STAR results on strangeness production in beam energy scan program

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Abstract. We present the recent STAR results on the production of strange hadrons ($K^0, \phi, \Lambda, \Xi$ and $\Omega$) in $p_sNN=7.7-39$ GeV $Au+Au$ collisions in the RHIC beam energy scan program. We investigate the strangeness enhancement and strangeness equilibration as a function of beam energy and system size at RHIC. Nuclear modification factors and particle ratios will be highlighted. Implications on partonic vs. hadronic dynamics as a function of the beam energy will be discussed.

1. Introduction
Lattice quantum chromodynamics (QCD) calculations suggest that, at high temperature and low baryon chemical potential ($\mu_B$), the transition from the Quark Gluon Plasma (QGP) to the state of a hadron gas is smooth and continuous (cross-over transition) [1]. At lower temperatures and high $\mu_B$, theoretical calculations predict a first order phase transition [2] which may end at a critical point [3]. The mapping of the QCD phase diagram is the main motivation of RHIC heavy ion program.

Strange quark production is expected to be sensitive to the phase transition, because its mass is presumably much higher than system temperature in hadronic phase, but lower than system temperature in partonic phase [4]. This suggests the enhancement of strange hadron yields compared to light hadrons in the partonic phase, which has been discovered in central Pb-Pb collisions at Super Proton Synchrotron (SPS) at $\sqrt{s_{NN}}=7.7-17.3$ GeV [5–8]. In addition, the strange quark production is specially important because of its small hadronic cross-section and sensitivity to the partonic phase of collision dynamics. Strange hadrons, especially the multistrange hadrons like $\Omega$ and $\phi$ are excellent probes to study the QGP properties and the QCD phase boundary [9]. Differential measurements are performed at top RHIC energy of $\sqrt{s_{NN}}=200$ GeV to understand the dynamics of partons in the QGP phase. Baryon to meson ratios have been found to be large compared to those from elementary collisions [10–14]. The measured elliptic flow $v_2$ has been found to scale with the number of constituent quarks (NCQ) for both baryons and mesons [15] in $Au+Au$ collisions at the top RHIC energy. In order to explain these observations, theoretical model calculations require the development of collectivity among constituent quarks during the partonic phase [16–20]. This partonic collectivity has been considered as an important evidence for the formation of deconfined QCD matter with partonic degrees of freedom in $Au+Au$ collisions at the highest RHIC energy [10–20].
To fully map out the phase diagram of the QCD matter, a Beam Energy Scan (BES) program has been initiated at RHIC with Au+Au collisions at $\sqrt{s_{NN}} = 7.7, 11.5, 19.6, 27$ and $39$ GeV [21] in year 2010 and 2011, and $\sqrt{s_{NN}} = 14.5$ in year 2014. These collisions allow us to reach a broad range of temperature and $\mu_B$ in the QCD phase diagram [22] and search for a possible beam energy region where the underlying dynamics are different from those of partonic matter observed in Au+Au collisions at the top RHIC energy. Here we present the STAR results on strange hadrons production ($K^0_S$, $\phi$, $\Lambda$, $\Xi$ and $\Omega$) in above collisions. We investigate the strangeness enhancement and strangeness equilibration as a function of beam energy and system size at RHIC. Nuclear modification factors and particle ratios will be highlighted. The implications on partonic vs. hadronic dynamics as a function of the beam energy will be discussed.

Figure 1. (a) Yield ratios of $dN/dy(\bar{\Lambda})/dN/dy(\Lambda)$ in mid-rapidity ($|y| < 0.5$) as a function of number of participant nucleons ($N_{\text{part}}$) in $\sqrt{s_{NN}} = 7.7 - 39$ GeV Au+Au collisions. (b) Mid-rapidity $dN/dy/N_{\text{part}}$ as a function of $N_{\text{part}}$ for $\Lambda$ and $\bar{\Lambda}$ in Au+Au collisions at 7.7 GeV. (c) $p_T$ dependence of invariant yield ratios of $\bar{\Lambda}/\Lambda$ in mid-rapidity Au+Au at 7.7 GeV. (d) Similar as Figure 1(a), but for $dN/dy(\Xi^+)/dN/dy(\Xi^-)$ ratios.

