Identified charge hadron spectra and ratios in
Au+Au and d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

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Abstract. PHENIX has recently reported [1] measurements of identified charged hadron spectra and ratios in Au+Au and d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Identified hadrons are an important probe of both hot and cold nuclear matter. The intermediate $p_T$ region, 2–5 GeV/c, is of particular interest. In Au+Au collisions, the production of mesons is suppressed in this $p_T$ region relative to that in p+p collisions, while the production of baryons is nearly unmodified. On the other hand, in d+Au collisions, the meson production exhibits a slight enhancement in this $p_T$ region while the baryon production exhibits a much stronger enhancement. In these proceedings, the $p_T$ spectra and ratios of identified charged hadrons $\pi^\pm$, $K^\pm$, $p$, and $\bar{p}$ in 5 different centrality classes for each collision species will be discussed.

1. Introduction
The content presented this talk and in these proceedings is from a recent PHENIX paper on identified charged hadrons [1]. The particles are identified using the time-of-flight detector in the west arm (TOFW) of the PHENIX central spectrometer. The TOFW provides excellent PID capabilities, with $4\sigma \pi/K$ separation up to $p_T$ of 2.5 GeV/c, and $4\sigma K/p$ separation up to $p_T$ of 4 GeV/c. The $p_T$ reach can be extended greatly by exclusion cuts, where in addition to requiring that the $m^2$ of the particle is within $2\sigma$ of the mean, a further requirement that the $m^2$ of the particle is beyond $2\sigma$ of the mean of the other particles is also employed. In this analysis, this allows identification of pions and protons up to 6 GeV/c (5 GeV/c) in $p_T$ and kaons up to 4 GeV/c (3.5 GeV/c) in $p_T$ in Au+Au (d+Au) collisions.

2. Spectra
The $p_T$ spectra for all species and both collision systems are presented in Ref. [1]. In principle all the information reported therein and in these proceedings is encoded in the spectra. Particle ratios, however, often help illustrate differences between particle species, centrality classes, collisions systems, etc. There has been tremendous interest at this conference and elsewhere in hydrodynamical flow in small systems like d+Au and p+Pb, which is best evinced in the spectra themselves. The author anticipates and encourages theoretical studies of these spectra. The spectra are not shown in these proceedings in the interest of not exceeding the page limit.
3. Ratios

3.1. $p/\pi$ and $K/\pi$ ratios

Presented in Figures 1 and 2 are the $K^+/\pi^+$ (upper panels) and $K^-/\pi^-$ (lower panels) as a function of $p_T$ for Au+Au and d+Au collisions, respectively. PHENIX data from p+p collisions [2] are shown as a reference. The $K/\pi$ ratio in Au+Au shows a weak centrality dependence, with the ratio rising slightly as the collisions become more central. This is indicative of the well-known strangeness enhancement in the medium. The enhancement is also $p_T$ dependent, with the ratios being roughly equal at low $p_T$ and then the enhancement steadily increasing up to $p_T \approx 2$ GeV/c, above which the enhancement levels off and is flat. This detailed measurement of the $p_T$ dependence of this ratio can hopefully shed light on the strangeness production mechanism(s) in the medium. In d+Au collisions this effect is notably absent, as no centrality dependence is seen whatsoever, with the caveat that the span of $N_{part}$ values is small. Finally, note that for the most peripheral Au+Au and all d+Au centralities the $K/\pi$ ratios are consistent with those in p+p collisions in the overlapping $p_T$ region.

![Figure 1. $K^+/\pi^+$ (upper panel) and $K^-/\pi^-$ (lower panel) as a function of $p_T$ in Au+Au collisions.](image1)

![Figure 2. $K^+/\pi^+$ (upper panel) and $K^-/\pi^-$ (lower panel) as a function of $p_T$ in Au+Au collisions.](image2)

