Scaling Properties of ϕ-Meson and Light Charged Hadron Production in Small and Large Systems at PHENIX

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Abstract. Recent results on the identified charged-hadron ($\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$) production at midrapidity region ($|\eta| < 0.35$) have been measured by the PHENIX experiment in p + Al, ^{3}He + Au, Cu + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV and U + U collisions at $\sqrt{s_{NN}}$ = 193 GeV. These measurements are presented through the invariant transverse-momentum (p_T) and transverse-mass (m_T) spectra for different collision centralities. The averaged freeze-out temperature value for different systems was found to be 166.1 ± 2.2 MeV, and do not exhibit any dependence on the collision centrality and $\langle N_{\rm part}\rangle$ values. The particle ratios of K/π and p/π have been measured in different centrality ranges of large and small collision systems. The values of K/π ratios measured in all considered collision systems were found to be consistent with those measured in p+p collisions. Furthermore, the identified charged-hadron nuclear-modification factors (R_{AB}) are also presented. Enhancement of proton R_{AB} values over meson R_{AB} values was observed in central ^{3}He+Au, Cu+Au, and U+U collisions. The proton R_{AB} values measured in p+Al collision system were found to be consistent with R_{AB} values of ϕ, $\pi^{\pm}$, $K^{\pm}$, and π^0 mesons, suggesting that the size of the system produced in p+Al collisions is too small for recombination to cause a noticeable increase in proton production.

1 Introduction

Light hadrons are considerably produced in high-energy heavy-ion collisions and provide a wealth of information about properties of created QCD medium and reaction dynamics. These include, in particular, the implications of collective flow in small and large systems and the impact of recombination on baryon and strangeness enhancement. The system size dependence studies of different observable are crucial to investigate the properties of quark-gluon plasma (QGP) and hadronization based on initial conditions of the collisions [1].

This paper presents recently finalized measurements by PHENIX on the production of identified charged hadron ($\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$) in small and large system size, p+Al, p/d/^{3}He/Cu+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV, and U+U collisions at $\sqrt{s_{NN}}$ = 193 GeV, and results were published recently [2]. The data sets used in the present analysis were collected by the PHENIX experiment [3]. The latter consisted of three components: global detectors, the central spectrometers, and the muon arm spectrometers. These measurements use the central spectrometers ($|\eta| < 0.35$), and provide precise tracking and particle identification for electrons, charged hadrons, and photons. Tracking and momentum determination are provided by drift chambers and pad chambers. Particle identification is provided by time of flight, ring-imaging Cherenkov detectors, and electromagnetic calorimeters.

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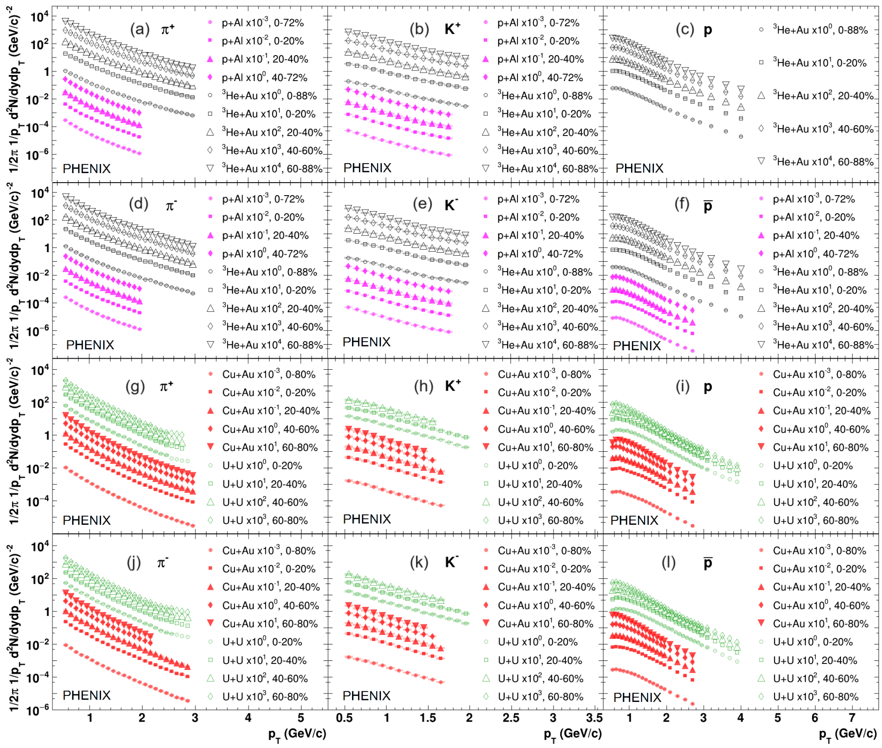


