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Strangeness production in STAR beam energy scan

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We report the STAR measurements of strange hadrons (K^0_S, Λ, Ξ, Ω and ϕ) production at mid-rapidity in Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7 – 39 GeV from the RHIC beam energy scan (BES) program. The collision energy dependence of strange baryon yields are presented. The strange anti-baryon to baryon ratios ($\overline{\Lambda}/\Lambda$, $\overline{\Xi}^+/\Xi^-$, $\overline{\Omega}^+/\Omega^-$) are used to test the statistical thermal model and then extract the strangeness chemical freeze-out parameters (μ_B/T and μ_S/T). The nuclear modification factors and baryon to meson ratios ($\overline{\Lambda}/K^0_S$ and Ω/ϕ) are presented. The physics implications for collision dynamics are discussed.

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1. Introduction

Study of QCD phase diagram is the main motivation of the RHIC beam energy scan program [1]. Systematic study of Au+Au collisions from $\sqrt{s_{NN}}$ = 39 GeV down to 7.7 GeV in the RHIC BES program may help to achieve the following goals: 1) searching for the QCD critical point where the first order phase transition at finite μ_B ends and identifying the phase boundary of the first order phase transition; 2) locating the particular collision energy where the deconfinement starts to happen, i.e. the onset of deconfinement.

Strange hadrons are excellent probes for identifying the phase boundary and onset of deconfinement. Strangeness enhancement in A+A with respect to p+p collisions has long been suggested as a signature of Quark-Gluon Plasma (QGP) formation in these collisions [2]. Until now, strangeness has been extensively measured in many experiments at different accelerator facilities [3–19]. Generally, the yields of strange hadrons in nuclear collisions are close to those expected from statistical models [20–23]. The precise measurement of strange hadron yields in heavy ion collisions in BES will certainly lead to a better understanding of strangeness production mechanism in nuclear collisions and a more reliable extraction of the chemical freeze-out parameters.

On the other hand, it has been observed at RHIC that, at high p_T, the nuclear modification factor R_{CP} of various particles is much less than unity for Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV [24], indicating the significant energy loss of the scattered partons in the dense matter (“jet quenching"). By measuring the R_{CP} of strange hadrons in BES, one can potentially pin down the beam energy at which interactions with the medium begin to affect hard partons [1]. At intermediate p_T, it was found at RHIC that, the p/π and Λ/K^0_S ratios are larger than unity in more central events. These ratios are much higher than that observed in elementary collisions [24–26]. These phenomena hint toward different hadronization mechanisms in this p_T range. There are recombination/coalescence models which allow soft partons to coalesce into hadrons, or soft and hard partons to recombine into hadrons [27]. They naturally reproduce enhanced baryon to meson ratios when the parton p_T distribution is exponential. Such models require constituent quarks to coalesce or recombine, and hence the observation of coalescence or recombination behavior is one of the corner-stone pieces of evidence for the formation of the strongly interacting Quark-Gluon Plasma. It is also interesting to investigate at which collision energies these phenomena are prevalent [1], in order to locate the energy point at which the onset of the deconfinement happens.

We present the strangeness data obtained from the Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7, 11.5, 19.6, 27 and 39 GeV, collected by the STAR experiment during the first phase of the RHIC beam energy scan program in 2010 and 2011.

2. Results

Figure 1 shows the collision energy dependence of the particle yield (dN/dy) at mid-rapidity for K^0_S, Λ, $\overline{\Lambda}$, Ξ^- and $\overline{\Xi}^+$ from the most central (0-5%) Au+Au collisions, compared to corresponding data from NA49, NA57 and CERES, as well as the STAR data at higher energies. The NA57 and NA49 data are from the most central Pb+Pb collisions, and their data have been re-scaled according to the estimated numbers of wounded nucleons, $\langle N_W \rangle$. The scale factor is $N_{part}/\langle N_W \rangle$, where N_{part} is the number of participants in the most central (0-5%) Au+Au collisions in STAR.

