SYSTEM SIZE DEPENDENCE OF FREEZE-OUT PROPERTIES AT RHIC

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The STAR experiment at RHIC has measured identified $\pi^\pm$, $K^\pm$ and $p(\overline{p})$ spectra and ratios from $\sqrt{s_{NN}} = 62.4$ and 200 GeV Cu+Cu collisions. The new Cu+Cu results are studied with hydro-motivated blast-wave and statistical model frameworks in order to characterize the freeze-out properties of this system. Along with measurements from Au+Au and p+p collisions, the obtained freeze-out parameters are discussed as a function of collision energy, system size, centrality and inferred energy density. This multi-dimensional systematic study reveals the importance of the collision geometry and further our understanding of the QCD phases.

1. Introduction

Identified $\pi^\pm$, $K^\pm$ and $p(\overline{p})$ particle spectra in heavy-ion collisions at different center-of-mass energies provide a unique tool to explore the QCD phase diagram. Analysis of Cu+Cu data, collected by the STAR experiment, extends the systematic studies of bulk properties by addressing the energy and system size dependence of freeze-out parameters at RHIC.

Previous studies of the freeze-out parameters in 200 and 62.4 GeV Au+Au collisions within a chemical and kinetic equilibrium model, showed a similar chemical freeze-out temperature and an increasing radial flow with centrality. The centrality independence of the extracted chemical freeze-out temperature indicates that, for different initial conditions, collisions evolve to the same freeze-out condition.
The values of the chemical freeze-out temperature and the critical temperature, predicted by the Lattice QCD, are close for all centralities, which suggests that the chemical freeze-out coincides with hadronization and therefore provides a lower limit estimate for a temperature of prehadronic state. For kinetic freeze-out, which occurs later, an increase in centrality results in a decreasing temperature and increasing flow velocity. Most measured bulk properties show a smooth systematic change with the charged hadron multiplicity and appear to form smooth curves with similar results from lower-energy collisions.

With systematic studies of yields and momentum spectra in Cu+Cu collisions, at the same center-of-mass energies as for Au+Au collisions, we constrain the initial conditions of the created medium and address the degree of its thermalization.

2. Identified Particle Spectra

For this analysis, charged particles are identified using their ionization energy loss $dE/dx$ in the STAR Time Projection Chamber (TPC) [7], which is situated in a uniform 0.5 T magnetic field along the beam line. The Cu+Cu events are divided into centrality classes based on the multiplicity distribution within $|\eta| < 0.5$. Six 10% bins are used to represent the top 60% of the inelastic collision cross-section.

The raw (uncorrected) particle yields are obtained from the mean $\langle dE/dx \rangle$ distributions. Unidentified spectra are first divided into bins of transverse momentum ($\Delta p_T = 0.25$ MeV), one bin in rapidity ($|y| < 0.1$), and the six bins in centrality. Next, projections of $dE/dx$ for a given momentum and centrality bin are fit with a four-Gaussian function, representing the different particle species ($\pi, K, p$ and $e$) which are clearly separated in this transverse momentum region $0.2 < p_T < 0.8$ GeV/c for $\pi^\pm$, $K^\pm$ and $0.4 < p_T < 1.2$ GeV/c for $p(\bar{p})$; the integral of each Gaussian provides the yield. Once identified, these yields are further corrected for detector acceptance, tracking inefficiency and background contributions. The described analysis technique [2] is consistent for all low $p_T$ measurements for different center-of-mass energies and colliding systems.

The particle spectra for $\pi^\pm$, $K^\pm$ and $p(\bar{p})$ in Cu+Cu collisions are measured for both $\sqrt{s_{NN}} = 62.4$ and 200 GeV. The particle and anti-particle spectral shapes are similar for each centrality class. For both center-of-mass energies, a mass dependence is observed in the slope of the particle spectra.

3. Kinetic Freeze-out Properties

The hydro-motivated Blast-wave model assumes a boosted thermal source in transverse and longitudinal directions [5]. From simultaneous fits to the $\pi^\pm$, $K^\pm$ and $p(\bar{p})$ spectra in each centrality class three fit parameters are extracted: the flow velocity ($\beta$), the kinetic freeze-out temperature ($T_{\text{kin}}$) and the shape of the flow profile ($n$). For the case of pions, the range below 0.5 GeV/c is excluded from the fits in order to reduce effects from resonance contributions.
Results of the kinetic fit parameters $T_{\text{kin}}$ and $\beta$ for Cu+Cu and Au+Au collisions are shown in Fig. 1 and Table 1. The studies show that all particle spectra for $\pi^\pm$, $K^\pm$ and $p(\bar{p})$ in Cu+Cu and Au+Au systems can be described by a common set of freeze-out parameters. Furthermore, the freeze-out parameters extracted are similar for an equivalent number of produced charged-particles, $N_{ch}$, independent of both collision system and center-of-mass energy. As can be seen from Fig. 2, the centrality dependence of $T_{\text{kin}}$ and $\beta$ evolves smoothly from p+p to Cu+Cu and Au+Au collisions.

