Multiplicity and Rapidity Dependent Study of (Multi)-strange Hadrons in d+Au collisions using the STAR detector

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Abstract. Strangeness enhancement has long been considered as a signature of the quark-gluon plasma formation in heavy-ion collisions. Strangeness enhancement has also been observed in small systems at the Large Hadron Collider (LHC), but the underlying physics still needs to be fully understood. This motivates us to study the strange hadron production in small systems at RHIC. We present new measurements of (multi-)strange hadrons (K^0_S, Λ, Ξ and Ω) in d+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV, collected by STAR in 2016. We report the multiplicity and rapidity dependence of strange hadron transverse momentum (p_T) spectra, p_T-integrated yields dN/dy, average transverse momentum ($\langle p_T \rangle$), yield ratios of these strange hadrons to pions, nuclear modification factors and rapidity asymmetry for these particles in d+Au collisions.

1 Introduction

The production of strange hadrons in high-energy hadronic interactions provides a way to investigate the properties of quantum chromodynamics (QCD), the theory of strongly interacting matter. Unlike up (u) and down (d) quarks, strange (s) quarks are not present as valence quarks in the initial state and are created during the collisions. Strangeness enhancement in heavy ion collisions with respect to proton-proton (p+p) collisions has been suggested as a signature of quark-gluon plasma (QGP) formation [1]. However, the creation of QGP in small systems is still under intense debate.

Asymmetric small collision systems like proton-nucleus (p–A) and deuteron-nucleus (d–A) can be considered as control experiments where the formation of an extended QGP phase is not expected. These collision systems are used for baseline measurements to study the possible effects of cold nuclear matter and to disentangle them from hot dense matter effects signifying the QGP formation in heavy-ion collisions. Cold nuclear matter effects can be evident through Cronin enhancement at intermediate p_T due to the transverse momentum broadening. The process of generating hadrons can be affected by various factors that include modifications in parton distribution functions within nuclei, the possibility of parton saturation, multiple scatterings of the partons traversing the nucleus, and the radial flow. It is anticipated that the magnitude of these effects may vary with the rapidity of the produced particles.

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The abundances of strange particles relative to pions in heavy-ion collisions for top RHIC and LHC energies do not show a significant dependence on the initial volume (collision centrality) [2].

Nuclear effects can be quantified using variables such as nuclear modification factor and rapidity asymmetry. The nuclear modification factor is defined as the ratio of the yield of a particle in heavy-ion collisions to its yield in *p*+*p* collisions, scaled by the number of binary nucleon-nucleon inelastic collisions [3].

$$R_{AB}(p_T) = \frac{\mathrm{Yield}_{AB}}{\langle N_{bin}\rangle \mathrm{Yield}_{pp}} \tag{1}$$

where $\langle N_{bin}\rangle$ is the average number of binary nucleon-nucleon collisions. A comparative study of particle production in forward and backward rapidity regions uses rapidity asymmetry (Y_{Asym}) [4]. Y_{Asym} is defined as

$$Y_{Asym}(p_T) = \frac{Y_B(p_T)}{Y_F(p_T)} \tag{2}$$

where Y_B and Y_F are particle yields in backward and forward rapidity regions, respectively.

2 Analysis Details

A successful run of *d*+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV was carried out in 2016 at RHIC. A total of approximately 100 million good events have been selected in STAR for the reconstruction of K^0_s, $\Lambda(\bar{\Lambda})$, $\Xi(\bar{\Xi})$, $\Omega(\bar{\Omega})$. K^0_s, $\Lambda(\bar{\Lambda})$, $\Xi(\bar{\Xi})$, $\Omega(\bar{\Omega})$ are weakly decaying particles, and they travel a certain distance before decaying into daughter particles ($K^0_S \rightarrow \pi^+ + \pi^-$, $\Lambda(\bar{\Lambda}) \rightarrow p(\bar{p}) + \pi^-(\pi^+)$, $\Xi^-(\bar{\Xi}^+) \rightarrow \Lambda(\bar{\Lambda}) + \pi^-(\pi^+)$, $\Omega^-(\bar{\Omega}^+) \rightarrow \Lambda(\bar{\Lambda}) + K^-(\bar{K}^+)$). The daughter particles (π, K and p) are identified via measuring $\langle dE/dx\rangle$ using Time Projection Chamber (TPC).