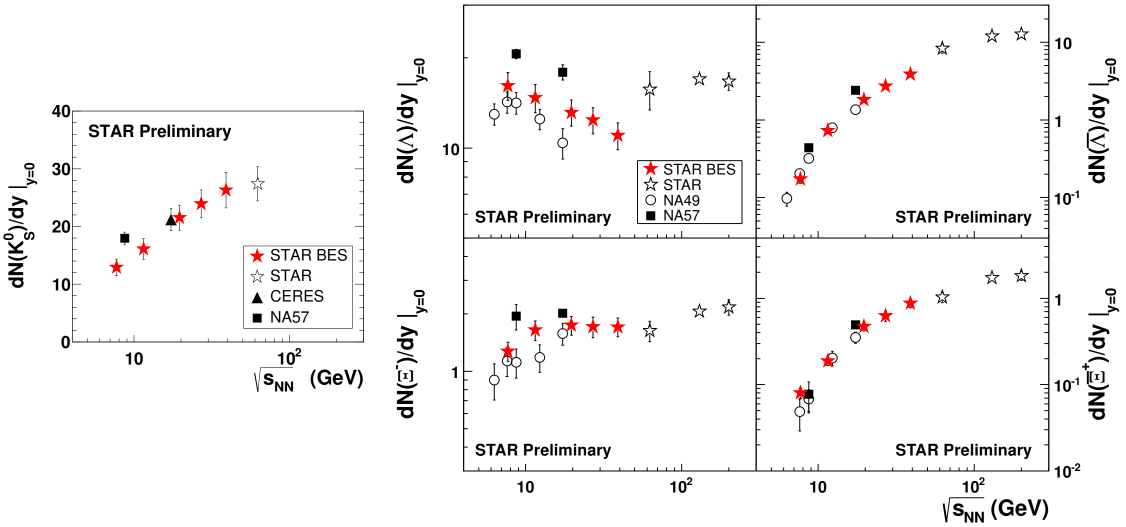

Figure 1: Collision energy dependence of strange hadron yields at mid-rapidity in most central (0-5%) Au+Au collisions. $\Lambda(\overline{\Lambda})$ yields are corrected for weak decay feed-down. Errors are the quadratic sum of statistical and systematic errors. Also shown are the results from most central heavy ion collisions at STAR [13, 15–17, 28], NA57 [8], NA49 [9, 29], and Pb+Au collisions from CERES [11]. The rapidity ranges are $|y| < 0.5$ for STAR and NA57, $|y| < 0.4$ for NA49 $\Lambda(\overline{\Lambda})$ and $|y| < 0.5$ for NA49 $\Xi^-(\overline{\Xi}^+)$. CERES data are the extrapolated values based on the measurements at backward rapidity.

A Monte Carlo Glauber model [30] estimation gives $N_{part} = 337.4 \pm 2.3$, 338.4 ± 2.1, 338.0 ± 2.3, 343.3 ± 2.0 and 341.8 ± 2.3 at $\sqrt{s_{NN}} = 7.7$, 11.5, 19.6, 27 and 39 GeV. For simplicity, a N_{part} value of 338 is used in the scale factor. Figure 1 shows that STAR BES data lie on a trend established by the corresponding data from NA49, NA57, CERES and previous STAR data. There seems to be a non-monotonic $\sqrt{s_{NN}}$ dependence in the Λ dN/dy, which may originate from the interplay of slow rise of Λ total multiplicity and the change of shape in rapidity distribution in the same energy range [9].

Figure 2 shows the anti-baryon to baryon ratios ($\overline{B}/B$) from STAR BES and comparisons to STAR higher energies and NA49 data. It seems that STAR BES data and NA49 data are consistent and in the published energy dependence trend. For all energies, the data show $\overline{\Omega}^+/\Omega^- > \overline{\Xi}^+/\Xi^- > \overline{\Lambda}/\Lambda$, which are consistent with the predictions from the statistical thermal models [20, 22, 23].

In statistical thermal models, particle yields are related to its invariant mass, degeneracy factor, chemical potential (μ) of each particle type, strangeness saturation factor (γ_s), and chemical freeze-out temperature (T) [31]. When we take the anti-baryon to baryon ratios, the parameters are canceled except the μ_B/T and μ_S/T: $\ln(ratio) = -2\mu_B/T + \mu_S/T \cdot \Delta S$, where μ_B is the baryon chemical potential, and μ_S is the strangeness chemical potential. The ΔS in the formula is the strangeness-number difference between anti-baryon and baryon. The above formula for a certain particle type is a straight line constrained by the parameters μ_B/T and μ_S/T. The μ_B/T and μ_S/T are the properties of the collision system, independent of the particle type. When we draw the $\ln(ratio)$ of $\overline{\Lambda}/\Lambda$, $\overline{\Xi}^+/\Xi^-$, and $\overline{\Omega}^+/\Omega^-$ in one plot, with μ_B/T on the x-axis and μ_S/T on the y-axis, the three lines should cross at one point, if the statistical thermal model assumptions are valid [32]. With this method, we can test the statistical thermal model. The 39 GeV results are