Table 1. The obtained preliminary kinetic freeze-out fit parameters for 0-10% central Cu+Cu collisions at 62.4 and 200 GeV and the corresponding fit parameters for 0-5% central Au+Au collisions.

| Parameter | 200 GeV Cu+Cu | 200 GeV Au+Au | 62.4 GeV Cu+Cu | 62.4 GeV Au+Au |
|-----------|---------------|---------------|----------------|---------------|
| $T_{\text{kin}}$ (MeV) | 112±9 | 89±12 | 115±7 | 93.8±4.1 |
| $\beta$ | 0.52±0.07 | 0.59±0.06 | 0.48±0.06 | 0.54±0.01 |

Fig. 1. Left panel: Kinetic freeze-out temperature $T_{\text{kin}}$ versus flow velocity $\beta$ for 62.4 and 200 GeV Au+Au (black) and Cu+Cu (red) collisions. For comparison, results for minimum bias p+p collisions at 200 GeV are also shown (blue). Right panel: Integrated anti-particle $\langle p_T \rangle$ for Au+Au (black) and Cu+Cu (red) collisions as a function of charged hadron multiplicity density ($dN_{ch}/d\eta$) at mid-rapidity for 62.4 and 200 GeV. Minimum bias p+p collisions at 200 GeV are also shown (blue).

Note that we are not interpreting the extracted small, but finite, value of $\beta$ in p+p collisions as an indication of collectivity in elementary systems. The observed value is a reflection of the well known difference in the $m_T$ spectral shapes of $\pi^\pm$, $K^\pm$ and $p(\bar{p})$ in p+p and A+A collisions.\(^2\)
The particle mean-$p_T$ are found to increase with centrality, depicted as $N_{ch}$ in Fig. 1 (left panel). As for the kinetic freeze-out parameters, a smooth centrality dependence of the particle mean-$p_T$, for all particle species, is observed from p+p to Cu+Cu and Au+Au collisions. The mean-$p_T$ results are produced from Blast-wave fits to the $K^\pm$ and $p$($\bar{p}$) spectra and from Bose-Einstein fits over the entire fiducial spectra for $\pi^\pm$. Such remarkable similarities in the obtained kinetic freeze-out parameters as a function of produced charged-particles observed for both Cu+Cu and Au+Au systems and for both center-of-mass energies, 200 and 62.4 GeV, raises the question: Are the bulk properties entropy driven?

4. Testing Hadro-Chemistry

In the statistical model framework, particle yield ratios can be used to provide information on the chemical freeze-out properties of the system, including the chemical temperature at chemical freeze-out, strangeness and baryon production.

The Cu+Cu particle ratios for each centrality bin are fit to derive four fit parameters: the chemical freeze-out temperature ($T_{ch}$), the baryon chemical potential ($\mu_B$), the strangeness chemical potential ($\mu_S$) and the strangeness suppression ($\gamma_S$).

Fig. 3 summarizes the systematics of chemical freeze-out parameters $T_{ch}$ and $\mu_B$ for 62.4 and 200 Cu+Cu collisions, compared to Au+Au and p+p results. The left panel shows that a universal chemical freeze-out temperature is observed for all studied systems. The chemical freeze-out temperature for different colliding systems shows the same systematic dependence as a function of charged particle multiplicity density at mid-rapidity, as illustrated in the right panel of Fig. 3. The
apparent absence of a decreasing trend in $T_{ch}$, in contrast with the $T_{kin}$ systematics, suggests that collisions with different initial energy densities evolve to the same chemical freeze-out, which then must coincide with hadronization.

5. Summary

The STAR collaboration has enlarged the variety of hadron spectra measurements at RHIC by providing new results for Cu+Cu collisions at two different center-of-mass energies, $\sqrt{s_{NN}}$ = 62.4 and 200 GeV. The data have been studied within the framework of both a blast-wave and a statistical model to investigate the final hadronic state properties as a function of collision energy, system size, centrality and inferred energy density.

This multi-dimensional systematic study of the kinetic and chemical freeze-out parameters has revealed remarkable similarities in the description of the studied systems. The freeze-out parameters are found to be independent of the collision system and center-of-mass energy. Furthermore, the parameters from different systems show a smooth evolution with centrality and similar properties at the same number of produced charged-particles, which is believed to be connected to the initial energy density or the size of the initial collision geometric overlap.

The bulk properties are most probably determined in the initial stages of the collision and driven by the initial energy density.
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