2. Results
Figure 1(a) shows the yield ratios of $dN/dy(\bar{\Lambda})/dN/dy(\Lambda)$ in mid-rapidity ($|y| < 0.5$) as a function of $N_{\text{part}}$ in $\sqrt{s_{NN}} = 7.7 - 39$ GeV Au+Au collisions. The ratios decrease with $N_{\text{part}}$ in each collision energy, suggesting higher $\bar{\Lambda}/\Lambda$ ratios in peripheral collisions compared to central collisions. The peripheral-central differences are more prominent at lower collisional energies such as 7.7 GeV. From Figure 1(b) one can see that the $N_{\text{part}}$-scaled $\Lambda$ yields show a generally increasing trend with increasing $N_{\text{part}}$, suggesting a stronger baryon transport to mid-rapidity.
due to more multiple scatterings in central collisions compared to peripheral collisions. For $\bar{\Lambda}$, the $N_{\text{part}}$-scaled yields increase with $N_{\text{part}}$ at small $N_{\text{part}}$. It turns down in central collisions with large $N_{\text{part}}$. There may be two effects here: one is the strangeness enhancement with increasing $N_{\text{part}}$; the other is more $\bar{\Lambda}$ absorption in the central collisions where the baryon density is higher. Experimental data [23] and model calculations [24] suggest a maximum net baryon density around $p_{\text{NN}} = 7.7$ GeV. This means a significant anti-baryon absorption at 7.7 GeV, which is consistent with our data. The $p_T$ dependence of $\bar{\Lambda}/\Lambda$ invariant yield ratios in 7.7 GeV (Fig. 1(c)) shows the loss of low $p_T$ $\bar{\Lambda}$ in central collisions. This may be caused by larger absorption cross sections of $\bar{\Lambda}$ hyperons at low $p_T$. The $dN/dy(\Xi)/dN/dy(\Xi^{-})$ ratios show a similar pattern as $dN/dy(\bar{\Lambda})/dN/dy(\Lambda)$ ratios, which might be understood with similar mechanism of $\Lambda(\bar{\Lambda})$ production.

Figure 2 shows the ratios of strange particles to pions. $\bar{\Lambda}/\pi$ and $\Xi^{\mp}/\pi$ ratios agree with SHM model predictions, but they are higher than the UrQMD predictions. The deviation from UrQMD predictions is larger for multi-strange baryons $\Xi^{\mp}$. From these ratios, we can see clearly $\bar{\Lambda}$, and $\Xi^{\mp}$ yield enhancement compared to pions with increasing collision energy. Similar behavior has been found for hidden strangeness ($\phi$ meson). The enhancement factor for $\phi/\pi$ ratio is smaller than that of $\bar{\Lambda}/\pi$ and $\Xi^{\mp}/\pi$ ratios, partly because of anti-baryon absorption at low energy at which the new baryon density is high.

In Figure 3, we present the $R_{\text{CP}}$ of $K^0_S$, $\phi$, $\Lambda$, $\Xi^-$, and $\Omega^-$ in Au+Au $\sqrt{s_{\text{NN}}} = 7.7 - 39$ GeV collisions. The $R_{\text{CP}}$ is defined as the ratios of particle yields in central collisions over those in peripheral ones scaled by the number of inelastic binary collisions $N_{\text{bin}}$. Here, $N_{\text{bin}}$ is determined from Monte Carlo Glauber model calculations [40]. The $R_{\text{CP}}$ will be unity if nucleus-nucleus collisions are just simple superpositions of nucleon-nucleon collisions. Deviation of these ratios from unity would imply contributions from nuclear or medium effects. For $p_T$ above 2 GeV/c, one can see from Figure 3 that $K^0_S$ $R_{\text{CP}}$ increases with decreasing beam energies, indicating that the partonic energy loss effect becomes less important. While the cold nuclear matter effect (Cronin effect) [41] starts to take over at $\sqrt{s_{\text{NN}}} = 11.5$ and 7.7 GeV, and enhances the hadron yields at intermediate $p_T$. The energy evolution of strange hadron $R_{\text{CP}}$ reflects the decreasing
partonic effects with decreasing beam energies. In addition, the particle $R_{CP}$ differences are apparent at $\sqrt{s_{NN}} \geq 19.6$ GeV. However, the differences becomes smaller at $\sqrt{s_{NN}} = 11.5$ and 7.7 GeV, which may suggest different properties of the system created in $\sqrt{s_{NN}} = 11.5$ and 7.7 GeV Au+Au collisions compared to those in $\sqrt{s_{NN}} \geq 19.6$ GeV.