Presented in Figures 3 and 4 are the $p/\pi^+$ (upper panels) and $\bar{p}/\pi^-$ (lower panels) as a function of $p_T$ for Au+Au and d+Au collisions, respectively. PHENIX data from p+p collisions [2] are shown as a reference. The $p/\pi$ ratio in Au+Au shows a strong centrality dependence. In d+Au the centrality dependence at first appears weak, but in fact should be regarded as quite strong given the small range of $N_{part}$ in the d+Au centrality selections. In both collision systems, the ratio rises quickly, reaches a maximum between 2–2.5 GeV/c in $p_T$, and then falls off slowly. This maximum point is closer to 2 GeV/c in d+Au. There appears to be a centrality dependence to this maximum in Au+Au, as for example the maximum for peripheral Au+Au appears to be closer to 2 GeV/c (like the d+Au) but closer to 2.5 GeV/c for the most central.
3.2. Nuclear modification factors

Shown in Figures 5 and 6 are $R_{AA}$ and $R_{dA}$, respectively, as a function of $p_T$ in the various centrality classes. The p+p reference data for π/K/p are from Ref. [2]. Also shown are π$^0$ data taken from Refs. [3, 4] and φ data taken from Ref. [5].

As exhibited in the $R_{AA}$, charged and neutral pions show fairly significant suppression. The charged kaons exhibit a very similar $p_T$ shape as the charged pions, although an overall higher level. The φ meson is at a yet higher level in turn. All three mesons π, K, and φ are suppressed but with decreasing suppression in that order. This ordering cannot be attributed to mass alone since the φ is heavier than the proton but has a significantly lower $R_{AA}$. On the other hand, this ordering also coincides with increasing strangeness content, meaning it could be attributable to strangeness enhancement. In the $R_{dA}$ all mesons exhibit essentially identical behavior, showing little or no modification. This suggests that any differences in particle production between d+Au and p+p collisions are not attributable to particle mass or strangeness content.

In both the $R_{AA}$ and $R_{dA}$ the protons exhibit a strong enhancement relative the mesons, which is also seen in the $p/\pi$ ratios. The behavior is clearly consistent with different behaviors for baryons and mesons. The physical origin of differences between baryons and mesons has been frequently attributed to hadronization by parton recombination, which has some success in describing the experimental data [6]. However, an alternative explanation, such as that involving baryon junctions, should not be forgotten, and the author invites further theoretical investigation of the present work.

3.3. Comparison between peripheral Au+Au and central d+Au

As alluded to in previous sections, there are remarkable similarities between peripheral Au+Au and central d+Au. A direct comparison between the two is justified by this alone. However, this can be further motivated by the very similar Glauber parameters for the two systems. The $N_{coll}$ values are 14.8±3.0 and 15.1±1.0 for peripheral Au+Au and central d+Au, respectively; the
N_{part} values are 14.7±2.9 and 15.3±0.8 for peripheral Au+Au and central d+Au, respectively.

Shown in Figures 7 and 8 are the K/π and p/π ratios, respectively, as a function of p_{T} in both peripheral Au+Au and central d+Au. As can be seen, the ratios are essentially identical in the two systems.

A direct ratio of the spectra in the two systems is presented in Figure 9. No scaling is applied. However, as noted above, the respective N_{coll} and N_{part} are very similar, so a scaling by either of these values would result in a negligible change.

This ratio is very striking. For p_{T} values of 2.5 GeV/c and higher, the ratio is flat and independent of p_{T}, and is further identical for each particle species. This indicates that the baryon enhancement in each system is quantitatively the same and that the baryon enhancement is likely driven by the same mechanism. This in turn provides significant theoretical constraints.

At lower p_{T} the ratio trends upwards. A mass and/or particle type separation may be evident, although the three species are consistent within systematic uncertainties. There are many potential physical effects at play. For example, there is a rapidity shift in soft particle production in d+Au collisions due to the participant asymmetry [7]. This naturally creates a
deficit of particle production at low $p_T$ and could explain the observed upward trend in this ratio. Additionally, if there is radial flow in central d+Au collisions and it is stronger than that in peripheral Au+Au, that could also explain this trend, with additional benefit of explaining the mass ordering that may be present.

References
[1] Adare A et al 2013 Phys. Rev. C 88 024906
[2] Adare A et al 2011 Phys. Rev. C 83 064903
[3] Adler S S et al 2007 Phys. Rev. Lett. 98 172302
[4] Adare A et al 2008 Phys. Rev. Lett. 101 232301
[5] Adare A et al 2011 Phys. Rev. C 83 024909
[6] Zhu L and Hwa R C 2013 Preprint 1307.3328
[7] Back B B et al 2004 Phys. Rev. Lett. 93 082301