Strangeness and bulk freeze-out properties at RHIC

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Abstract.

Identified charged kaon, pion, and proton spectra and ratios from $\sqrt{s_{NN}} = 200$ and 62.4 GeV Cu+Cu collisions are studied with a hydro-motivated blast-wave and a statistical model framework in order to explore the strangeness production at RHIC and characterize the bulk freeze-out properties of the created system. The spectra are measured at mid-rapidity ($|y| < 0.1$) over the transverse momentum range of $0.25 < p_T < 1.2$ GeV/c with particle identification derived from the ionization energy loss in the STAR Time Projection Chamber.

The multi-dimensional systematic study of $\pi^{\pm}$, $K^{\pm}$, $p$ and $\bar{p}$ production in Cu+Cu, Au+Au, d+Au and p+p collisions is used to discuss the energy, system size and inferred energy density dependence of freeze-out parameters and strangeness production. The new data from Cu+Cu collisions bridge the gap between the smaller d+Au and larger Au+Au systems, allowing a detailed study of the onset of strangeness equilibration at RHIC.

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1. Introduction

Systematic studies of the QCD phase diagram [1] have been enriched by the addition of new RHIC data from Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ and 62.4 GeV. The STAR experiment has measured identified particle spectra of $\pi^{\pm}$, $K^{\pm}$, protons and anti-protons at mid-rapidity $|y| < 0.1$ over the transverse momentum range of $0.25 < p_T < 0.80$ GeV/c (pions and kaons) and $0.40 < p_T < 1.20$ GeV/c for (anti)protons. Comparative analysis to the previously measured spectra from Au+Au, d+Au and p+p collisions at RHIC [2][4] is used to address the energy and system size effects on freeze-out properties and, particularly, on strangeness production.

It has been shown that freeze-out parameters in Au+Au collisions at $\sqrt{s_{NN}} = 200$ and 62.4 GeV, have a similar chemical freeze-out temperature at all centralities and have a decreasing $T_{kin}$ towards more central events [2]. At the same time the radial flow velocity, $\beta$, increases with centrality.
The centrality independence of the extracted chemical freeze-out temperature, indicated that, for different initial conditions, collisions evolve to the same chemical freeze-out. For all studied centralities the values for the chemical freeze-out temperature are close to the critical temperature, predicted by Lattice QCD calculations, while changes in $T_{\text{kin}}$ and $\beta$ are consistent with higher energy/pressure in the initial state for more central events. This suggested that chemical freeze-out coincides with hadronization and therefore provides a lower limit estimate for a temperature of the prehadronic state [3]. Most measured bulk properties in Cu+Cu show a smooth systematic change with the charged hadron multiplicity, and appear to follow the same systematic trends as the lower-energy data [2, 4], bridging the gap between the smaller d+Au and the larger Au+Au systems.

2. STAR Experiment

The results presented in these proceedings are based on the identification of charged particles traversing the Time Projection Chamber (TPC) [5] in the STAR detector. Different ionization energy loss patterns are experienced in the TPC for particles of different masses, which can be exploited for identification in the low-$p_T$ region. The momentum measurement is given by the curvature of the particle trajectories as they pass through a 0.5 T magnetic field. To determine the centrality of the collision, the number of charged tracks at mid-rapidity is used. The data is presented in six centrality classes with each bin corresponding to 10% of the total inelastic cross-section.

The transverse momentum spectra are obtained from the mean $\langle dE/dx \rangle$ for each of $\Delta p_T = 50\text{MeV}/c$ momentum bins. For this, projections of the $dE/dx$ for a given momentum are fit with a four-Gaussian function representing the four particle species of a given charge ($\pi$, K, p and $\bar{p}$). The integral of each Gaussian provides the raw yield at a given momenta. These raw yields are corrected for detector acceptance, tracking inefficiency and background contributions. The same analysis technique is used for measurements of all different collision systems and center-of-mass energies [2].

3. Preliminary Results

3.1. Particle Spectra

The $\pi^\pm$, $K^\pm$ and p and $\bar{p}$ transverse momentum spectra are measured for two center-of-mass energies in Cu+Cu collisions, $\sqrt{s_{\text{NN}}} = 200$ and 62.4 GeV. The particle and anti-particle spectral shapes are similar for all species at each centrality bin. At both collision energies a mass-dependence is observed in the slope of the particle spectra.

3.2. Kinetic freeze-out properties

Within a given centrality bin the particle spectra are fitted simultaneously by the Blast-wave model [6], which assumes a radially boosted thermal source. The hydro-
motivated fits provide information about the radial flow velocity ($\beta$), the kinetic freeze-out temperature ($T_{\text{kin}}$) and the flow profile shape ($n$) at final freeze-out. The effects from resonance contributions to the pion spectra shape are reduced by excluding the very low-$p_T$ pion data points (below $< 0.5 \text{ GeV}/c$).

The particle spectra are well described by a common set of freeze-out parameters, for all colliding energies. The fit results are shown in figure 1 left panel. For an equivalent number of charged particles at mid-rapidity, $dN_{ch}/d\eta$, the $T_{\text{kin}}$ and $\beta$ show similar dependences in both Cu+Cu and Au+Au collisions, evolving smoothly from p+p to central Au+Au. $T_{\text{kin}}$ decreases with centrality and thus implying freeze-out occurs at lower temperature in more central collisions (see the right panel on figure 3).

