Pseudorapidity distributions of charged particles in asymmetric collisions using Tsallis thermodynamics

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Abstract

The pseudo-rapidity distributions of the charged particles produced in the asymmetric collision systems p+Al, p+Au and ^{3}He+Au at $ sqrt{s_{NN}} = 200$ GeV are evaluated in the framework of a fireball model with Tsallis thermodynamics. The fireball model assumes that the experimentally measured particles are produced by fireballs following the Tsallis distribution and it can effectively describe the experimental data. Our results as well as previous results for d+Au collisions at $ sqrt{s_{NN}} = 200$ GeV and p+Pb collisions at $ sqrt{s_{NN}} = 5.02$ TeV validate that the fireball model based on Tsallis thermodynamics can provide a universal framework for pseudo-rapidity distribution of the charged particles produced in asymmetric collision systems. We predict the centrality dependence of the total charged particle multiplicity in the p+Al, p+Au and ^{3}He+Au collisions. Additionally, the dependences of the fireball model parameters (y_{0a}, y_{0A}, $ sigma_{a}$ and $ sigma_{A}$) on the centrality and system size are studied.

Full Text

Preamble

Pseudorapidity distributions of charged particles in asymmetric collisions using Tsallis thermodynamics

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The pseudo-rapidity distributions of charged particles produced in asymmetric collision systems p+Al, p+Au, and ^{3}He+Au at sN N = 200 GeV are evaluated in the framework of a fireball model with Tsallis thermodynamics. The fireball model assumes that the experimentally measured particles are produced by fireballs following the Tsallis distribution and it can effectively describe the experimental data. Our results for sN N = 200 GeV as well as sN N = 5.02 TeV validate previous results for d+Au collisions that the fireball model based on Tsallis thermodynamics can provide a universal framework for pseudo-rapidity distribution of the charged particles produced in asymmetric collision systems. We predict the centrality dependence of the total charged particle multiplicity in the p+Al, p+Au, and ^{3}He+Au collisions. Additionally, the dependences of the fireball model parameters (y_0 , y_0 , σ , and σ) on the centrality and system size are studied.

Keywords: Tsallis thermodynamics, Fireball model, Pseudo-rapidity distribution, Heavy-ion collisions, Charged particles

Introduction

High-energy heavy-ion collisions provide a unique way to understand the origin of the universe. However, their processes cannot be directly observed in experiment. We can only study the collision process indirectly by analyzing the properties of the final particles produced in the collisions. The pseudo-rapidity distribution of charged particles is one of the important experimental observables. The study of this observable could lead to a better understanding of the properties of the particles produced in the collisions, the particle production mechanism, and so on. There have been numerous works in previous studies using different models, such as HIJING [?], AMPT [?], EPOS-LHC [?], a multi-source thermal model [?, ?], a new revised Landau hydrodynamics model [?], a 1+1 dimensional hydrodynamics model [?, ?], a dynamical initial state model coupled to (3+1)D viscous relativistic hydrodynamics [?], and so on, to analyze the existing experimental data of pseudo-rapidity distributions of charged particles [?]. Although these models are based on different physical ideas, valuable physical information on the collision process has been extracted and learned.

Recently, a fireball model based on Tsallis thermodynamics was utilized to analyze the pseudo-rapidity distribution of charged particles measured in high-energy heavy-ion collisions [?]. In our previous works [?, ?], we used the fireball model to study the pseudo-rapidity distributions of charged particles produced in p+p(p) collisions for energies ranging from sN N = 23.6 GeV to 13 TeV and

A+A collisions at RHIC and LHC, and extended the fireball model to asymmetric collision systems, i.e., d+Au collisions at sN N = 200 GeV and p+Pb collisions at sN N = 5.02 TeV, by considering the asymmetric collision geometry configuration. In this paper, we utilize recently published data from the PHENIX Collaboration [?] at RHIC to systematically study the pseudo-rapidity distributions of charged particles produced in asymmetric collision systems, including p+Al, p+Au, and ^{3}He+Au collisions at sN N = 200 GeV. We also predict the total multiplicities of charged particles from the fireball model and study their centrality dependence. Further, we analyze the centrality and system size dependencies of the fireball model parameters obtained from the pseudo-rapidity distributions of charged particles.

