π/K/p production and Cronin effect from p+p, d+Au and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV from the PHENIX experiment.

Felix Matathias† for the PHENIX§ collaboration

†Department of Physics and Astronomy,
State University of New York at Stony Brook, Stony Brook, NY, 11794

Abstract.
We present results on identified particle production in p+p, d+Au and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV at mid-rapidity measured by the PHENIX experiment. The centrality and flavor dependence of the Cronin effect in d+Au collisions is measured. The Cronin effect for the protons in d+Au is larger than that for the pions, but not large enough to account for the “anomalous” proton to pion ratio in central Au+Au collisions.

In the search for the Quark Gluon Plasma at the Relativistic Heavy Ion Collider it was discovered that hadron production at high transverse momentum ($p_T \geq 2$ GeV/c) is suppressed in central Au+Au collisions ¹ compared to nucleon-nucleon collisions. Furthermore, the yields of p and $\bar{p}$ near 2 GeV/c in central events ²³ are comparable to the yield of pions ($p/\pi \sim 1$), in contrast to the proton-to-pion ratios of $\sim 0.1 - 0.3$ in p+p ⁴. Novel mechanisms of particle production in the environment of hot and dense nuclear matter were proposed ⁵⁶⁷⁸ to explain this phenomenon. The determination of the properties of this environment is not straightforward though and requires control over the interplay between many competing nuclear effects ⁹ that influence the particle spectra. These include shadowing, enhanced production at moderate $p_T$ (Cronin effect ¹⁰), and energy loss. It is therefore of paramount importance to perform a control experiment to quantify these competing mechanisms and distinguish effects of the surrounding cold nuclear matter (initial state effects) from those originating from highly excited nuclear matter (final state effects).

Consequently, RHIC collided d+Au at $\sqrt{s_{NN}} = 200$ GeV, and also provided p+p collisions for a baseline measurement. PHENIX measured identified particle spectra, yields, ratios, and nuclear modification factors from these data. The d+Au experiment, besides serving as a comparison measurement for relativistic heavy ion collisions, acquires a significance of its own. The centrality dependence of particle production in d+Au collisions can provide detailed information on the microscopic origin of the Cronin effect and possibly provide insights on the baryon enhancement. Also, protons exhibit a larger Cronin effect than pions and kaons at lower energies ¹¹ and at RHIC ¹² while no theoretical calculations can account for the species dependence of the effect.

§ For the full PHENIX Collaboration author list and acknowledgments, see Appendix “Collaborations” of this volume.
The data were collected in RUN02 for Au+Au and p+p collisions at $\sqrt{s_{NN}} = 200$ GeV; in RUN03, d+Au collisions at the same energy were studied. A detailed presentation of the Au+Au analysis can be found in [3]. In the following we discuss the analysis of the p+p and d+Au data. Minimum bias events with vertex position along the beam axis within $|z| < 30$ cm were triggered by the Beam-Beam Counters (BBC) located at $|\eta| = 3.0-3.9$. The minimum bias trigger accepts $(88 \pm 4\%)$ of all inelastic d+Au collisions and $(51.6 \pm 9.8\%)$ of all p+p inelastic collisions that satisfy the vertex condition. A total of $1.4 \times 10^7$ d+Au events and $1.35 \times 10^7$ p+p events were analyzed.

Charged particles are tracked using the central arm spectrometers. The spectrometer on the east side of the PHENIX detector (east arm) contains the following subsystems used in this analysis: drift chamber (DC), pad chamber (PC1) and time-of-flight (TOF). Identified charged particles are measured using a portion of the east arm spectrometer covering pseudo-rapidity $\Delta \eta = 0.7$ and $\Delta \phi = \pi/8$ in azimuthal angle. Particle identification is based on particle mass calculated from the momentum measured by the DC and the velocity obtained from the time-of-flight and the path length along the trajectory.

Collision centrality is selected in d+Au using the south (Au-going side) BBC (BBCS). We assume that the BBCS signal is proportional to the number of participating nucleons ($N_{\text{part}}^{Au}$) in the Au nucleus, and that the hits in the BBCS are uncorrelated to each other. Using a Glauber simulation of d+Au collisions the distribution of $N_{\text{part}}^{Au}$ is generated for different impact parameters. For a given
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Figure 2. Nuclear modification factor $R_{CP}$ for pions and protons in d+Au and Au+Au collisions.

centrality the charge distribution of the BBCS is described by a negative binomial distribution. Parameters are assumed to be proportional to $N_{Au}^{part}$, and fitted to reproduce the data, yielding a BBCS charge response function. We define 4 centrality classes in d+Au collisions with $N_{coll}$ = 15.0 ± 1.0, 10.4 ± 0.7, 6.9 ± 0.6 and 3.2 ± 0.3.

The proton to pion ratio from p+p, d+Au and Au+Au is shown in Figure 1. The protons are not feed-down corrected in this ratio since this correction was not available for the d+Au and p+p data. For feed-down corrected $p$ and $\bar{p}$ spectra in Au+Au see [3]. The $p/\pi$ ratio in d+Au is very similar to the peripheral Au+Au while the p+p ratio is somewhat lower. It is evident that the high value of the $p/\pi$ ratio in central Au+Au collisions can only be attributed to the hot and dense nuclear matter created in this class of collisions while the baseline measurement is much lower.

Figure 2 shows the central to peripheral ratio in d+Au and Au+Au for $N_{coll}$ scaled $p_T$ spectra of $(\bar{p} + p)/2$ and pions. We define the central to peripheral ratio $R_{CP}$ as:

$$R_{CP} = \frac{\text{Yield}_{\text{central}} / (N_{\text{central}})}{\text{Yield}_{\text{peripheral}} / (N_{\text{peripheral}})}$$  \hspace{1cm} (1)

Although the protons have a larger Cronin effect than the pions in d+Au, on the order of 20-25%, this phenomenon can not account for the approximately factor of 3 enhancement of the protons with respect to the pions in the Au+Au case. Therefore the enhancement of the protons relative to the pions in central Au+Au is not just due to the species-dependent Cronin effect. The baryon production mechanism must depend on the produced medium; even if it is already present in d+Au, the effect is necessarily much smaller [13].

Figure 3 shows $R_{dAu}$, the nuclear modification factor using the p+p spectrum as a reference, for pions and protons in two momentum bins. The modification factors are plotted as a function of the number of collisions suffered by the deuteron participant nucleons. The lower momentum bin is in the $p_T$ region where $R_{dAu}$ is less than 1.0, and the dependence on the number of collisions is minimal. In the higher $p_T$ bin,
$R_{dAu}$ shows a steady increase with the number of collisions. The rate of increase is larger for baryons than for mesons.

Traditional explanations of the Cronin effect involve multiple soft scattering of incoming partons that lead to an enhancement at intermediate $p_T$. There are various theoretical models \cite{13} of the multiple scattering, predicting somewhat different dependence upon the number of scattering centers. Recently, Hwa and collaborators \cite{13} have shown an alternative explanation of the Cronin effect, attributed to the recombination of shower quarks with those from the medium, even in d+Au collisions.

In summary, we have presented the centrality and species dependence of identified particle spectra in all 3 collision systems studied at RHIC to date. The proton to pion ratio in d+Au is similar to the peripheral Au+Au while the corresponding ratio in p+p is somewhat lower. The nuclear modification factor in d+Au for protons shows a larger Cronin effect than that for pions but not large enough to account for the abundance of protons in central Au+Au collisions.

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