The enhancement of baryon-to-meson ratios at intermediate-$p_T$ compared to elementary collisions is interpreted as a consequence of hadron formation from parton recombination and parton collectivity [16–20]. Therefore, the baryon-to-meson ratios are expected to be sensitive to parton dynamics of the collision system. Figure 4 shows the baryon-to-meson ratios, $N(\bar{X})/N(K_S^0)$, as a function of $p_T$ in mid-rapidity $|y| < 0.5$ from Au+Au collisions at $\sqrt{s_{NN}} = 7.7 - 39$ GeV. The intermediate-$p_T$ $\bar{X}/K_S^0$ ratios are close to each other at 27 and 39 GeV, and show a slight decrease at 19.6 GeV. There is a sudden decrease of intermediate-$p_T$ $\bar{X}/K_S^0$ ratios between 19.6 and 14.5 GeV, suggesting a possible change of underlying hadron formation mechanism and/or parton dynamics between these two energies. For a detailed study on the centrality dependence of $\bar{X}/K_S^0$ ratios, one can refer to Ref. [42].
Figure 5. The baryon-to-meson ratio, \( N(\Omega^- + \Omega^+) / (2N(\phi)) \), as a function of \( p_T \) in mid-rapidity \(|y| < 0.5\) from Au+Au collisions at \( \sqrt{s_{NN}} = 7.7 - 200 \text{ GeV} \). The boxes denote systematical errors. The solid and dashed lines represent recombination model calculations for central collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) [17] with total and thermal strange quark contributions, respectively.

We use multi-strange hadrons, \( N(\Omega^- + \Omega^+) / (2N(\phi)) \) ratios, to further study the energy dependence of baryon-to-meson ratios. The \( \Omega \) hyperons and \( \phi \) mesons are expected to have relatively small hadronic interaction cross sections [43, 44]. Therefore, they can carry the information directly from the chemical freeze-out stage with little or no distortion due to hadronic rescattering. In addition, the measured \( \Omega \) and \( \phi \) yields suffer minimal distortion from decay feed-down. We present baryon-to-meson ratios, \( N(\Omega^- + \Omega^+) / (2N(\phi)) \), as a function of \( p_T \) from Au+Au collisions for various beam energies from \( \sqrt{s_{NN}} = 7.7 \) to 200 GeV in Figure 5 and for various collision centralities in Figure 6, respectively. Data from 200 GeV Au+Au collisions are from previously published STAR results [12]. Coalescence or recombination models [17–19] have been used to describe particle productions in nucleus-nucleus collisions at RHIC. In particular, a model calculation by Hwa and Yang for Au+Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) [17] predicted that most of the \( \Omega \) and \( \phi \) yields up to the intermediate \( p_T \) region are from coalescence/recombination of thermal strange quarks. The straight dotted line assumed that these thermal strange quarks have exponential \( p_T \) distributions. Deviations from the straight line at high \( p_T \) were attributed to recombination with strange quarks from high \( p_T \) showers. Deviations from the theory calculation at low \( p_T \) could indicate that thermal strange quarks may not have an exponential distribution. Possibly, other particle production dynamics may also contribute deviations from coalescence model calculations.