The K^0_s, $\Lambda(\bar{\Lambda})$, $\Xi(\bar{\Xi})$, $\Omega(\bar{\Omega})$ signals are extracted by reconstructing the invariant mass of the decay daughter pairs. The decay topology can be used to reconstruct and suppress the background. We have used double Gaussian and second order polynomial function to describe the signal and background invariant mass distributions respectively. Raw yield is estimated using functional fitting and bin counting method (which is considered in systematic uncertainty). Raw yield is determined within the mass window of $M_0 \pm 3\sigma$, where M_0 is mass of K^0_S (or $\Lambda/\Xi/\Omega$) and σ is the fitted width. Raw yield for each p_T interval is corrected for branching ratio, acceptence and efficiency to obtain corrected p_T spectra. Weak decay feed down correction from Ξ is applied to Λ.

3 Results and Discussions

Fig. 1 (left) shows the integrated yield particle-to-pion ratio for K^0_S, Λ, Ξ and Ω as a function of multiplicity for *d*+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. A smooth transition of these ratios from *p*+*p* to heavy ion collisions is observed. Data from different collision systems are consistent with each other at similar multiplicities [2] and yields of particles with more strangeness content decrease faster as we move from high to low multiplicities.

In Fig. 1 (right), nuclear modification factors for K^0_S, Λ and Ξ at mid rapidity ($|y| < 0.5$) for *d*+Au collision is presented, and Cronin-like enhancement is observed, which is stronger for baryons (Ξ, Λ, p) as compared to mesons (K^0_S, π).

In Fig. 2 (left), integrated yield and $\langle p_T\rangle$ as function of multiplicity for mid-rapidity in *p*+*p*, *d*+Au, Cu+Cu and Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV are shown. Integrated yield increases as a function of multiplicity, and we have also observed that particle production is

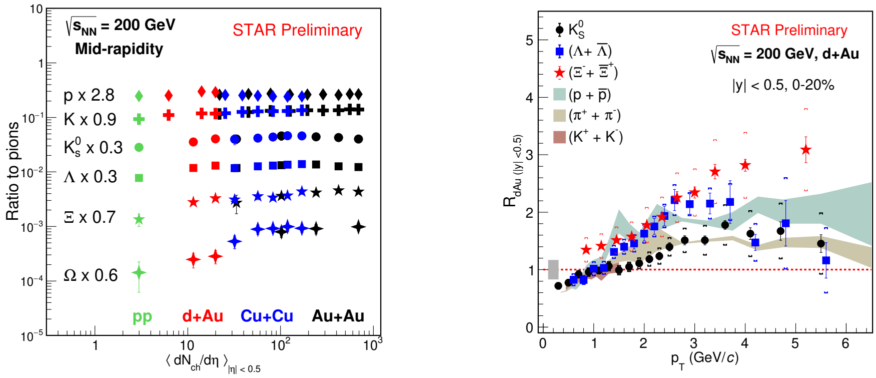

Figure 1: Integrated yield particle-to-pion ratio (left) for strange particles (K^0_S, Λ, Ξ and Ω) as a function of multiplicity for p+p, d+Au, Cu+Cu and Au+Au collisions and Nuclear modification factors (R_{dAu}) (right) for strange particles (K^0_S, Λ and Ξ) in d+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV.

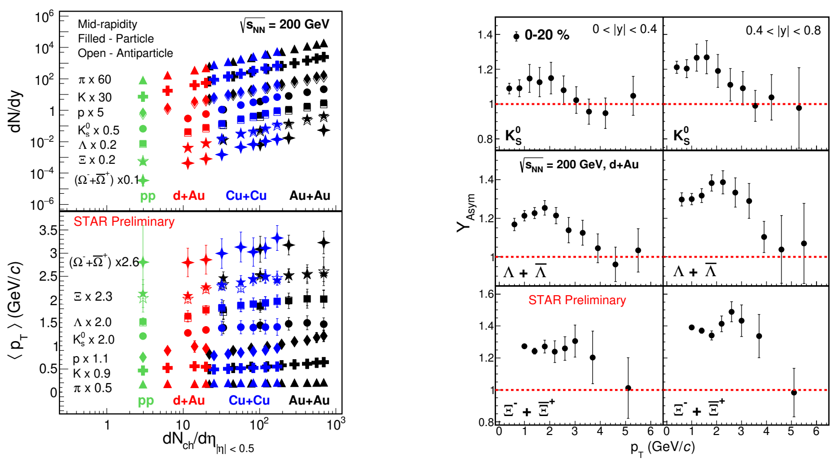

Figure 2: Integrated yield (dN/dy) and mean transverse momentum $\langle p_T \rangle$ (left) for strange particles (K^0_S, Λ, Ξ and Ω) as a function of multiplicity for p+p, d+Au, Cu+Cu and Au+Au collisions and rapidity asymmetry (Y_{Asym}) as a function of p_T (right) for strange particles (K^0_S, Λ and Ξ) in d+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV.