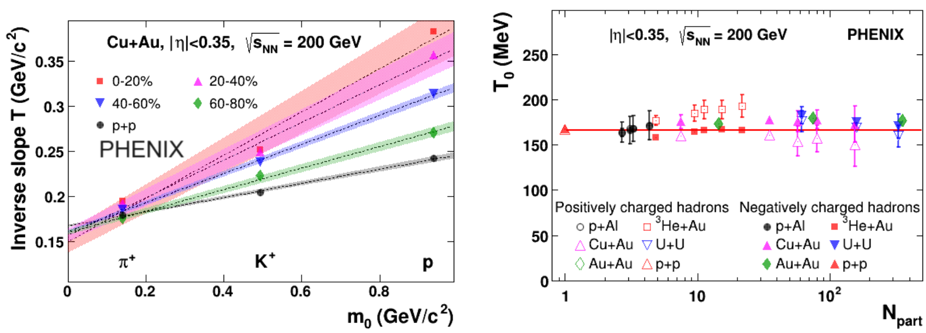
Figure 1. The π^+, π^-, K^+,K^-, p and $\bar{p}$ invariant p_T spectra measured in different centralities of p + Al, ^{3}He + Au, Cu + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV and U + U collisions at $\sqrt{s_{NN}}$ = 193 GeV.

2 Identified Charged Hadron Results in Small and Large Systems

• **Invariant Spectra and Freeze-out Temperature**: figure 1 shows the $\pi^{\pm}$, $K^{\pm}$, p, and $\bar{p}$ invariant transverse momentum spectra measured in p+Al, ^{3}He+Au, Cu+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV and in U + U collisions at $\sqrt{s_{NN}}$ = 193 GeV. We observe that the π, K, and p invariant spectra reveal different shapes as a function of p_T. To assess these differences, invariant-transverse-mass ($m_T = \sqrt{p_T^2 + m_0^2}$) spectra were calculated. We observe that the m_T invariant spectra of all identified charged hadrons have exponential form for $m_T < 1.5$ GeV and was approximated using following fit function:

$$\frac{1}{2\pi m_T}\frac{d^2N}{dm_T dy} = \frac{A}{2\pi T(T+m_0)}\exp\left(-\frac{m_T - m_0}{T}\right) \tag{1}$$

where T is the inverse-slope parameter, A is a normalization factor, and m_0 mass of the charged particle at rest. Figure 2(a) shows examples of T parameter vs. hadron mass (m_0) dependencies for different centralities of Cu + Au collisions. Ordering of pion, kaon, and proton inverse slope values $T_\pi < T_K < T_p$ can be seen in all centralities. By doing similar work in all systems, p+Al, ^{3}He+Au, and U + U, we obtained that the T values, calculated for pions in different centralities, are nearly of the same values in all collision systems. The T values, calculated for kaons, take intermediate values between pion and proton T-parameter values. The dotted lines on Fig. 2(a) represent linear fits of the $T(m_0)$ values from each centrality bin using thermal formula $T = T_0 + m\langle u_t\rangle^2$, where T_0 can be interpreted as a freeze-out temperature and $\langle u_t \rangle$ as the average collective velocity for all particle species. The fit parameters for positively charged (T_0^+, $\langle u_t \rangle^+$) and negatively charged (T_0^-, $\langle u_t \rangle^-$) hadrons calculated in p+Al, ^{3}He+Au, Cu+Au, and U+U collision systems are presented in Fig. 2(b) as a function of $\langle N_{\text{part}} \rangle$ values. The T_0 values calculated in collisions with different geometries and centralities were found to be coincident within uncertainties, indicating that the freeze-out temperature is approximately independent of $\langle N_{\text{part}} \rangle$ values. The averaged T_0 value was found to be 166.1 ± 2.2 MeV and is shown in the Fig. 2(b) with red solid line.



(a) Mass and centrality dependence of inverse slope (b) Freeze-out temperature as a function of $\langle N_{\text{part}} \rangle$

Figure 2. (a) Mass and centrality dependence of inverse slope parameters T for π^+, K^+ and p in Cu+Au collisions. The dotted lines represent a linear fits (see text). (b) Freeze-out temperature (T_0) as a function of $\langle N_{\text{part}} \rangle$ obtained for positively and negatively charged hadrons at different centralities of collision systems. The T_0 values measured in $p + p$ collisions are shown for comparison.

