Validity of Chemical Equilibrium Approach in the Study of Kinetic Freeze-out in p-Pb Collisions at LHC

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Transverse momentum spectra of identified pions $(\pi^- + \pi^+)$, kaons $((K^- + K^+), K_s^0)$, protons $(p + \bar{p})$ and lambdas $(\Lambda + \bar{\Lambda})$ produced at mid-rapidity $(0 < y_{cm} < 0.5)$ in p-Pb collisions at $\sqrt{S_{NN}} = 5.02$ TeV is studied for different collision centralities by using a Unified Statistical Thermal Freeze-out Model (USTFM). A fairly good agreement is seen between the calculated results and the experimental data points taken from the ALICE experiment. Kinetic freeze-out conditions are extracted from the fits of the transverse momentum spectra of these hadrons for each centrality class. A comparison of the obtained freeze-out parameters with those of heavy-ion collisions ($Pb+Pb$) is made and discussed.

1. Introduction

The p_T distributions and yields of particles of different masses at low and intermediate momenta of less than a few GeV (3-4 GeV) can provide important information about the system created in high energy hadron reactions. This is because a vast majority of the particles is produced in this soft region where a thermally equilibrated system is expected to be formed. The measurement of charged kaons is a significant tool to further understand the thermalization of the system and the mechanism of strangeness production in these collisions. In our previous analysis [1], we have studied the particle production in p-p and Pb-Pb collisions at LHC by employing a phenomenological Unified Statistical Thermal Freeze-out Model. Significant collective flow effects were seen in both the cases which gave a support to the assumption of almost complete thermalization of the produced system in these collisions at LHC. It will therefore be interesting to study the medium properties of the system produced in p-Pb collisions which may be treated as the intermediate between p-p and p-Pb collision systems. In order to address the particle production in the QCD matter produced in p-Pb collisions, a systematic study of the identified particles over a broad p_T range is required. We, therefore in this analysis, have used the same phenomenological approach to reproduce the mid-rapidity $(0 < y_{cm} < 0.5)$ p_T - distributions of identified particles produced in p-Pb collisions at the LHC energy of $\sqrt{S_{NN}} = 5.02$ TeV.

The Model

In our model it is assumed that the system reaches a state of thermo-chemical equilibrium at freeze-out. The momentum distributions of hadrons, emitted from within an expanding fireball, are characterized by the Lorentz-invariant Cooper-Frye formula [2] as

$$E\frac{d^3n}{d^3p} = \frac{g}{(2\pi)^3}\int f\left(\frac{p^\mu u^\mu}{T}, \lambda\right) p^\mu d\Sigma_f \quad (1)$$

where Σ_f represents a 3-dimensional freeze-out hyper-surface and g = 2j+1 is the degree of degeneracy of the expanding relativistic hadronic gas and $\lambda = \exp(\mu/T)$ is the fugacity. The invariant cross-section will have the same value in all the Lorentz frames, i.e $E\frac{d^3n}{d^3p} = E^{'}\frac{d^3n}{d^3p'}$. The transverse velocity component of the hadronic fireball, β_T is assumed to vary with the transverse coordinate r in accordance with the Blast Wave model as $\beta_T(r) = \beta_T^s (r/R)^n$ where n is an index which fixes the profile of $\beta_T(r)$ in the transverse

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direction and β_T^s is the hadronic fluid surface transverse expansion velocity and is fixed in the model by using the parameterization $\beta_T^s = \beta_T^0\sqrt{1-\beta_z^2}$. This relation is also required to ensure that the net velocity β of any fluid element must satisfy $\beta = \sqrt{\beta_T^2+\beta_z^2} < 1$. Assuming a Boltzmann type of contribution for the parent (decaying) particles, the contribution of resonance particle decay to the final state particle transverse momentum spectra can be calculated from the equation

$$E^{'}\frac{d^3n}{d^3p^{'}} = \frac{1}{2p^{'}}\left\{\frac{m_h}{p^*}\right\}\lambda_h g_h \exp(-\alpha\theta E^{'}E^*) \left[\frac{\alpha}{\theta}\left\{E^{'}E^*\sinh(\alpha\theta p^{'}p^*) - p^{'}p^*\cosh(\alpha\theta p^{'}p^*)\right\} + T^2\sinh(\alpha\theta p^{'}p^*)\right]$$

where α and θ are given by m_h/m^2 and $1/T$, respectively. The subscript h in the above equation stands for the decaying (parent) hadron. The two body decay kinematics gives the product hadron's momentum and energy in the "rest frame of the decaying hadron" as $p^* = (E^{*2}-m^2)^{1/2}$ and $E^* = \frac{m_h^2-m_j^2+m^2}{2m_h}$ where m_j indicates the mass of the other decay hadron produced along with the first one

2. Results

TABLE I: Kinetic freez-out parameters obtained for different particles at different centralities

Particle	Centrality	β_0^T	T(MeV)
$(\pi^- + \pi^+)$	(0-5)%	0.95 ± 0.01	75 ± 2
	(80-100)%	0.93 ± 0.02	67 ± 3
$(K^- + K^+)$	(0-5)%	0.93 ± 0.01	133 ± 2
	(80-100)%	0.72 ± 0.02	120 ± 3
K_s^0	(0-5)%	0.87 ± 0.01	143 ± 2
	(40-60)%	0.82 ± 0.02	149 ± 3
$(p + \bar{p})$	(0-5)%	0.87 ± 0.01	149 ± 3
	(80-100)%	0.77 ± 0.01	122 ± 3
$(\Lambda + \bar{\Lambda})$	(0-5)%	0.77 ± 0.01	162 ± 1
	(80-100)%	0.66 ± 0.02	185 ± 3

It is seen from the table I that a significant value of collective flow is observed for all the studied particles in case of p-Pb collisions at LHC. This hints towards the thermalization of the produced system in p-Pb collisions and the possible formation of Quark Gluon Plasma in p-Pb collisions at LHC [3] at the early stage of the collisions.

3. Summary and Conclusions

In summary, we have successfully reproduced the mid-rapidity ($0 < y_{cm} < 0.5$) p_T spectra of pions ($\pi^- + \pi^+$), kaons ($(K^- + K^+), K_s^0$), protons ($p + \bar{p}$) and Lambdas ($\Lambda + \bar{\Lambda}$) produced in p-Pb collisions at LHC and compared with the predictions of Unified Statistical Thermal Freeze-out Model (USTFM). A reasonably good agreement between the theoretical results and the experimental data hints at the almost complete thermalization of the produced system. Centrality dependence of the freeze-out parameters is studied and it is seen that the collective flow of all hadronic species show a slow decrease towards peripheral collisions which is also seen in the nucleus-nucleus collisions at LHC and RHIC. The thermal freeze-out temperature of lighter particles, such as pions and Kaons, shows a quite different behavior with changing centrality as compared to that found in heavy-ion collisions. Baryons are found to show a consistent increase in temperature and decrease in collective flow effects towards peripheral collisions, a pattern observed in the nucleus-nucleus collisions also at LHC and RHIC. The p-Pb system is thus seen to behave more or less like a heavy-ion collision system.

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