mainly driven by multiplicity and not by collision system. A hint of an increase in $\langle p_T \rangle$ is observed for heavier particles, which supports the picture of radial flow.

We have also measured the transverse momentum dependence of Y_{Asym} for K^0_s, Λ and Ξ in two rapidity intervals ($0 < |y| < 0.4$, $0.4 < |y| < 0.8$) in d+Au collision at $\sqrt{s_{NN}}$ = 200 GeV. Y_{Asym} values deviate from unity at low p_T (< 3 GeV/c), suggesting the presence of a rapidity dependence in the nuclear effects. Y_{Asym} is consistent with unity at high p_T, hinting that nuclear effects become weaker at high p_T as shown in Fig. 2 (right). Asymmetry is more prominent for larger rapidity interval and heavier particles.

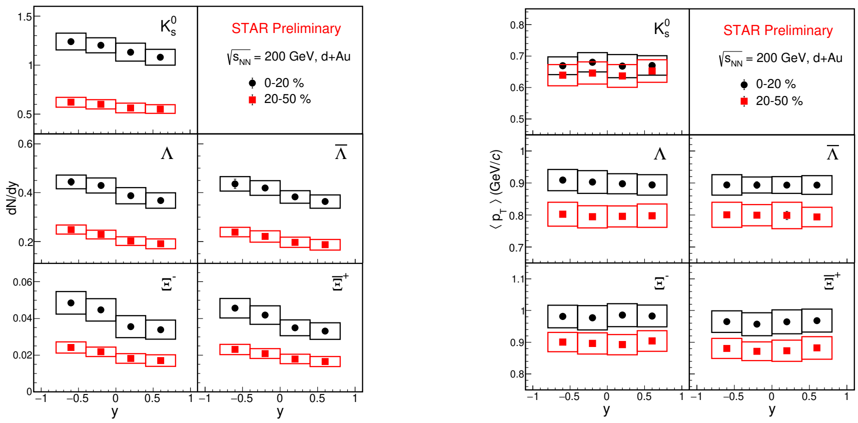

Figure 3: dN/dy (left) and $\langle p_T \rangle$ (Right) of strange particles (K^0_s, $\Lambda(\bar{\Lambda})$ and $\Xi(\bar{\Xi})$) as a function of rapidity in d+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV for multiplicity classes 0-20% and 20-50%.

In Fig. 3, integrated yield (dN/dy) and mean transverse momentum ($\langle p_T \rangle$) are calculated for different rapiditiy intervals (0 < |y| < 0.4, 0.4 < |y| < 0.8). For strange particles K^0_s, $\Lambda(\bar{\Lambda})$ and $\Xi(\bar{\Xi})$, integrated yield (dN/dy) decreases slightly from negative (Au going side) to positive (d going side) rapidity but mean transverse momentum ($\langle p_T \rangle$) is constant in the measured rapidity range which suggests a similar radial flow for rapidity ranging from -0.8 < y < 0.8.

4 Summary

We present new measurements of multiplicity and rapidity dependence of (multi-)strange hadrons (K^0_s, $\Lambda(\bar{\Lambda})$, $\Xi(\bar{\Xi})$ and $\Omega(\bar{\Omega})$) production in d+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV with the STAR experiment. p_T-integrated yields of strange and multi-strange particles relative to pions increase significantly with multiplicity. Results suggest that strange particle production is independent of the collision system and mainly driven by multiplicity. The observed enhancement increases with strangeness content rather than with mass or baryon number of the hadron. Hint of Cronin-like enhancement is observed for 0-20% centrality for K^0_S, Λ and Ξ. $Y_{Asym} > 1$ at low p_T, indicating the presence of the nuclear effects. The Y_{Asym} is more prominent for heavier mass and larger rapidity interval.

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