Study of strange particle $p_T$ spectra in heavy-ion collisions at relativistic energies

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Abstract. The transverse momentum distributions of strange and multi-strange hadrons produced in most central Au+Au collisions at RHIC-BES energies were studied using the Boltzmann-Gibbs blast-wave model. The energy dependence of the kinetic freeze-out parameters is presented and discussed.

1 Introduction

One of the main goals of the relativistic nuclear collisions studies is to investigate the behavior of nuclear matter under extreme conditions of temperature and energy density [1, 2]. In a relativistic nuclear collision a large number of secondary particles are produced, and based on their analysis information about the evolution of the system produced in the collision can be obtained. An important phenomenon that can be studied at kinetic freeze-out stage is the collective transverse flow of nuclear matter as it is entirely generated in the collision. This collective flow of the system occurs due to large pressure gradients generated by the intense interactions between the produced particles. As the particles interact within the system, they acquire a collective flow velocity, having the effect of increasing their momentum. Thus, the shape of the transverse momentum spectra is influenced by the presence of the transverse collective flow and, using different parameterizations, this collective flow can be quantified.

One of the models used to extract the kinetic freeze-out parameters is the Boltzmann-Gibbs blast-wave (BW) model [3, 4]. The shape of each spectrum is determined by the kinetic (thermal) freeze-out temperature, the collective transverse expansion velocity, the particle mass, and the choice of flow profile (the dependence of the transverse flow velocity on the radius of the expanding source). The $p_T$ spectrum of produced particles can be described by the following formula:

$$\frac{dN}{dp_T} \sim \int_{0}^{R} r \, dr \, m_T I_0 \left( \frac{p_T \sinh \rho}{T} \right) K_1 \left( \frac{m_T \cosh \rho}{T} \right)$$  \hspace{1cm} (1)

where $T$ is the kinetic freeze-out temperature, $m_T = \sqrt{p_T^2 + m^2}$ is the transverse mass, $m$ is the particle mass, $p_T = \tanh^{-1} \beta_T (r)$ and $I_0$ and $K_1$ are the modified Bessel functions. The radial transverse flow velocity profile can be parametrized as:

$$\beta_T (r) = \beta_s \left( \frac{r}{R} \right)^n$$  \hspace{1cm} (2)

where $\beta_s$ is the surface flow velocity, the $n$ is the exponent which describes the flow profile and $r/R$ is the relative radial position in the thermal source. Assuming a uniform particle density, the average transverse collective flow velocity can be calculated as:

$$\langle \beta_T \rangle = \frac{2}{2 + n} \beta_s$$  \hspace{1cm} (3)

2 Results

The $p_T$ spectra of strange and multi-strange hadrons such as $K^0_S$, $\Lambda$, $\Xi$, $\Omega$, $\phi$, $\Omega^-$, and $\Omega^0$ produced in most central Au+Au collisions at RHIC-BES energies ($\sqrt{s_NN} = 7.7, 11.5, 19.6, 27$ and $39$ GeV) were fitted with Eq. 1. Data are taken from [5, 6]. Figure 1 shows the BW fits to the STAR $p_T$ spectra, fitted up to $p_T < 3$ GeV/$c$. The fit parameters are the kinetic freeze-out temperature, $T$, the average transverse flow velocity, $\langle \beta_T \rangle$, and the exponent of the flow profile, $n$.

The kinetic freeze-out temperature as a function of average transverse flow velocity is presented in Figure 2. The strange BW fit parameters are compared to the corresponding parameters extracted from the bulk ($\pi^\pm$, $K^\pm$, $p$, and $\bar{p}$) $p_T$ spectra BW fits. The bulk $T$ and $\langle \beta_T \rangle$ values are taken from [7]. For all energies, the values of strange particles $T$ are larger than the corresponding $T$ values extracted from BW fits on bulk particles $p_T$ spectra [7].

The average flow velocities of strange hadrons are smaller than the corresponding values of bulk particles [7]. These results could indicate that, with increasing energy, the strange particles decouple earlier in time in the system’s evolution, at a higher kinetic freeze-out and having a smaller flow velocity because collective flow builds up...
Figure 1. The transverse momentum spectra of $K^0$, $\Lambda$, $\bar{\Lambda}$, $\Xi^-$, $\bar{\Xi}^-$, $\phi$, $\Omega^-$, and $\bar{\Omega}^-$ produced at midrapidity ($|y| < 0.5$) in most central Au+Au collisions at $\sqrt{s_{NN}} = 7.7, 11.5, 19.6, 27, \text{ and } 39 \text{ GeV}$ as obtained by the STAR Collaboration [5, 6]. Dotted lines are the simultaneous fits to data using BGBW model.