The paper is organized as follows. In Section II, the fireball model with Tsallis thermodynamics is briefly introduced. In Section III, the fitting results of the fireball model and the total charged particle multiplicities extracted from the fireball model are shown. The dependences of the model parameters on the centrality and size of the collision systems are also presented. A brief conclusion is drawn in Section IV.

II. Theoretical Descriptions

In the self-consistent Tsallis thermodynamics, the Tsallis distribution is proposed as a generalization of the Boltzmann-Gibbs distribution [?]. To describe the transverse momentum spectrum of particles, the Tsallis distribution is written as [?]:

$$\frac{d^{2N}}{2\pi p_T dp_T dy} = \frac{gV}{(2\pi)^3}\left[1+(q-1)\frac{m_T\cosh y-\mu}{T}\right]^{-q/(q-1)} m_T\cosh y$$

where $m_T = \sqrt{p_T^2+m_0^2}$ is the transverse mass, m_0 is the particle rest mass, y is the rapidity, q is the entropic factor which measures the non-additivity of the entropy [?, ?], μ is the chemical potential, and T is the temperature. The Boltzmann distribution is recovered when $q = 1$. We take $\mu = 0$ because the multiplicities of π^+ and π^- are equal and they are the majority of particles produced in the collision systems considered. For mid-rapidity $y \approx 0$, Eq. (1) can be rewritten as:

$$\frac{d^{2N}}{2\pi p_T dp_T dy} = \frac{gV}{(2\pi)^3}\left[1+(q-1)\frac{m_T}{T}\right]^{-q/(q-1)}$$

The parameters q and T are extracted from the experimental transverse momentum spectrum of the particles.

In the fireball model with Tsallis thermodynamics [?], the particles measured in the experiment were produced by fireballs following the Tsallis distribution Eq. (1). The density distribution of these fireballs in rapidity space is $\nu(y_f)$, where

y_f is the rapidity of the fireball. Therefore the transverse momentum spectrum of particles can be written as:

$$\frac{d^{2N}}{2\pi p_T dp_T dy} = A\int_{-\infty}^{\infty} \nu(y_f)\frac{m_T \cosh(y-y_f)}{(2\pi)^3}\left[1+(q-1)\frac{m_T \cosh(y-y_f)}{T}\right]^{-q/(q-1)} dy_f$$

where N is the total particle multiplicity and A is the normalization constant such that:

$$\int_{-\infty}^{\infty}\int_{0}^{\infty} \frac{d^{2N}}{2\pi p_T dp_T dy} p_T dp_T dy = N$$

Sometimes, the experimental data are measured in pseudo-rapidity η space. To describe the experimental data $dN/d\eta$, we substitute the relation between rapidity and pseudo-rapidity [**?**]:

$$\cosh y = \sqrt{1+\frac{p_T^2}{m_0^2}\sinh^2\eta}$$

into Eq. (3) and integrate the transverse momentum to obtain [**?**, **?**]:

$$\frac{dN}{d\eta} = A\int_{-\infty}^{\infty}\int_{0}^{\infty} dp_T p_T \times \nu(y_f)\frac{m_T \cosh(y-y_f)}{(2\pi)^2}\left[1+(q-1)\frac{m_T \cosh(y-y_f)}{T}\right]^{-q/(q-1)}$$

Because of the term $\sqrt{T\cosh^2 y + m_0^2}$, Eq. (6) cannot be analytically integrated over p_T and it is done numerically.

In this paper the asymmetric collision systems are studied, so the distribution $\nu(y_f)$ is assumed to be the sum of two asymmetric q-Gaussian functions [**?**]:

$$\nu(y_f) = \left[1+(q'-1)\frac{(y_f-y_{0a})^2}{\sigma_a^2}\right]^{-1/(q'-1)} + x\left[1+(q'-1)\frac{(y_f+y_{0A})^2}{\sigma_A^2}\right]^{-1/(q'-1)}$$

where $y_{0a(A)}$ and $\sigma_{a(A)}$ are the centroid position and width of fireball distribution in the direction of the light (heavy) nucleus beam, respectively. The normalization of Eq. (8) is handled by the normalization constant A in Eq. (3). x is the parameter to characterize the extent of asymmetry which was first proposed in our previous work [**?**]. In this work, we take $q' = q$ same as in [**?**]. A representative figure of Eq. (8) is shown in Appendix A with the parameters obtained for the p+Al collisions at 0-5% centrality and sN N = 200 GeV.

