Excitation functions of kinetic freeze-out temperature and transverse flow velocity in proton-proton collisions

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Abstract: Transverse momentum spectra of negative and positive pions produced at mid-(pseudo)rapidity in proton-proton (pp) collisions over a center-of-mass energy, $\sqrt{s}$, range from a few GeV to more than 10 TeV are analyzed by the blast-wave model with Boltzmann-Gibbs statistics. The model results are approximately in agreement with the experimental data measured by the NA61/SHINE, PHENIX, STAR, ALICE, and CMS Collaborations. It is shown that both the excitation functions of kinetic freeze-out temperature ($T_0$) of emission source and transverse flow velocity ($\beta_T$) of produced particles have a hill at $\sqrt{s} \approx 10$ GeV, a drop at dozens of GeV, and then an increase from dozens of GeV to more than 10 TeV.

Keywords: Excitation function of kinetic freeze-out temperature, excitation function of transverse flow velocity, proton-proton collisions

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1 Introduction

Chemical and thermal or kinetic freeze-outs are two of important stages of system evolution in high energy collisions. The excitation degrees of interacting system at the two stages are possibly different from each other. To describe different excitation degrees of interacting system at the two stages, one can use chemical and kinetic freeze-out temperatures respectively. Generally, at the stage of chemical freeze-out, the ratios of different types of particles are no longer changed, and the chemical freeze-out temperature can be obtained from the ratios of different particles in the framework of thermal model [1–4]. At the stage of kinetic freeze-out, the transverse momentum spectra of different particles are no longer changed, and the kinetic freeze-out temperature can be obtained from the transverse momentum spectra [5–8].

It should be pointed out that the transverse momentum spectra even though in narrow range contain both the contributions of random thermal motion and transverse flow of particles. The former and the latter reflect the excitation degree and collective expansion of the interacting system (or emission source) respectively. To extract the kinetic freeze-out temperature from transverse momentum spectra, we have to exclude the contribution of transverse flow, that is, we have to disengage the random thermal motion and transverse flow. There are more than one methods to disengage the two issues. The simplest and easiest method is to use the blast-wave model [5–8] to analyze the transverse momentum spectra, though other method such as the alternative method [6, 9–15] can obtain similar results [16].

The early blast-wave model is based on the Boltzmann-Gibbs statistics [5–7]. An alternative blast-wave model is used due to the Tsallis statistics [8]. Both the types of blast-wave model can be used to disengage the random thermal motion and transverse flow. Then, the kinetic freeze-out temperature of interacting system and transverse flow velocity of light flavor particles can be extracted. Most of light flavor particles are produced in soft excitation process and have narrow transverse momentum range up to $2 \sim 3$ GeV/c. A few part of light flavor particles are produced in hard scattering process and have higher transverse momenta. Generally, heavy flavor particles are produced via hard scattering process. From the point of view of disengaging or extraction, particles produced in hard scattering process are not needed to consider by us.

The excitation function of the kinetic freeze-out temperature, that is, its dependence on collision energy, are very interesting for us to study the properties of high energy collisions. Although there are many similar studies on this topic, the results seem to be inconsistent. For example, over a center-of-mass energy, $\sqrt{s_{NN}}$, range from a few GeV to a few TeV, the excitation function of
the kinetic freeze-out temperature in gold-gold (Au-Au) and lead-lead (Pb-Pb) collisions initially increases and then inconsistently saturates [17, 18], increases [19], or decreases [20, 21] with the increase of collision energy. On the contrary, the excitation function of the chemical freeze-out temperature shows initially increases and then consistently saturates with collision energy [1–4]. Comparatively, as the basic processes in nucleus-nucleus collisions, proton-proton (pp or p-p) collisions are minor in the study of the mentioned excitation functions.

It is worth to study the excitation function of the kinetic freeze-out temperature in pp collisions and to judge its tendency at the LHC. In this paper, by using the blast-wave model with Boltzmann-Gibbs statistics [5–7], we study the excitation functions of some concerned quantities in pp collisions which are closer to peripheral nuclear collisions comparing with central nuclear collisions. The experimental transverse momentum spectra of negative and positive pions ($\pi^-$ and $\pi^+$) measured at the mid-rapidity by the NA61/SHINE Collaboration at the the Super Proton Synchrotron (SPS) and its beam energy scan (BES) program [22], the PHENIX Collaboration at the Relativistic Heavy Ion Collider (RHIC) [23], the STAR Collaboration at the RHIC [6], as well as the ALICE and CMS Collaborations at the the Large Hadron Collider (LHC) [24–26] are analyzed.

