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We present the scaling properties of $\Lambda$, $\Xi$, $\Omega$ and their anti-particles produced at mid-rapidity in $Au + Au$ collisions at RHIC at $\sqrt{s_{NN}} = 200$ GeV. The yield of multi-strange baryons per participant nucleon increases from peripheral to central collisions more rapidly than the $\Lambda$ yield, which appears to correspond to an increasing strange quark density of matter produced. The value of the strange phase space occupancy factor $\gamma_s$, obtained from a thermal model fit to the data, approaches unity for the most central collisions. We also show that the nuclear modification factors, $R_{CP}$, of $\Lambda$ and $\Xi$ are consistent with each other and with that of protons in the transverse momentum range $2.0 < p_T < 5.0$ GeV/c. This scaling behaviour is consistent with a scenario of hadron formation from constituent quark degrees of freedom through quark recombination or coalescence.
Lattice Quantum ChromoDynamics calculations predict that a new state of matter, the Quark Gluon Plasma (QGP), can be formed at zero baryon density in nuclear collisions when the temperature exceeds 160 – 170 MeV \([1]\). Strange quarks, whose mass is comparable to the critical temperature, are expected to be abundantly produced by thermal parton interactions in the high temperature QGP phase. Due to the corresponding increase in the strange quark density, hyperon production is expected to be enhanced in high energy nuclear collisions, the enhancement increasing with the number of strange valence quarks in the hyperon \(\Xi\). Such an effect has already been observed in various fixed-target experiments at lower energy by comparing the number of hyperons previously observed in various fixed-target experiments to the enhancement increasing with the number of strange valence quarks in the hyperon \(\Xi\). Such an effect has already been observed in various fixed-target experiments.

In this letter, we study the centrality dependence of hyperon production in \(\text{Au} + \text{Au}\) collisions \([3, 4, 5]\). In this framework, the amount of strangeness produced in each collision in the pseudo-rapidity range \(|\eta| < 1.8\) was measured in rapidity intervals of \(|\eta| < 0.5, 0.75, 1, 0.75, 2\). The detector operates within a solenoidal magnetic field of 0.5 Tesla whose axis is aligned with the beam. A central trigger barrel, covering the pseudo-rapidity region \(|\eta| < 1\), and two zero-degree calorimeters are used to trigger detectors. A total of \(1.6 \times 10^6\) minimum-bias trigger collisions and \(1.5 \times 10^6\) central trigger collisions were used for this analysis. A detailed description of the analysis including particle reconstruction, track quality, decay vertex topology cuts and calculation of the detection efficiency can be found elsewhere \([21, 22, 23]\). In this study \(\Lambda(\bar{\Lambda}), \Xi^- (\bar{\Xi}^+)\) and \(\Omega^- (\Omega^+)\) have been measured in rapidity intervals of \(|y| < 1, 0.75, 0.75\), respectively. In order to increase statistics, the results for \(\Omega^-\) and \(\Omega^+\) have been combined. Within the chosen rapidity intervals the particle reconstruction efficiency is a function of transverse momentum and lifetime. The efficiency calculations were based on the probability of finding Monte Carlo generated particles after processing them through a TPC detector response simulation, embedding them into real events and then reconstructing them as real data. The collision centrality was defined by the charged particle multiplicity measured in the TPC in the pseudo-rapidity range \(|\eta| < 0.5\). Five centrality bins were selected corresponding to the following ranges in the total hadronic cross section \((0 – 5\%, 10 – 20\%, 20 – 40\%, 40 – 60\%, 60 – 80\%)\). The \(0 – 5\%\) bin represents the most central collisions and was obtained from the central trigger sample. The remaining bins were obtained from the minimum-bias sample. Due to relatively poor statistics, the 5-10\% bin and the \(\Omega\) \(10-20\%\) and \(60-80\%\) bins were omitted from this analysis.

Figure 1 shows the transverse momentum distributions of \(\Lambda(\bar{\Lambda}), \Xi^- (\bar{\Xi}^+)\) and \(\Omega^- (\Omega^+)\) measured at mid-rapidity and as function of centrality. The errors shown on the data points are statistical only. The \(\Lambda\) spectra were corrected for feed-down from multi-strange baryon weak decays, based upon the measured \(\Xi\) and \(\Omega\) spectra. The feed-down correction depends sensitively on both exper-
The systematic error on the reconstructed yields was studied as a function of $p_T$. Three main factors contribute to the systematic error: (i) subtle differences between the Monte Carlo simulation and real data, which make the reconstructed yields sensitive to the choice of geometric cuts used to improve the signal to background ratio, (ii) sensitivity to the method used to subtract the remaining background after geometric cuts have been applied, and (iii) measured differences in the yield dependent on the direction of the applied magnetic field. At low $p_T$, the dominant contribution to the systematic error is due to the choice of cuts. Here, the systematic error was estimated by varying the cuts about the optimal values and observing the change in the reconstructed yield. At high $p_T$, the systematic error is dominated by the differences observed in the reconstructed yield for the two magnetic field settings. In order to determine the systematic uncertainty on the total yield and the inverse slope parameter for each particle and centrality class, $p_T$ dependent systematic errors were added to the data points shown in figure 1 and included in a second fit. The systematic errors shown in Table I reflect the difference between the two fits. We also investigated the choice of function used to fit the data. Although the Boltzmann function gave a better fit, an exponential function could not be excluded. Exponential fits to the data gave a 5-6% higher yield on average and a larger inverse slope parameter by 40-50 MeV. These differences are not included in the errors shown in Table I.