III. Results and Discussion

Because the data of the transverse momentum spectra of charged particles produced in p+Al, p+Au, and ^{3}He+Au collisions at sN N = 200 GeV have not been released yet, the data of the transverse momentum spectra of π^0 produced from these collisions are obtained from [?] in this study. Using Eq. (2) by taking $g = 1$ and V as a free parameter, the parameters T and q for the Tsallis distribution are extracted and listed in Table 2 in Appendix B. A representative figure of transverse momentum spectra of π^0 for p+Al collisions at sN N = 200 GeV is shown in Appendix C. It is worth noting that the transverse momentum spectrum of π^0 is very similar to that of $\pi^\pm$ at sN N = 200 GeV for a given collision centrality, so the temperature parameter T extracted from π^0 should reasonably characterize the property of the collision system. We take the parameters T and q from the closest centrality when the centrality of the particle transverse momentum spectrum and the centrality of the charged particle pseudorapidity distribution are not the same. These two parameters and the fireball model with Tsallis thermodynamics, Eqs. (6) and (8), are then utilized to study the pseudorapidity distribution of charged particles produced in the collisions. The corresponding values of x in Eq. (8) are also listed in Table 3 in Appendix B.

In Figs. 1, 2, and 3, the results of the pseudorapidity distributions of charged particles from the fireball model with Tsallis thermodynamics for different centrality bins in p+Al, p+Au, and ^{3}He+Au collisions at sN N = 200 GeV are shown. The fireball model effectively describes the experimental data within the errors. Notably, the data quality of the pseudorapidity distributions of charged particles is not as good as that for d+Au collisions at sN N = 200 GeV shown in [?], i.e., in terms of larger errors, a fewer number of data points, as well as a lower pseudorapidity coverage, which leads to larger uncertainties in the fireball model parameters and affects our analyses of the fireball model parameters versus collision centrality and collision system size to some extent later in the following. The pseudorapidity distribution of charged particles for centrality 5-10% is lower than the case for centrality 10-20% in some pseudorapidity regions for ^{3}He+Au collisions, which is observed in Fig. 3. A larger x at centrality 5-10% compared with the others for ^{3}He+Au collisions is also observed in Table 3. We emphasize that the same fitting protocol is applied for all the pseudorapidity distribution data of charged particles.

Because the collision system is asymmetric, the pseudorapidity distribution of charged particles has significant forward/backward asymmetry. Fewer particles are produced in the direction of the light nucleus (p, ^{3}He) beam compared to the heavy nucleus (Al, Au) beam. As in the d+Au collision system at sN N = 200 GeV and the p+Pb collision system at sN N = 5.02 TeV we studied in [?], the pseudorapidity distributions of charged particles produced by these collision systems also become more symmetric from central to peripheral collisions. This is because peripheral collisions for asymmetric systems are more similar to symmetric p+p collisions according to collision geometry.

We then evaluate the centrality dependence of the total multiplicities of charged particles produced in these collision systems. Integrating Eq. (6) over $\eta \in [-10, 10]$, we obtain the total multiplicity of charged particles for each centrality from the fireball model. Because the corresponding experimental data are not yet available, we only analyze the results extracted from the fireball model and treat them as predictions. Figure 4 [Figure 4: see original paper] shows the total multiplicities of charged particles calculated from the fireball model versus collision centrality c, where $c = 0$ represents the most central collisions and $c = 1$ represents the most peripheral collisions. It can be observed that the fitting function taken from [**?**] can effectively describe the centrality dependence of the total multiplicities of charged particles. As the centrality changes from central to peripheral collisions, fewer charged particles are produced.

We also analyze both the centrality and system size dependence of the parameters (y_{0a}, y_{0A}, σ_a, and σ_A) of the fireball model. In Fig. 5 [Figure 5: see original paper], the dependence of the fireball model parameters on collision centrality in p+Al, p+Au, and ^{3}He+Au collisions at sN N = 200 GeV is shown. Inspired by the linear relation of the centrality dependence of the fireball model parameters for d+Au collisions at sN N = 200 GeV and p+Pb collisions at sN N = 5.02 TeV shown in Fig. 12 of our previous work [**?**], linear fittings are performed to guide the eyes in Fig. 5, and the fitting functions are listed in Table 1 . The negative and positive slopes of the linear fittings for the fireball model parameters (y_{0a}, y_{0A}, and σ_A) versus centrality are similar to those of the d+Au and p+Pb collisions in [**?**].