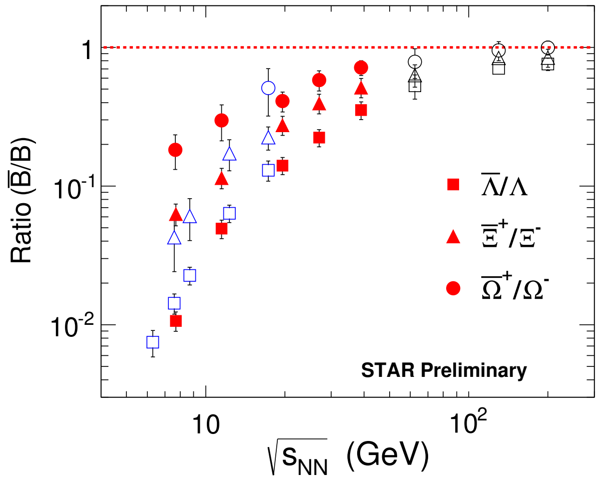

Figure 2: The $\sqrt{s_{NN}}$ dependence of $\overline{\Lambda}/\Lambda$, $\overline{\Xi}^+/\Xi^-$, and $\overline{\Omega}^+/\Omega^-$ ratios at mid-rapidity in the most central Au+Au collisions from STAR and Pb+Pb collisions from NA49. Solid symbols are STAR BES data; open symbols are STAR data at higher energies (>62 GeV) [13, 15–17, 28], and NA49 data [9, 29] at SPS energy range.

shown in Fig. 3 (left), and the statistical thermal model seems to describe our measurements well also for other energies. For each collision energy, we fit the ln($ratio$) as a function of ΔS with a straight line to determine the μ_B/T and μ_S/T (see Fig. 3 (right) for the fitting at 39 GeV). The μ_B/T and μ_S/T from 7.7 to 39 GeV are shown in Fig. 4, and the μ_B/T values fall on the curve of parameterization with μ_B and T from thermal model fitting of AGS, SPS, and RHIC 130 GeV central collision data [33]. Recently, the 39 GeV μ_B/T and μ_S/T data was compared with lattice QCD calculation, and it was found that the strangeness freeze-out temperature $T = 155 \pm 5$ MeV [34, 35] in the most central 39 GeV Au+Au collisions.

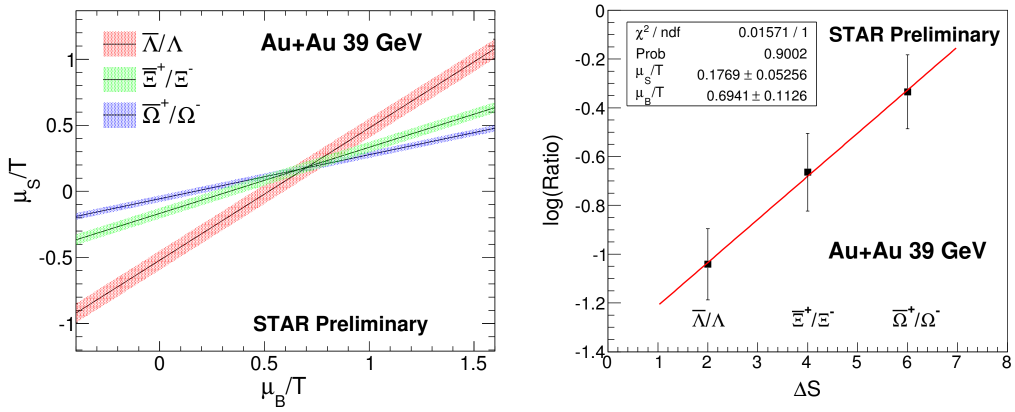

Figure 3: (left) Testing of statistical thermal model in μ_B/T and μ_S/T parameter space with strange anti-baryon to baryon ratios in Au+Au 39 GeV central collisions. (right) Fitting ln($ratio$) vs ΔS with a straight line to determine μ_B/T and μ_S/T in Au+Au 39 GeV central collisions.