Figure 2(a) presents the strange anti-particle yields, $dN/dy$, divided by $N_{part}$, normalized to the most peripheral centrality interval (60 – 80%), plotted as a function of $N_{part}$. The gray, black and dashed bands represent the errors on the normalization to the most peripheral bin for the $\Xi^+$, $\Lambda$ and $\bar{p}$. Other errors shown are statistical only. (b) $\gamma_s$ as a function of $N_{part}$ calculated from thermal model fits to the measured particle yields ($\pi,K,p$ $\Lambda,\Xi,\Omega$ and their anti-particles) at 200 GeV. Values for $e^- + e^-$ and $p + \bar{p}$ collisions at $\sqrt{s_{NN}} = 91$ and 200 GeV respectively and for Pb+Pb SPS collisions at $\sqrt{s_{NN}} = 17.2$ GeV are shown for comparison.

### Table I

| Centrality | $\gamma_s$ |
|------------|------------|
| 0-5%       | 0.8        |
| 10-20%     | 0.6        |
| 20-40%     | 0.8        |
| 40-60%     | 1.0        |
| 60-80%     | 1.2        |

Figure 2(b) presents the integrated yield $dN/dy$ at mid-rapidity for $\Xi^+$, $\Lambda$ and $\bar{p}$ divided by $N_{part}$, normalized to the most peripheral centrality interval (60 – 80%), plotted as a function of $N_{part}$. The data are presented in Table I. The contribution to the $\Lambda$ spectrum from $\Xi^+$ and $\Omega$ decays is at the 15% level. The feed-down contribution to the $\Xi^+$ yield is due to the choice of cuts. Here, the systematic error is dominated by the differences observed in the reconstructed yield for the two magnetic field settings. In order to determine the systematic uncertainty on the total yield and the inverse slope parameter for each particle and centrality class, $p_T$ dependent systematic errors were added to the data points shown in figure 1 and included in a second fit. The systematic errors shown in Table I reflect the difference between the two fits. We also investigated the choice of function used to fit the data. Although the Boltzmann function gave a better fit, an exponential function could not be excluded. Exponential fits to the data gave a 5-6% higher yield on average and a larger inverse slope parameter by 40-50 MeV. These differences are not included in the errors shown in Table I.

Figure 1: Transverse momentum distributions of (a) $\Lambda$($\bar{\Lambda}$) for $|y| < 1.0$, (b) $\Xi^-$ ($\Xi^+$) for $|y| < 0.75$ and (c) $\Omega^- + \Omega^+$ for $|y| < 0.75$ in $Au+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV as a function of centrality. The $\Lambda$ spectra were corrected for weak decay of $\Xi$, $\Xi^0$ and $\Omega$. Scale factors were applied to the spectra for clarity. Only statistical errors are shown. The dashed curves show a Boltzmann fit to the $\Lambda$, $\Xi^-$ and $\Omega^-$+$\Omega^+$ data, the fits to the $\bar{\Lambda}$ and $\Xi^+$ are omitted for clarity.

FIG. 2: (a) The corrected integrated yield $dN/dy$ at mid-rapidity for $\Xi^+$, $\Lambda$ and $\bar{p}$ divided by $N_{part}$, calculated from thermal model fits to the measured particle yields ($\pi,K,p$ $\Lambda,\Xi,\Omega$ and their anti-particles) at 200 GeV. Values for $e^- + e^-$ and $p + \bar{p}$ collisions at $\sqrt{s_{NN}} = 91$ and 200 GeV respectively and for Pb+Pb SPS collisions at $\sqrt{s_{NN}} = 17.2$ GeV are shown for comparison.
hierarchy of particle production dependent upon strange quark content, which has also been observed at lower energies [2, 4]. This may reflect an increase in the strange quark density in more central collisions.

