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INDICATION OF DIFFERENTIAL KINETIC FREEZE-OUT AT RHIC AND LHC ENERGIES*

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The transverse momentum spectra at the RHIC and LHC for $A+A$ and $p+p$ collisions are studied with Tsallis distributions in different approaches *i.e.* with and without radial flow. The information on the freeze-out surface in terms of freeze-out volume, temperature, chemical potential and radial flow velocities for different particle species are obtained. These parameters are found to show a systematic behavior with mass dependence. It is observed that the heavier particles freeze-out early as compared to lighter particles and freeze-out surfaces are different for different particles, which is a direct signature of mass-dependent differential freeze-out. Further, we observe that the radial flow velocity decreases with increasing mass. This confirms the mass ordering behavior in collectivity observed in heavy-ion collisions. It is also observed that the systems created in peripheral heavy-ion collisions and in proton–proton collisions are of similar thermodynamic nature.

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1. Introduction

The particles produced in heavy-ion collisions carry information about the collision dynamics and evolution of the system. Therefore, the study of particle's invariant transverse momentum (p_{T}) spectra is an important

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tool to understand the system dynamics. Tsallis non-extensive statistics is commonly used to analyze the p_{T}-spectra in hadronic and nuclear collisions at high energies. In the present work, we use different forms of Tsallis distribution [1] to extract the thermodynamic parameters at $\sqrt{s_{NN}} = 200$ GeV and 2.76 TeV for $A+A$ and $p+p$ collisions. The mass dependence of these parameters shows a differential freeze-out scenario and also a similarity in $p+p$ and $A+A$ collisions at both energies.

2. Tsallis non-extensive statistics without radial flow

The Tsallis distribution function at mid-rapidity ($y = 0$), with finite chemical potential and without radial flow [1] is given by

$$\frac{1}{p_{\mathrm{T}}} \frac{\mathrm{d}^2 N}{\mathrm{d}p_{\mathrm{T}} \mathrm{d}y}\bigg|_{y=0} = \frac{gVm_{\mathrm{T}}}{(2\pi)^2} \left[1 + (q-1)\frac{m_{\mathrm{T}} - \mu}{T}\right]^{-\frac{q}{q-1}} , \tag{1}$$

where m_{T} is the transverse mass of a particle given by $\sqrt{p_{\mathrm{T}}^2 + m^2}$, g is the degeneracy and μ is the chemical potential, V is the volume, T is the Tsallis temperature, and q is the Tsallis non-extensive parameter. In view of higher center-of-mass energies, one considers $\mu \simeq 0$, and thus the above equation modifies to [1]

$$\frac{1}{p_{\mathrm{T}}} \frac{\mathrm{d}^2 N}{\mathrm{d}p_{\mathrm{T}} \mathrm{d}y}\bigg|_{y=0} = \frac{gVm_{\mathrm{T}}}{(2\pi)^2} \left[1 + (q-1)\frac{m_{\mathrm{T}}}{T}\right]^{-\frac{q}{q-1}} . \tag{2}$$

3. Tsallis non-extensive statistics with radial flow

In Ref. [2], the Tsallis distribution function has been expanded in Taylor series, after the inclusion of radial flow. The form of the distribution up to first order in $(q-1)$ is given by

$$\begin{aligned} &\frac{1}{2\pi p_{\mathrm{T}}} \frac{\mathrm{d}^2 N}{\mathrm{d}p_{\mathrm{T}} \mathrm{d}y} = \frac{gV}{(2\pi)^3} \\ &\times \Big\{ 2T[rI_0(s)K_1(r) - sI_1(s)K_0(r)] - (q-1)Tr^2 I_0(s)[K_0(r) \\ &+K_2(r)] + 4(q-1)\ TrsI_1(s)K_1(r) - (q-1)Ts^2K_0(r)[I_0(s) \\ &+I_2(s)] + \frac{(q-1)}{4}Tr^3 I_0(s)[K_3(r) + 3K_1(r)] - \frac{3(q-1)}{2}Tr^2 s \\ &\times[K_2(r) + K_0(r)]I_1(s) + \frac{3(q-1)}{2}Ts^2 r[I_0(s) + I_2(s)]K_1(r) \\ &- \frac{(q-1)}{4}Ts^3[I_3(s) + 3I_1(s)]K_0(r) \Big\} , \end{aligned} \tag{3}$$

where, $r \equiv \frac{\gamma m_{\mathrm{T}}}{T}$, $s \equiv \frac{\gamma v p_{\mathrm{T}}}{T}$, $I_n(s)$ and $K_n(r)$ are the modified Bessel functions of the first and second kind, and v is the radial flow velocity. For high energy collisions, the value of q is $1 \leq q \leq 1.2$ [2].

4. Results and discussion

The analysis of p_{T} spectra around mid-rapidity is performed at $\sqrt{s_{NN}} =$ 200 GeV and 2.76 TeV using Eqs. (1)–(3) for $A{+}A$ and $p{+}p$ collisions. It is well-known that the number of binary collisions increase with number of participants. So the system created in central collisions reaches equilibrium quickly as compared to peripheral collisions. Hence, one uses non-extensive statistics while describing the thermodynamics of peripheral collisions.