Figure 5 (left) shows the R_{CP} of K^0_S, Λ, Ξ and Ω at mid-rapidity from STAR BES. At $\sqrt{s_{NN}}$ $\geq$ 19.6 GeV, the K^0_S $R_{CP} \leq 1$ for $p_T > 1.5$ GeV/c and much less than those of baryons. This

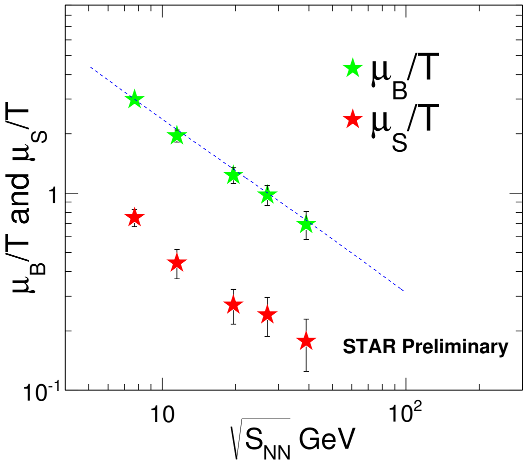

Figure 4: The $\sqrt{s_{\rm NN}}$ dependence of the μ_B/T and μ_S/T parameters in central Au+Au collisions. The curve is the parameterization with μ_B and T from the thermal model fitting of AGS, SPS, and RHIC 130 GeV data [33].

K^0_S high-p_T suppression and baryon/meson separation is qualitatively consistent with results from higher RHIC energies [24]. However, for $\sqrt{s_{\rm NN}} \leq 11.5$ GeV, although the maximum accessible p_T is smaller at these two energies, the R_{CP} data seem qualitatively different from that at $\sqrt{s_{\rm NN}} \geq$ 19.6 GeV: there is no suppression for K^0_S at $p_T > 1.5$ GeV/c; and the baryon/meson separation becomes less significant at intermediate p_T. Figure 5 (right) shows the $\overline{\Lambda}/K^0_S$ ratios as a function of p_T in different centralities from Au+Au collisions in STAR BES. At $\sqrt{s_{\rm NN}} \geq 19.6$ GeV, the $\overline{\Lambda}/K^0_S$ can reach a maximum value towards unity at $p_T \sim 2.5$ GeV/c in the most central collisions, while in the peripheral collisions, the maximum value is only about 0.3 – 0.5. This shows that there is baryon enhancement at intermediate p_T for $\sqrt{s_{\rm NN}} \geq 19.6$ GeV, which is similar to that observed at higher energies. However, for Au+Au collisions at $\sqrt{s_{\rm NN}} \leq 11.5$ GeV, the maximum values of $\overline{\Lambda}/K^0_S$ in the measured p_T range is much smaller than unity, and the difference between 0-5% and 40-60% is also less significant. This indicates much less baryon to meson enhancement at intermediate p_T in Au+Au collisions at $\sqrt{s_{\rm NN}} \leq 11.5$ GeV.

Figure 6 shows the baryon-to-meson ratio, $N(\Omega^-{+}\Omega^+)/2N(\phi)$, as a function of p_T in Au+Au central collisions at $\sqrt{s_{\rm NN}}$ = 11.5 – 200 GeV. The 200 GeV data are from previous STAR measurements [36]. In central Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV, the intermediate-p_T (2 – 4 GeV/c) Ω/ϕ ratio is explained by mainly thermal strange quark recombination in the deconfined matter [37]. The $N(\Omega^-{+}\Omega^+)/2N(\phi)$ ratios in $\sqrt{s_{\rm NN}}$ = 19.6, 27, and 39 GeV are close to that in 200 GeV. However, the ratios at 11.5 GeV seem to deviate from the trend with a χ^2/ndf of 8.3/2 for $p_T >$ 2.4 GeV/c. The difference in the ratios between 11.5 GeV data and those above 19.6 GeV may indicate a significant change in the underlying p_T distributions for strange quarks which recombine/coalesce to form the final Ω and ϕ particles in our measurement, and might suggest that there is no substantial deconfined phase in 11.5 GeV collisions.