The remainder of this paper is structured as follows. The formalism and method are shortly described in Section 2. Results and discussion are given in Section 3. In Section 4, we summarize our main observations and conclusions.

## 2 Formalism and method

There are two main processes of particle productions, namely the soft excitation process and the hard scattering process, in high energy collisions. For the soft excitation process, the model used in the present work is the blast-wave model [5–8] that has wide applications in particle productions. The model is based on two types of statistics. One is the Boltzmann-Gibbs statistics [5–7] and another one is the Tsallis statistics [8]. As an application of the model, we present directly its formalisms in the following. Although the model has abundant connotations, we focus only on the formalism of transverse momentum ($p_T$) distribution in which the kinetic freeze-out temperature ($T_0$) and mean transverse flow velocity ($\beta_T$) are included.

We are interested in the blast-wave model with Boltzmann-Gibbs statistics in its original form. According to refs. [5–7], the blast-wave model with Boltzmann-Gibbs statistics results in the probability density distribution of $p_T$ to be

\[
f_1(p_T) = \frac{1}{N} \frac{dN}{dp_T} = C_1 p_T m_T \int_0^R r dr \times \nonumber
I_0 \left[ \frac{p_T \sinh(\rho)}{T_0} \right] K_1 \left[ \frac{m_T \cosh(\rho)}{T_0} \right] ,
\]

(1)

where $C_1$ is the normalized constant, $m_T = \sqrt{p_T^2 + m_0^2}$ is the transverse mass, $m_0$ is the rest mass, $r$ is the radial coordinate in the thermal source, $R$ is the maximum $r$ which can be regarded as the transverse size of participant in the case of neglecting the expansion of source, $r/R$ is the relative radial position which has in fact more meanings than $r$ and $R$ themselves, $I_0$ and $K_1$ are the modified Bessel functions of the first and second kinds respectively, $\rho = \tanh^{-1}[\beta(r)]$ is the boost angle, $\beta(r) = \beta_S (r/R)^{n_0}$ is a self-similar flow profile, $\beta_S$ is the flow velocity on the surface, and $n_0 = 2$ is used in the original form [5]. There is the relation between $\beta_T$ and $\beta(r)$. As a mean of $\beta(r)$, $\beta_T = (2/R^2) \int_0^R r \beta(r) dr = 2\beta_S/(n_0 + 2)$.

Although the blast-wave model with Tsallis statistics is not be used in the present work, we would like to present it here for a comparison in its original form. According to ref. [8], the blast-wave model with Tsallis statistics results in the $p_T$ distribution to be

\[
f_2(p_T) = \frac{1}{N} \frac{dN}{dp_T} = C_2 p_T m_T \int_{-\pi}^\pi d\phi \int_0^R r dr \left\{ 1 + \frac{q - 1}{T_0} \left[ m_T \cosh(\rho) - p_T \sinh(\rho) \cos(\phi) \right] \right\}^{-1/(q-1)} ,
\]

(2)

where $C_2$ is the normalized constant, $q$ is an entropy index that characterizes the degree of non-equilibrium, $\phi$ denotes the azimuthal angle, and $n_0 = 1$ is used in the original form [8]. Because of $n_0$ being an insensitive quantity, the results corresponding to $n_0 = 1$ and 2 for the blast-wave model with Boltzmann-Gibbs or Tsallis statistics are harmonious [16]. In addition, the index $-1/(q - 1)$ used in Eq. (2) can be replaced by $-q/(q - 1)$ due to $q$ being very close to 1. This substitution results in a small and negligible difference in the Tsallis distribution [27, 28].

For a not too wide $p_T$ spectrum, the above two equations can be used to describe the $p_T$ spectrum and to extract the kinetic freeze-out temperature and transverse flow velocity. For a wide $p_T$ spectrum, we have to consider the contribution of hard scattering process. According to the quantum chromodynamics (QCD) calculus [29–31], the contribution of hard scattering process is parameterized to be an inverse power-law

\[
f_H(p_T) = \frac{1}{N} \frac{dN}{dp_T} = A p_T \left( 1 + \frac{p_T}{p_0} \right)^{-n}
\]