In Figure 5 the measured \( N(\Omega^- + \Omega^+) / (2N(\phi)) \) ratios from central Au+Au collisions at \( \sqrt{s_{NN}} = 19.6, 27 \) and 39 GeV follow closely the ratio from 200 GeV and are consistent with a picture of coalescence/recombination dynamics over a broad \( p_T \) range of 1–4 GeV/c. The ratios at 11.5 GeV seem to deviate from the trend observed at higher beam energies. In particular, the ratios at 11.5 GeV appear to turn down around \( p_T \) of 2 GeV/c while those at higher beam energies such as 39 and 200 GeV peak at \( p_T \) of 3 GeV/c or above. The collision centrality dependence of the \( N(\Omega^- + \Omega^+) / (2N(\phi)) \) ratios in Figure 6(a)-(d) shows significant differences between the 40% – 60% centrality bin and the other centrality bins for Au+Au collisions at 19.6 and 27 GeV. Furthermore, the ratios from the peripheral collisions of 40% – 60% at 27 GeV are similar in magnitude to the ratios from collisions at 11.5 GeV. Because the \( \Omega \) and \( \phi \) particles have small hadronic rescattering cross sections [45], the change in these ratios is likely
Figure 6. Centrality dependence of $N(\Omega^- + \overline{\Omega}^+)/2N(\phi)$ ratios, as a function of $p_T$ in mid-rapidity ($|y| < 0.5$) from Au+Au collisions at $\sqrt{s_{NN}} = 11.5$, 19.6, 27 and 39 GeV. The boxes denote systematical errors.

to originate from the partonic phase. The decrease in the $N(\Omega^- + \overline{\Omega}^+)/2N(\phi)$ ratios from central collisions at 11.5 GeV compared to those at 19.6 GeV or above may indicate a significant change in the hadron formation dynamics and/or in strange quark $p_T$ distributions at the lower energy. Such a change may arise from a transition from hadronic to partonic dynamics with increasing beam energy. The turn-over in the ratios from Au+Au collisions below 11.5 GeV beam energy is unlikely due to contributions of high $p_T$ shower partons as suggested by model calculation from Hwa and Yang [17] because of relatively low $p_T$ particles involved.

3. Summary
In summary, we have presented the recent STAR results on the production of strange hadrons ($K_S^0$, $\phi$, $\Lambda$, $\Xi$ and $\Omega$) in $\sqrt{s_{NN}} = 7.7 – 39$ GeV Au+Au collisions in the RHIC beam energy scan program. The comparisons between $\Lambda$ yields and $\overline{\Lambda}$ yields suggest that baryon transport and anti-baryon absorption processes are important in relatively low beam energies. There is a clear $\phi$, $\Xi$, $\overline{\Xi}$ yield enhancement compared to pions with increasing collision energy. Strange hadron $R_{CP}$ increases with decreasing beam energies, indicating that the partonic energy loss effect becomes less important at low beam energies. At intermediate $p_T$, particle $R_{CP}$ difference becomes smaller at $\sqrt{s_{NN}} = 7.7$ and 11.5 GeV. The intermediate-$p_T$ $\Lambda/K_S^0$ ratios between 19.6 and 14.5 GeV show a sudden decrease. The $N(\Omega^- + \overline{\Omega}^+)/2N(\phi)$ ratios at intermediate $p_T$ in peripheral collisions are found to be lower than those in central collisions at 19.6, 27 and 39 GeV. The ratios from 11.5 GeV central collisions are systematically lower than those from collisions at 19.6 GeV or above for $p_T > 2.4$ GeV/c. These features suggest that there is likely a change in the underlying strange quark dynamics in the bulk QCD matter responsible for strange hadron production with the decreasing beam energy. Our measurements point to collision energies below 19.6 GeV for further investigation of a possible transition from partonic dominant matter
($\sqrt{s_{NN}} > 19.6$ GeV) to hadronic dominant matter ($\sqrt{s_{NN}} < 11.5$ GeV).

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