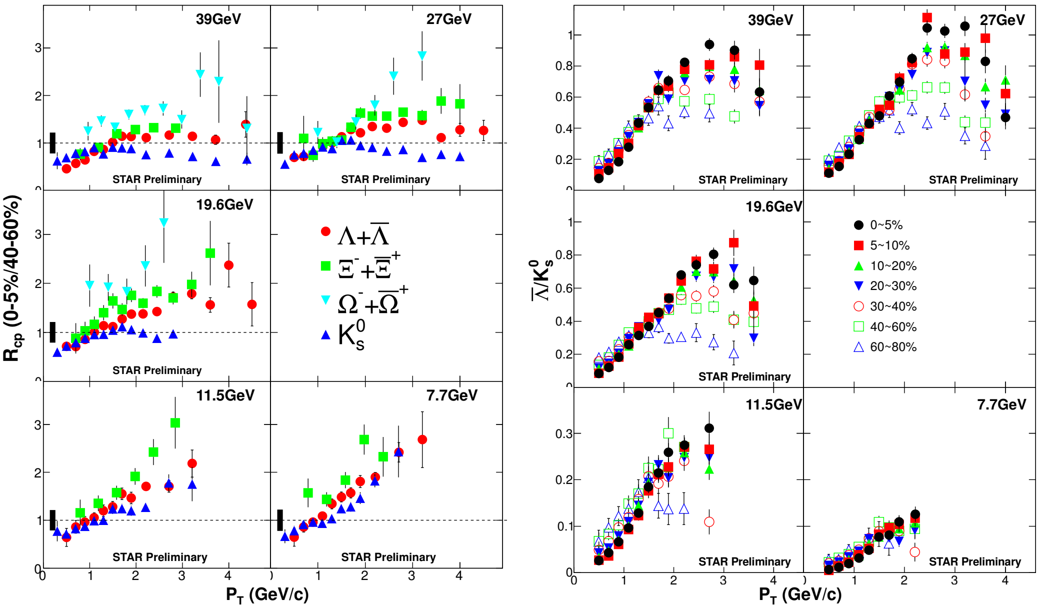

Figure 5: (left) K^0_S, Λ, Ξ and Ω R_{CP}(0-5%)/(40-60%) at mid-rapidity ($|y| < 0.5$) in Au+Au collisions at $\sqrt{s_{NN}} = 39 - 7.7$ GeV. Errors are statistical. The left black band is the normalization error from N_{bin}. (right) $\overline{\Lambda}/K^0_S$ ratio as a function of p_T at mid-rapidity ($|y| < 0.5$) in different centralities from Au+Au collisions at $\sqrt{s_{NN}} = 39 - 7.7$ GeV. Errors are statistical.

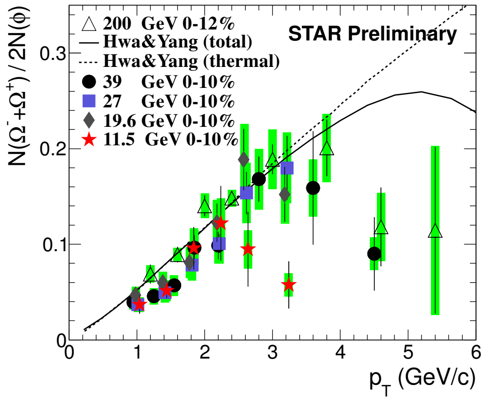

Figure 6: The baryon-to-meson ratio, $N(\Omega^-+\Omega^+)/2N(\phi)$ as a function of p_T at mid-rapidity ($|y| < 0.5$) from central Au+Au collisions at $\sqrt{s_{NN}} = 11.5 - 200$ GeV. Green bands denote systematical errors. The solid and dashed lines represent recombination model calculations for central collisions at $\sqrt{s_{NN}} = 200$ GeV [37] with total and thermal strange quark contributions, respectively.

3. Summary

We presented recent STAR measurements on strange hadron productions in the first phase of RHIC beam energy scan program. The strange hadron yields from STAR BES seem to follow a trend with published data from RHIC and SPS. The statistical thermal model has been tested with the measured anti-baryon to baryon ratios, and strangeness chemical freeze-out parameters μ_B/T and μ_S/T are extracted for most central collisions at each BES energy. For $\sqrt{s_{NN}} \leq 11.5$ GeV, we also observe: K^0_S R_{CP} are larger than unity for $p_T > 1.5$ GeV/c; $\overline{\Lambda}/K^0_S$ ratio in the most central collisions is much less than unity at intermediate p_{T} and the difference between central and peripheral collisions gets reduced; Ω/ϕ ratio seems to reach the maximum value at much lower p_{T}. These measurements point to a beam energy region between 11.5 and 19.6 GeV as a favored range for further investigation of the deconfinement phase transition.

Acknowledgments

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