(3)
which is the Hagedorn function [32, 33], where \( p_0 \) and \( n \) are free parameters, and \( A \) is the normalization constant related to the free parameters. In literature [34, 35–39], and [40], there are respectively modified Hagedorn functions

\[
f_H(p_T) = \frac{1}{N} \frac{dN}{dp_T} = A \left( \frac{p_T^2}{m_T} \right) \left( 1 + \frac{p_T}{p_0} \right)^{-n},
\]

(4)

and

\[
f_H(p_T) = \frac{1}{N} \frac{dN}{dp_T} = A p_T \left( 1 + \frac{p_T^2}{p_0^2} \right)^{-n},
\]

(5)

where the three normalization constants \( A \), free parameters \( p_0 \), and free parameters \( n \) are severally different, though the same symbols are used to avoid trivial expression.

The experimental \( p_T \) spectrum distributed in a wide range can be described by a superposition of the soft excitation and hard scattering processes. We have

\[
f_0(p_T) = k f_S(p_T) + (1 - k) f_H(p_T),
\]

(7)

where \( k \) denotes the contribution fraction of the soft excitation process, and \( f_S(p_T) \) denotes one of Eqs. (1) and (2). As for the three \( f_H(p_T) \), we squint towards the first one due to its more applications. According to Hagedorn’s model [32], we may also use the usual step function to superpose the two functions. That is

\[
f_0(p_T) = A_1 \theta(p_1 - p_T) f_S(p_T) + A_2 \theta(p_T - p_1) f_H(p_T),
\]

(8)

where \( A_1 \) and \( A_2 \) are constants which result in the two components to be equal to each other at \( p_T = p_1 \) and \( p_T = p_2 \).

Eq. (8) is revised to

\[
f_0(p_T) = A_1 \theta(p_1 - p_T) f_V S(p_T) + A_2 \theta(p_T - p_1) \theta(p_2 - p_T) f_S(p_T) + A_3 \theta(p_T - p_2) f_H(p_T),
\]

(10)

where \( A_1, A_2, \) and \( A_3 \) are constants which result in the two contiguous components to be equal to each other at \( p_T = p_1 \) and \( p_T = p_2 \).

The above two types of superpositions (Eqs. (7) and (8)) have different treatments for the soft and hard components in the whole \( p_T \) range. Eq. (7) means that the soft component contributes in a range from 0 up to \( \sim 2 \) GeV/c or a little more. The hard component contributes in the whole \( p_T \) range, though the main contributor in the low \( p_T \) range is the soft component and the sole contributor in the high \( p_T \) range is the hard component. Eq. (8) shows that the soft component contributes in a range from 0 up to \( p_1 \), and the hard component contributes in a range from \( p_1 \) up to the maximum. The boundary of the contributions of soft and hard components is \( p_1 \). There is no mixed range for the two components in Eq. (8).

In the case of including only the soft component, Eqs. (7) and (8) are the same. In the case of including both the soft and hard components, their common parameters such as \( T_0, \beta_T, p_0, \) and \( n \) should be severally different from each other. To avoid large differences, we should select the experimental data in a narrow \( p_T \) range. In addition, most experimental data in the very-low \( p_T \) range are not available. The very-soft component in Eqs. (9) and (10) are in fact negligible. Thus, in the case of neglecting the very-soft component, Eqs. (9) and (10) are degenerated to Eqs. (7) and (8) respectively. We shall use Eq. (7) in the present work, where \( f_S(p_T) \) and \( f_H(p_T) \) are exactly Eqs. (1) and (3) respectively. If we regard Eq. (2) as \( f_S(p_T) \), the situation is similar due to Eqs. (1) and (2) being harmonious [16], though one more parameter (the entropy index \( q \)) is needed in Eq. (2).