Figure 2. The dependence of kinetic freeze-out temperature on average transverse flow velocity. Full symbols are from BGBW fits on $K^0$, $\Lambda$, $\bar{\Lambda}$, $\Xi^-$, $\bar{\Xi}^-$, $\phi$, $\Omega^-$, and $\bar{\Omega}^-$ $p_T$ spectra. The open symbols are the $\pi^+$, $K^+$, $p$ and $\bar{p}$ BW fits results taken from Ref. [7].

over the entire evolution of the collision system. Therefore, if the strange particles are emitted when the system is hotter, their collective flow is smaller. These results are consistent with previous SPS and RHIC results [8–13].

Due to different hadronic interaction cross sections, the produced particles freeze-out from the fireball at different times and therefore the system can have sequential freeze-out stages: particles with smaller interaction cross-section can decouple sooner from the system, followed by the bulk particles at a later FO stage [15, 16].

Because it is known that the strange particles may exhibit different production mechanisms and interaction cross-sections [17–19], the particles have been divided into two groups — those which share valence quarks with the nucleons ($K^0$, $\Lambda$, and $\Xi^-$) and those which do not ($\bar{\Lambda}$, $\bar{\Xi}^-$, $\phi$, $\Omega^-$, and $\bar{\Omega}^-$). The fit parameters obtained from fits on $p_T$ spectra of the two groups of strange particles in most central Au+Au collisions at $\sqrt{s_{NN}} = 7.7–39 \text{ GeV}$ are presented in the Figs. 3-5.

The $n$ exponent extracted from the $\bar{\Lambda}$, $\bar{\Xi}^-$, $\phi$, $\Omega^-$, and $\bar{\Omega}^-$ spectra fits is very close to 0 for all energies suggesting a constant flow profile for these particles in the analyzed energy range. The values of $n$ parameter of the two groups of particles are similar for $\sqrt{s_{NN}} = 7.7–11.5 \text{ GeV}$. For $\sqrt{s_{NN}} = 19.6–39 \text{ GeV}$, the values of $n$ parameter of $K^0$, $\Lambda$, and $\Xi^-$ group are larger compared to $\bar{\Lambda}$, $\bar{\Xi}^-$, $\phi$, $\Omega^-$, and $\bar{\Omega}^-$ group and increase with energy. This behaviour could indicate that the $K^0$, $\Lambda$, and $\Xi^-$ group gives a stronger constraint to $n$ parameter.

The two groups of strange particles have different $p_T$ spectra shapes. The $K^0$ $p_T$ spectrum is steeper than $\Lambda$ and $\Xi^-$ spectra and due to higher statistics, fit results seems to be driven by the $K^0$ $p_T$ spectrum rather than the other two spectra. For steeper spectra, the $n$ parameter has a
larger value and corresponds to a higher $T$ and a smaller $\langle \beta_T \rangle$. For the other group, their $p_T$ spectra are more curved at low $p_T$ compared to $K_S^0$ $p_T$ spectrum, therefore are described by a smaller value of $n$ parameter. For smaller values of $n$ parameter, $\langle \beta_T \rangle$ parameter is larger and the corresponding $T$ is smaller. The average transverse flow velocity of $\Lambda$, $\Xi^-$, $\phi$, $\Omega^-$, and $\Omega^-$ group is larger by $\sim 15\%$ than that of $K_S^0$, $\Lambda$, and $\Xi^-$ group.

We compared our results with previous results obtained in Pb+Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV by the NA57 Collaboration [8, 9]. The NA57 results using the BW model on $p_T$ spectra of strange particles were obtained assuming a linear transverse flow velocity profile ($n = 1$). Therefore, we fixed the $n$ parameter describing the flow profile at the value $n = 1$.

The $T$ and $\langle \beta_T \rangle$ obtained considering a linear dependence of the flow velocity on the radial position in the thermal source ($n = 1$) are shown in Fig. 6 and Fig. 7. For a fixed value of $n$ parameter, the more curved $p_T$ spectra in the low $p_T$ region are described by a larger $\langle \beta_T \rangle$. The average transverse flow velocity is larger for $\Lambda$, $\Xi^-$, $\phi$, $\Omega^-$, and $\Omega^-$ group. The kinetic temperature is larger for $K_S^0$, $\Lambda$, and $\Xi^-$ group and increases very slowly with energy for both strange particle groups. Our results are consistent within errors with SPS results.

3 Conclusions

The $p_T$ spectra of strange particles produced in most central Au+Au collisions at RHIC-BES energies were studied with BW model and the radial transverse flow and the kinetic freeze-out temperature of the system were extracted. In the RHIC-BES energy range, the strange hadrons have a
larger freeze-out temperature than that of bulk hadrons and a smaller average flow velocity. These results can indicate a double kinetic freeze-out scenario due to the separate decoupling of bulk and strange particles. In addition, the particles containing strangeness were examined separately to study their radial flow and freeze-out. These results are consistent with previous SPS results.

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