The particle mean-$p_T$ results are obtained from the measured spectra, extrapolated outside the fiducial range by Blast-wave fits for the kaons and (anti)proton, and by Bose-Einstein fits for the pions. The particle mean-$p_T$ increases with $dN_{ch}/d\eta$ (figure 1 right panel), which is consistent with an increase in radial flow with centrality.

A model dependent connection between the number of produced charged particles and the initial gluon density of the colliding system [7] can be used to interpret that the bulk properties are most probably determined at the initial stages of the collision and are driven by the initial energy density.

**Figure 1.** (color online) Left panel: The Kinetic freeze-out temperature, $T_{\text{kin}}$, versus flow velocity, $\beta$ is shown for $\sqrt{s_{NN}} = 200$ and 62.4 GeV Au+Au (black) and Cu+Cu (red) collisions. For comparison, results for minimum-bias p+p collisions at 200 GeV are also shown. Right panel: Integrated $\langle p_T \rangle$ for negatively charged particles for Cu+Cu (red) and Au+Au (black) collisions as a function of $dN_{ch}/d\eta$ for 200 and 62.4 GeV. Minimum-bias p+p collisions at 200 GeV are also shown.
3.3. Particle Ratios

The ratio of particle yields for negatively charged kaons and pions is shown in figure 2 for a center-of-mass energy of 200 GeV. The $K/\pi$ ratio in the Cu+Cu system follows the same trend with the charged hadron multiplicity, $dN_{ch}/d\eta$, as previously found in Au+Au data [2]. There is no strong evidence for additional strangeness enhancement in the smaller system as reported at SPS energies [8, 9], despite the observed increase in the integrated particle spectra yields with respect to p+p data for a given value of $N_{part}$ [10]. The baryon to meson ratios, also shown on the figure 2, are found to be the same for Au+Au and Cu+Cu systems. The lack of a strong centrality dependence over the covered range points to similar freeze-out conditions for the studied collisions.

![Figure 2](image.png)

Figure 2. (color online) Particle yield ratios at 200 GeV for Cu+Cu (red) and Au+Au (black) collisions versus the number of charged hadron multiplicity density, $dN_{ch}/d\eta$, at mid-rapidity. The closed triangles show the $K^-/\pi^-$ ratios, the closed circles are the ratios for $\bar{p}/\pi^-$. The open symbols are the ratios from min-bias p+p collisions.

3.4. Chemical freeze-out properties

The particle yield ratios are further analyzed within the framework of the statistical model [11]. The model describes the chemical freeze-out properties of the colliding system by the chemical freeze-out temperature ($T_{ch}$), the baryon and strangeness chemical potentials ($\mu_B$, $\mu_S$) and the strangeness suppression factor ($\gamma_S$). The parameters are obtained using only $\pi^\pm$, $K^\pm$, $p(\bar{p})$ measurements.

Within the systematic errors on the fit parameters the strangeness suppression factor $\gamma_S$ in Cu+Cu, is consistent with the results for the Au+Au data [2]. This parameter shows a similar dependence with $dN_{ch}/d\eta$, as in the Au+Au system. The values of $\gamma_S$ approaching unity for the central collisions implies that the produced strangeness is close to approximate equilibrium.
The chemical freeze-out temperature, $T_{ch}$, as a function of baryon-chemical potential, $\mu_B$, for different systems is shown in the left panel of figure 3. For all systems and center-of-mass energies $T_{ch}$ appears to be universal. The value of the baryon chemical potential reflects the decrease in baryon density from $\sqrt{s_{NN}} = 62.4$ to 200 GeV. At an equivalent center-of-mass energy $\mu_B$ is higher for the larger system. The constant value of $T_{ch}$ implies that collisions with different net-baryon densities evolve to the same chemical freeze-out and points to a universal hadronization of the system.

Figure 3. (color online) Left panel: The Chemical freeze-out temperature, $T_{ch}$, versus the baryon chemical potential, $\mu_B$, for central Au+Au (0-5% - black) and Cu+Cu collisions (0-10% - red). Minimum-bias p+p data at 200 GeV are also shown (blue). Right panel: $T_{ch}(T_{kin})$ versus charged hadron multiplicity at $\sqrt{s_{NN}} = 62.4$ (open symbols) and 200 GeV (closed symbols) for Cu+Cu (red) and Au+Au (black) collisions. For comparison, results for minimum-bias p+p collisions at 200 GeV are also shown (blue).

4. Summary

The STAR collaboration has presented measurements of identified charged hadron spectra in Cu+Cu collisions for two center-of-mass energies, 200 and 62.4 GeV. These new results of $\pi^{\pm}$, $K^{\pm}$, $p(\bar{p})$ have further enriched the variety of low-$p_T$ spectra at RHIC. The data have been studied within the statistical and Blast-wave model frameworks in order to characterize the properties of the final hadronic state of the colliding system as a function of system size, collision energy, centrality and the inferred energy density.

This multi-dimensional systematic study reveals remarkable similarities between the studied systems. The obtained particle ratios, mean-$p_T$ and the freeze-out parameters, including the strangeness saturation factor $\gamma_s$, are found to be intrinsically related for all collision systems and center-of-mass energies. A smooth evolution with $N_{ch}$ and similar properties at the same number of produced charged hadrons are observed. A
model dependent connection between the number of produced charged particles and the initial gluon density of the colliding system \cite{7} can be used to interpret that the bulk properties are most probably determined at the initial stages of the collision and are driven by the initial energy density.

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Acknowledgments

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