3 Results and discussion

Figure 1 shows the transverse momentum spectra of \( \pi^- \) and \( \pi^+ \) produced at mid-(pseudo)rapidity in \( pp \) collisions at high center-of-mass energies, where different mid-(pseudo)rapidity (\( y \) or \( \eta \)) intervals and energies (\( \sqrt{s} \)) are marked in the panels. Different forms of the spectra are used due to different Collaborations, where \( N, \ E, \ p, \ \sigma, \) and \( N_{EV} \) denote the particle number, energy, momentum, cross-section, and event number, respectively. The closed and open symbols presented in panels (a)–(e) represent the data of \( \pi^- \) and \( \pi^+ \) mea-
Fig. 1. Transverse momentum spectra of $\pi^-$ and $\pi^+$ produced at mid-(pseudo)rapidity in $pp$ collisions at high energies, where the mid-(pseudo)rapidity intervals and energies are marked in the panels. The symbols presented in panels (a)–(e) represent the data of NA61/SHINE [22], PHENIX [23], STAR [6], ALICE [24], and CMS [25, 26] Collaborations, respectively, where in panel (a) only the spectra of $\pi^-$ is available. In some cases, different amounts marked in the panels are used to scale the data for clarity. The solid and dotted curves are our results calculated by Eq. (7). Following each $p_T$ spectrum, the ratio of data to fit is presented to monitor the departure of fit from data.
sured by the NA61/SHINE [22], PHENIX [23], STAR [6], ALICE [24], and CMS [25, 26] Collaborations, respectively, where in panel (a) only the spectra of $π^-$ is available. In some cases, different amounts marked in the panels are used to scale the data for clarity. The solid and dotted curves are our results calculated by Eq. (7). Following each $p_T$ spectrum, the ratio of data to fit is presented to monitor the departure of fit from data. The values of free parameters ($T_0$, $β_T$, $k$, $p_0$, and $n$), normalization constant ($N_0$), $χ^2$/dof corresponding to the curves in Fig. 1 are listed in Table 1, where $χ^2$ and dof are listed in terms of $χ^2$/dof. One can see that Eq. (7) describes the $p_T$ spectra at mid-($p_T$)rapidity in $pp$ collisions over an energy range from a few GeV to more than 10 TeV. The free parameters show some laws in the considered energy range.

To see clearly the excitation functions of free parameters, Figures 2(a)–2(e) show the dependences of $T_0$, $β_T$, $p_0$, $n$, and $k$ on $\sqrt{s}$, respectively. The closed and open symbols represent the parameter values corresponding to $π^−$ and $π^+$ respectively, which are listed in Table 1. One can see that there is a significant difference between the results of $π^−$ and $π^+$ is not obvious. In the excitation functions of $T_0$ and $β_T$, there is a peak at $\sqrt{s} \approx 10$ GeV, a drop at dozens of GeV, and then an increase from dozens of GeV to more than 10 TeV. In the excitation functions of $p_0$ and $n$, there is a slight decrease and increase respectively in the case of the hard component being available. The excitation function of $k$ shows that the contribution $(1−k)$ of hard component slightly increases from dozens of GeV to more than 10 TeV, and it has no contribution at around 10 GeV.

Indeed, $\sqrt{s_{NN}} \approx 10$ GeV is a special energy for nucleus-nucleus collisions as indicated by Cleymans [41]. The present work shows that $\sqrt{s}$ $≈ 10$ GeV is also a special energy for $pp$ collisions. At this energy (11 GeV more specifically [41]), the final state has the highest net baryon density, a transition from a baryon-dominated to a meson-dominated final state takes place, and the ratios of strange particles to mesons show clear and pronounced maxima [41]. These properties result in this special energy.

At 11 GeV, the chemical freeze-out temperature in nucleus-nucleus collisions is about 151 MeV [41], and the present work shows that the kinetic freeze-out temperature in $pp$ collisions is about 105 MeV. If we do not consider the difference between nucleus-nucleus and $pp$ collisions, though cold nuclear effect exists in nucleus-nucleus collisions, the chemical freeze-out happens obviously earlier than the kinetic one. According to an ideal fluid consideration, the time evolution of temperature follows $T_f = T_i (\tau_i / \tau_f)^{1/3}$, where $T_i$ (= 300 MeV) and $\tau_i$ (≈ 1 fm) are the initial temperature and proper time respectively [42, 43], and $T_f$ and $\tau_f$ denote the final temperature and time respectively, the chemical and kinetic freeze-outs happen at 7.8 and 23.3 fm respectively.

Strictly, $T_0$ ($β_T$) obtained form the pion spectra in the present work is less than that averaged by weighting the yields of pions, kaons, protons, and other light particles. Fortunately, the fraction of the pion yield in high energy collisions are major (> 90%). The parameters and their tendencies obtained from the pion spectra are similar to those obtained from the spectra of all light particles. To study the excitation functions of $T_0$ and $β_T$, it does not matter if we use the spectra of pions instead of all light particles.