Firstly, Eq. (2) is used to study the invariant p_{T} spectra of identified particles, as shown in Fig. 1. It is found that the volume parameter decreases and the freeze-out temperature increases with increase in particle mass, leading to a differential freeze-out scenario. The q-parameter is found to be decreasing with mass for all the cases (for the numerical values, see appendix of Ref. [1]).

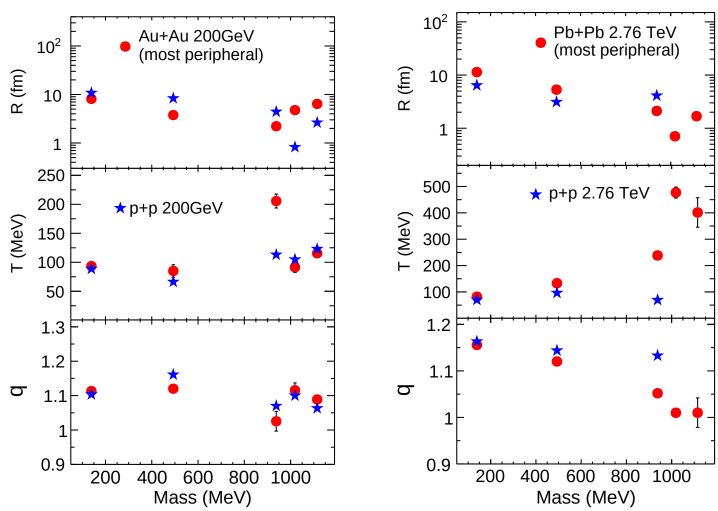

Fig. 1. Particle mass dependence of the thermodynamic parameters using Eq. (2) for most peripheral Au+Au and $p{+}p$ collisions at $\sqrt{s_{NN}} = 200$ GeV, and most peripheral Pb+Pb and $p{+}p$ collisions at $\sqrt{s_{NN}} = 2.76$ TeV [1].

Secondly, a similar procedure is followed using Eq. (1) for most central and peripheral Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Similar mass-dependent behavior is depicted in Fig. 2 (a), (b). The freeze-out radius parameter (R) is not necessarily the HBT radius and also μ is not necessarily the chemical potential of a particle. The extracted parameters T and μ

(Eq. (1)) are related by [1], $T = T_0 + (q-1)\mu$, where $T = T_0$ for $\mu = 0$. The parameters obtained from Eqs. (1) (*i.e.* T, μ and q) and (2) (*i.e.* $T \equiv T_0$) satisfy this relation.

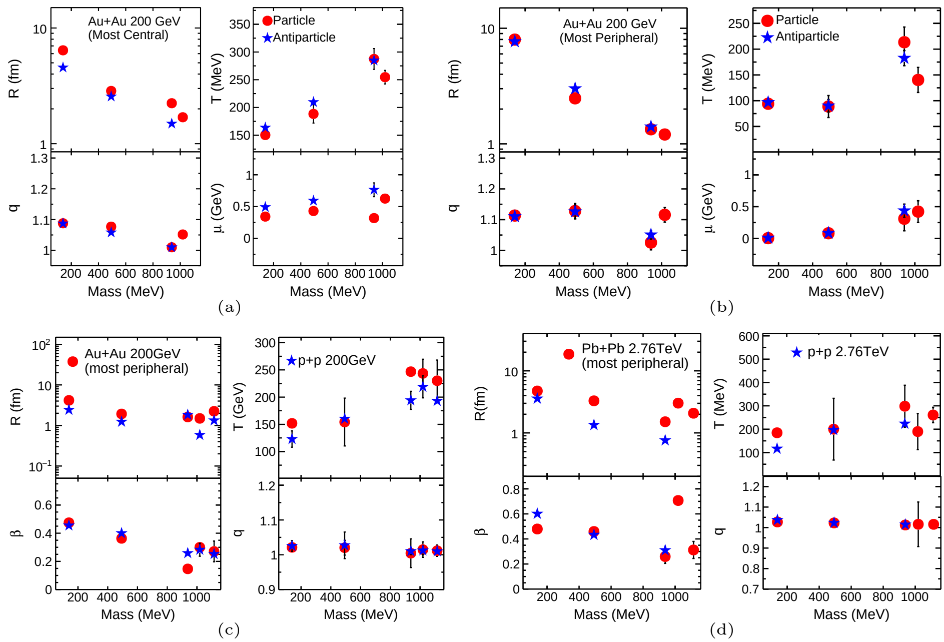

Fig. 2. Particle mass-dependent parameters using Eqs. (1), (3) for (a) most central, (b) most peripheral Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, (c) most peripheral Au+Au and p+p collisions at $\sqrt{s_{NN}} = 200$ GeV, (d) most peripheral Pb+Pb and p+p collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

Following the same procedure using Eq. (3), a similar mass dependency is observed as shown in Fig. 2 (c), (d). This decrease in q value may hint that the non-extensivity is shared by system dynamics. Here, the extra parameter radial flow ($v \equiv \beta c$) is observed to decrease with particle mass. This goes inline with hydrodynamic description of the evolution of a fireball created in high-energy collisions. In summary, the above observations indicate a differential freeze-out scenario at RHIC and LHC energies. Details of the analysis could be found in Ref. [1].

REFERENCES

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