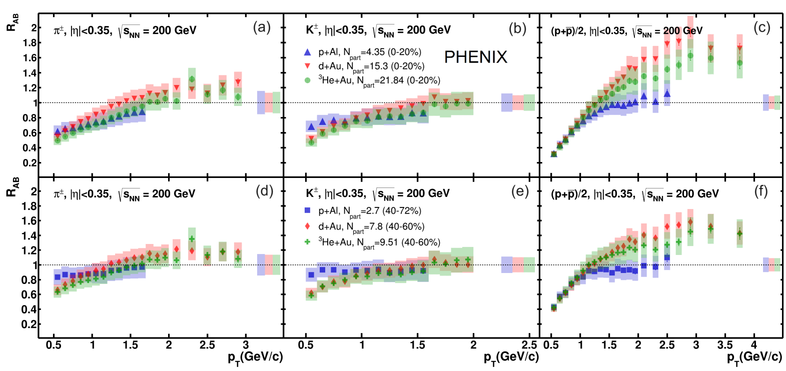
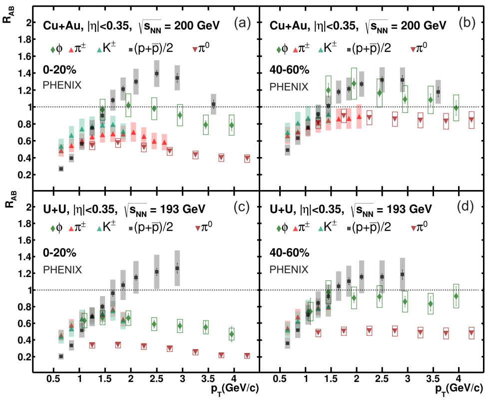
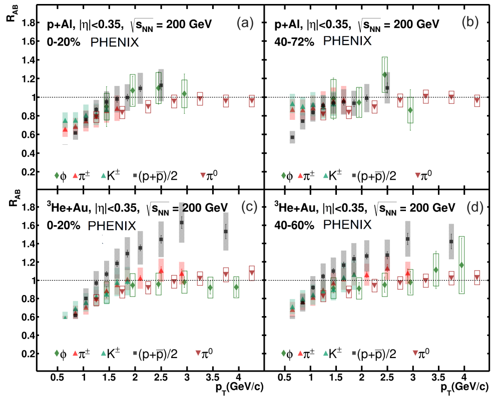


Figure 3. Identified charged hadron nuclear-modification factors as a function of p_T measured in central and peripheral p+Al, d + Au and ^{3}He+Au collisions. The dashed lines correspond to $R_{AB} = 1$ indicating absence of nuclear modification.

• **Particle Ratios:** the baryon production enhancement in nucleus-nucleus collisions is contemplated to be one of the signatures of QGP formation [4]. Based on this consideration, the ratios of p/π^+, $\bar{p}/\pi^-$ in different centralities of large (Cu+Au, U+U) and small ($p + p$, p+Al, ^{3}He+Au) collision systems have been measured and published recently by the PHENIX collaboration [2]. We observed in central collisions of large systems the p/π ratios reach the values of ≈ 0.6, but in peripheral collisions the values of p/π ratios are smaller than 0.4 in the whole p_T range. Furthermore, in small collision systems (p+Al, ^{3}He+Au), the values of p/π ratios are in good agreement to those measured in $p + p$ collisions [5].



(a) R_{AA} for central and peripheral Cu + Au, and U + U



(b) R_{AA} for central and peripheral p + Al, and ^{3}He+Au

Figure 4. R_{AB} for light hadron, ϕ, $\pi^{\pm}$, $K^{\pm}$, $(p+\bar{p})/2$ and π^0, as a function of p_T measured in central and peripheral: (a) in Cu+Au, and U+U collisions, and (b) p+Al and ^{3}He+Au collisions.

• **Nuclear Modification Factor:** figure 3 shows the identified charged-hadron R_{AB} values as a function of p_T in central and peripheral p+Al, d + Au, and ^{3}He+Au collisions. The R_{AB} values are found similar for collision systems with different geometries, but with the same $\langle N_{\rm part}\rangle$ values, indicating that identified charged-hadron production depends only on system size and not geometry. In addition, we observe the following features: 1) the slope of $R_{AB}(p_T)$ in p+Al collisions is flatter than it is in ^{3}He+Au and d + Au collisions, and 2) proton R_{AB} values in p+Al collisions at the intermediate p_T range (1.0 GeV/c < p_T < 2.5 GeV/c) are equal to unity, while in ^{3}He+Au and d + Au collisions proton R_{AB} is above unity. These observations suggest that the differences between p+Al and d/^{3}He+Au might be caused by the size of the p+Al system being insufficient to observe an increase in proton production.

3 Comparison of Identified Charged Hadron with ϕ-Meson and π^0

Figures 4(a) and 4(b) show the comparison of R_{AB} values of identified charged-hadron with ϕ-meson and π^0 in small and large collision systems, respectively. All these measurements of R_{AB} were obtained by the PHENIX experiment [2, 6]. These results elucidate following features: 1) in large collision systems and in the ^{3}He+Au collision system, proton R_{AB} values are enhanced over all meson R_{AB} values. Knowing that the mass of the ϕ-meson m_ϕ=1019 MeV/c^2 is similar to the proton mass m_p=938 MeV/c^2, therefore the enhancement of proton R_{AB} values over ϕ-meson R_{AB} values suggests differences in baryon versus meson production instead of a simple mass dependence, 2) in p+Al collisions proton R_{AB} values and R_{AB} values of all measured mesons are in good agreement within uncertainties.

4 Summary

The PHENIX experiment has established a comprehensive program to study the light hadron (ϕ, $\pi^{\pm}$, $K^{\pm}$, $(p+\bar{p})/2$ and π^0) production in small and large collisions systems by measuring invariant transverse-momentum and transverse-mass spectra, particle ratios, and nuclear modification factors. These results were presented and discussed in the scope to study the properties of created QCD medium and reaction dynamics at RHIC energies.

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