It should be noted that the main parameters $T_0$ and $β_T$ get entangled in some way. Although the excitation functions of $T_0$ ($β_T$) which are acceptable in the fit process are not sole, their tendencies are harmonious.
Fig. 2. Excitation functions of (a) $T_0$, (b) $\beta_T$, (c) $p_0$, (d) $n$, and (e) $k$. The closed and open symbols represent the parameter values corresponding to $\pi^-$ and $\pi^+$ respectively, which are listed in Table 1.
Combining with our previous works [16], we could say that there is a slight (~10%) increase in the excitation function of $T_0$ and an obvious (~35%) increase in the excitation function of $\beta_T$ from the RHIC to LHC. At least, the excitation functions of $T_0$ and $\beta_T$ do not decrease from the RHIC to LHC.

However, the excitation functions of $T_0$ and $\beta_T$ from the RHIC to LHC are not always incremental or invariant. For example, in refs. [17, 18], $T_0$ has no obvious change and $\beta_T$ has a slight (~10%) increase from the RHIC to LHC. In ref. [19], $T_0$ has a slight (~9%) increase and $\beta_T$ has a large (~65%) increase from the RHIC to LHC. In ref. [20, 21], $T_0$ has a slight (~5%) decrease from the RHIC to LHC and $\beta_T$ increases by ~20% from 39 to 200 GeV. It is convinced that $\beta_T$ increases from the RHIC to LHC, though the situation of $T_0$ is doubtful.

Although some works [44–47] reported a decrease of $T_0$ and an increase of $\beta_T$ from the RHIC to LHC, our re-scans on their plots show a different situation of $T_0$. For example, in ref. [44], our re-scans show that $T_0$ has no obvious change and $\beta_T$ has a slight (~9%) increase from the RHIC to LHC, though there is an obvious hill or there is an increase by ~30% in $T_0$ in 5–40 GeV comparing with that at the RHIC. Ref. [45] shows similar results to ref. [44] with the almost invariant $T_0$ from the top RHIC to LHC, an increase by ~28% in $T_0$ in 7–40 GeV comparing with that at the top RHIC, and an increase by ~8% in $\beta_T$ comparing with that at the top RHIC. Refs. [46, 47] shows similar result to refs. [44, 45] on $T_0$, though the excitation function of $\beta_T$ is not available.

In most cases, the correlation between $T_0$ and $\beta_T$ are not negative, though some works [44, 45] show negative correlation over a wide energy range. For a give $p_T$ spectrum, it seems that a larger $T_0$ corresponds to a smaller $\beta_T$, which shows a negative correlation. However, this negative correlation is not sole case. In fact, a couple of suitable $T_0$ and $\beta_T$ can fit a give $p_T$ spectrum. A series of $p_T$ spectra at different energies possibly show a positive correlation between $T_0$ and $\beta_T$, or independent of $T_0$ on $\beta_T$, in a narrow energy range.

4 Conclusions

To conclude, the transverse momentum spectra of $\pi^-$ and $\pi^+$ produced at mid-(pseudo)rapidity in $pp$ collisions over an energy range from a few GeV to more than 10 TeV have been analyzed by the superposition of the blast-wave model with Boltzmann-Gibbs statistics and the inverse power-law (Hagedorn function). The model results are in agreement with the experimental data of NA61/SHINE, PHENIX, STAR, ALICE, and CMS Collaborations. The values of related parameters are extracted from the fit process and the excitation functions of parameters are obtained.

Both the excitation functions of $T_0$ and $\beta_T$ show a hill at $\sqrt{s} \approx 10$ GeV, a drop at dozens of GeV, and an increase from dozens of GeV to more than 10 TeV. The excitation function of $p_0$ ($n$) shows a slight decrease (increase) in the case of the hard component being available. From the RHIC to LHC, there is a positive (negative) correlation between $T_0$ and $\beta_T$ ($p_0$ and $n$). The contribution of hard component slightly increases from dozens of GeV to more than 10 TeV, and it has no contribution at around 10 GeV.

From a few GeV to more than 10 TeV, the collision system takes place two main transitions. At around 10 GeV, a transition from a baryon-dominated to a meson-dominated intermediate and final state takes place. From dozens of GeV to more than 10 TeV, a transition from a meson-dominated to a parton-dominated intermediate state takes place, though both the final states are meson-dominated. It is a long-term target to search the critical energy at which a parton-dominated intermediate state appears initially.

Data Availability
All data are quoted from the mentioned references. All MATLAB codes used in the calculations are available to supply if necessary.

Conflicts of Interest
The authors declare that there is no conflict of interests regarding the publication of this paper.

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