can contribute to our understanding of the particle production and the evolution dynamics in the collision system. The Tsallis statistics has attracted extensive attention due to the investigation of final-state particles produced in nuclear collisions at high energies. Compared with Levy-Tsallis, Boltzmann, and Blast wave, the Tsallis distribution can describe the transverse momentum spectra at a large range. It can extract the temperature and the nonequilibrium degree, which provide the requirements of the R_{AA} calculation. It is successful in explaining the experimental data of the transverse momentum spectra and can obtain some thermodynamics information, such as the temperature and the chemical potential. In our previous work [34–37], the statistics model is only used to study the transverse momentum spectra of particles produced in one or more collision systems at different energies. The present work is a new attempt. The model is improved by the Tsallis statistics in relaxation time approximation. Considering relaxation time approximation of the collision term, we achieve the final-state distribution by solving the Boltzmann transport equation, where the initial distribution is inserted consistently. And, the expression of the R_{AA} calculation in the Tsallis statistics is derived. In our previous work [31–34], the Tsallis distribution can describe the p_T distributions of particles produced in one or more collision systems, such as p, Cu, Au, and Pb collisions at various energies. Compared with these collision systems, the Xe nucleus has a moderate prolate deformation. But, p_T distributions in Xe-Xe collisions can also be described well by the Tsallis distribution. The improved model can not only describe transverse momentum spectra but also

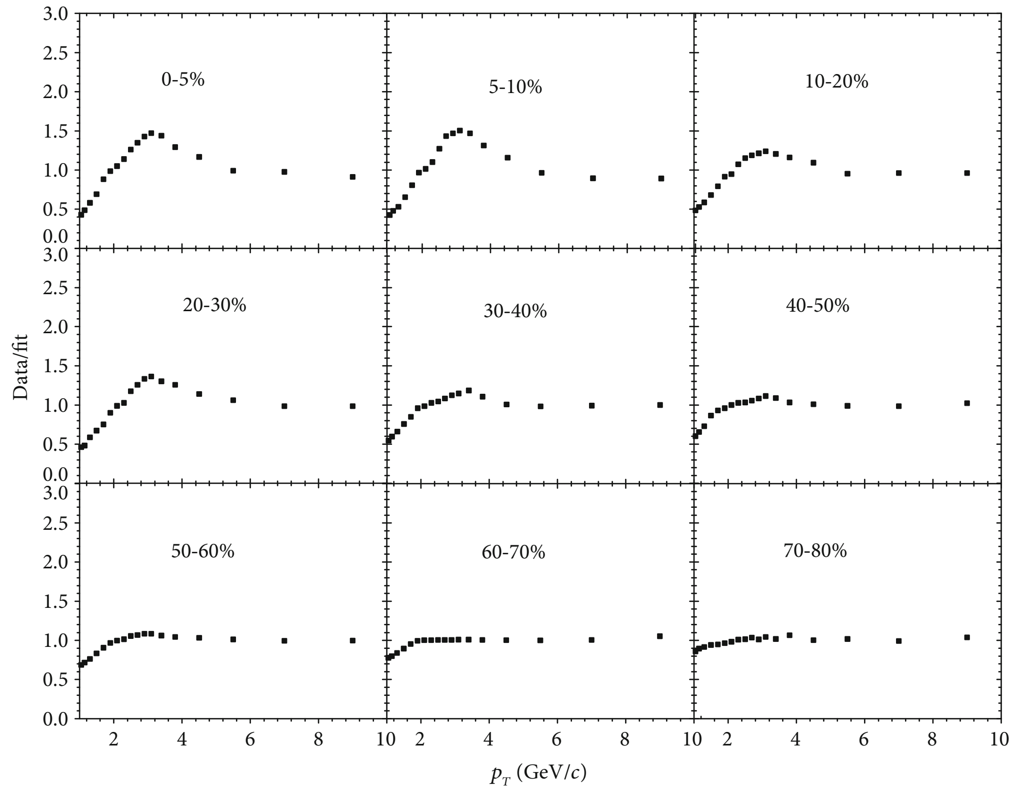

FIGURE 3: The data/fit of R_{AA} as a function of p_T for the different centrality classes.

reproduce the nuclear modification factor of particles in Xe-Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV in different centrality classes.

Data Availability

The used data in the model calculation are available and have been listed in Table 1.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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