Thermal-statistical models have been very successful in describing particle yields in various systems at different energies [4, 6]. Within such models, the densities of strange particles, including strange resonances, are governed by statistical laws. The possible non-equilibrium of strange quarks is taken into account by introducing a phase space occupancy factor, $\gamma_s$. With the measured yields of strange baryons and other hadrons, such as pions, kaons, protons and their anti-particles [24], we have performed a fit using the statistical model described in [25] to determine $\gamma_s$ as a function of the number of participants, as shown in figure 2(b). We find that the value of $\gamma_s$ increases from about 0.8 in peripheral collisions to about 1.0 in central collisions. In each case we obtained a freeze-out temperature around 165 MeV. According to the model, the $\Lambda$ yield depends linearly on $\gamma_s$ while the yield of $\Xi$ depends on $\gamma_s^2$. This is consistent with behavior observed in figure 2(a).

The fact that $\gamma_s$ approaches unity when $<N_{part}> > 150$ suggests that the strange quark abundance tends to equilibrate as the system-size increases. A recent analysis of hadron yields in nucleus-nucleus collisions at $\sqrt{s_{NN}} = 17.2$ GeV, using a different thermal model, also found that $\gamma_s$ approaches unity at mid-rapidity in central collisions [26], whereas statistical analyses of elementary $e^+e^-$ and $p+p$ collisions at various energies yield a value of $\gamma_s$ significantly less than unity [21, 22].

We studied the effect of including different combinations of particles in the fit and found that particle ratios involving protons and $\Lambda$ are important in constraining the freeze-out temperature and $\gamma_s$, respectively. The value and centrality dependence of $\gamma_s$ is relatively insensitive to the inclusion of other particle ratios in the fit. The errors shown in figure 2(b) reflect the variation of $\gamma_s$ found in this study.

In order to investigate the scaling behaviour of hyperon production in the intermediate transverse momentum region, figure 3 shows the nuclear modification factor ($R_{CP}$) [14] for $\Xi^- + \Xi^+$ and $\Omega + \Omega^-$. The nuclear modification factor was found by forming the ratio of the $p_T$ spectra of the $0-5\%$ and $40-60\%$ centrality bins, after normalising each spectrum to the average number of binary collisions, appropriate for each centrality range, obtained from a Monte Carlo Glauber calculation [10, 11]. The $40-60\%$ centrality bin was chosen as the reference because of the limited statistics of $\Omega + \Omega^-$ in the

![Figure 3](image-url)

**FIG. 3:** $R_{CP}$ for $\Xi^- + \Xi^+$ and $\Omega^- + \Omega^+$ at mid-rapidity (centrality interval: $0-5\%$ vs. $40-60\%$). A dashed line for charged hadrons and gray band for $\Lambda + \bar{\Lambda}$ are shown as comparison. The gray rectangles represent participant and binary scalings.
60 – 80% bin. Also shown in figure 3 are the previously published results for charged hadrons and Λ + Λ for the same centrality bins [14]. The dark gray rectangular boxes on the plot represent the expected $R_{CP}$ range for $N_{part}$ and $N_{bin}$ scalings, indicating the range of uncertainty in calculating the number of participants and of binary collisions for each centrality. Although the $p_T$ integrated yield per participating nucleon of Ξ increases faster with $N_{part}$ than for Λ hyperons, in the interval $1.8 < p_T < 3.5$ GeV/c, the $p_T$ dependence of $R_{CP}$ for $Ξ^− + Ξ^+$ and $Ω^− + Ω^+$ are similar and coincide with the trend previously shown for $Λ + Λ$. The $R_{CP}$ of hyperons exhibits little suppression while mesons (approximated by the dashed line) have a distinctly different trend. The difference in $R_{CP}$ for baryons and mesons in the intermediate $p_T$ region has previously been discussed in the framework of recombination (or coalescence) models [12, 14, 16, 29]. The results presented here appear to confirm that the difference is dependent upon the number of constituent quarks and is not a mass effect. Further weight is given to this argument by a recent measurement of the nuclear modification factor of protons [13], $K(892)$ [31] and φ mesons [31]. The similarity between Λ and Ξ $R_{CP}$ at intermediate $p_T$ reinforces the notion of a baryon-meson difference. Furthermore, it suggests that the strange quark distribution scales with centrality in a similar way to up and down quarks, since baryons with different strangeness content seem to follow the same pattern. This observation is consistent with recent elliptic flow measurements of Λ, Ξ and Ω at intermediate $p_T$ [32].

In this letter, we have presented the scaling properties of strange baryon production in $Au + Au$ collisions at $√(s_{NN}) = 200$ GeV. By studying the hyperon yields scaled by $N_{part}$ and the centrality dependence of $γ_s$, within the framework of a thermal model, we have found that strangeness equilibrium appears to have been achieved in central collisions at RHIC. We have also investigated the centrality dependence of the transverse momentum distributions of hyperons. We find that hyperon yields in central collisions fall below the expectation for binary scaling for $p_T > 3$ GeV/c and that the nuclear modification factor $R_{CP}$ is similar for all hyperons independent of their mass or strangeness content. In addition we note that the $R_{CP}$ of hyperons is similar to that of protons, a feature that is consistent with models of hadron formation based upon quark recombination.

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