It can be observed that the slopes of the linear fittings for parameter y_{0a} versus centrality are positive and the corresponding slopes for parameter y_{0A} versus centrality are negative for p+Al, p+Au, and d+Au collisions at sN N = 200 GeV. However, the slopes for parameters (y_{0a}, y_{0A}) reverse their signs respectively for ^{3}He+Au collision at sN N = 200 GeV compared to the above-mentioned cases. The slopes for parameters (y_{0a}, y_{0A}) are positive for p+Pb at sN N = 5.02 TeV. It can also be observed that there is a universal trend with increasing centrality for parameter $\sigma_{a(A)}$ except for the lightest collision system p+Al, i.e., σ_a increases with increasing centrality in the direction of the light nucleus beam and σ_A decreases with increasing centrality in the direction of the heavy nucleus beam. In the p+Al collision system, σ_a and σ_A have opposite trends with increasing centrality compared to their counterparts in the other collision systems. These different patterns indicate complex dynamics in asymmetric collisions relevant to the combinations of projectile and target as well as collision energy, which needs more investigation.

Figure 6 [Figure 6: see original paper] shows the collision system size dependence of the fireball model parameters at sN N = 200 GeV. For collision systems other than p+p, the parameters of the most central collisions are considered. In p+p and Au+Au collisions, the parameters satisfy $y_{0a} = y_{0A} = y_0$ and $\sigma_a = \sigma_A = \sigma$, where y_0 and σ are the rapidity centroid and width of fireball distribution in symmetric collision systems, as detailed in [**?**]. It can be deduced that when the light nucleus is p, y_{0a} decreases as the size of the heavy nucleus increases, whereas y_{0A} shows the opposite trend. This indicates that a larger heavy nucleus has stronger stopping power for p. When the heavy nucleus is Au, y_{0a} increases as the size of the light nucleus increases, whereas y_{0A} shows the opposite trend. This means that a larger light nucleus is more difficult to be stopped by Au but has stronger stopping power for Au. For parameters σ_a and σ_A, no conclusive patterns are observed. We expect that more discussion can be added when the data quality of the pseudorapidity distributions of charged particles is improved by experimentalists. These phenomena manifest the complex dynamics in asymmetric collisions.

IV. Summary

In this paper, we studied the pseudorapidity distributions of charged particles produced in p+Al, p+Au, and ^{3}He+Au collisions at sN N = 200 GeV using the fireball model with Tsallis thermodynamics. The model can well fit the experimental data from asymmetric collisions. We also extracted the total multiplicities of charged particles from the fireball model as predictions and analyzed their dependence on collision centrality. Notably, the data quality of the pseudorapidity distributions of charged particles produced in p+Al, p+Au, and ^{3}He+Au collisions at sN N = 200 GeV affected our results to some extent. Combining our previous results of d+Au collisions at sN N = 200 GeV and p+Pb collision at sN N = 5.02 TeV, we analyzed the centrality and system size dependence of the fireball model parameters (y_{0a}, y_{0A}, σ_a, and σ_A). Interesting patterns were revealed, which indicated complex dynamics in asymmetric collisions. Our results confirmed the conclusion made previously in [?] that the fireball model with Tsallis thermodynamics as a universal framework could also describe the pseudorapidity distribution of charged particles produced in asymmetric collision systems.

Appendix A: Fireball distribution of Eq. (8)

A representative figure of the fireball distribution of Eq. (8) using the parameters obtained for p+Al collisions at 0-5% centrality and sN N = 200 GeV is shown in Fig. 7 [Figure 7: see original paper].

Appendix B: Parameters q, T and x

The parameters q and T extracted by fitting the transverse momentum spectrum of particles [?] with the Tsallis distribution Eq. (2), as well as the parameter x in Eq. (8), are listed in Tables 2 and 3 .

Appendix C: The particle spectra fit

Using Eq. (2), the fitting figure of the transverse momentum spectra of π^0 produced in p+Al collisions at sN N = 200 GeV is shown in Fig. 8 [Figure 8:

see original paper]. Similar results are obtained for p+Au and ^{3}He+Au collision systems at sN N = 200 GeV [?].

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Note: Figure translations are in progress. See original paper for figures.