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Strangeness Enhancement in Cu-Cu and Au-Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

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We report new STAR measurements of midrapidity yields for the $\Lambda, \bar{\Lambda}, K^0, \Xi, \bar{\Xi}, \Omega, \bar{\Omega}$, particles in Cu + Cu collisions at $\sqrt{s_{NN}} = 200$ GeV, and midrapidity yields for the $\Lambda, \bar{\Lambda}, K^0$ particles in Au + Au collisions.
Relativistic heavy-ion collisions aim to create the QGP (quark-gluon plasma), a unique state of matter where quarks and gluons can move freely over large volumes in comparison to the typical size of a hadron. Measurements of strangeness enhancement in heavy-ion collisions were originally conceived to be a key signature of QGP formation [1]. It was argued that due to a drop in the strange quark’s dynamical mass, strangeness enhancement in the QGP would equilibrate on small time scales relative to those in a hadronic gas [2]. Assuming a thermally equilibrated QGP hadronizes into a maximum entropy state, a test for strange quark saturation in the early stages is provided by comparing final state hadron yields to thermal model predictions from the canonical formalism [3]. These predictions have qualitatively reproduced various aspects of the data from \( \text{Au} + \text{Au} \sqrt{s_{NN}} = 200 \text{ GeV} \) collisions at RHIC (Relativistic Heavy-Ion Collider); however, as with SPS (Super Proton Synchrotron) energies, a complete theoretical description has yet to be achieved [4]. We present midrapidity strange particle yields from \( \text{Cu} + \text{Cu} \) and \( \text{Au} + \text{Au} \sqrt{s_{NN}} = 200 \text{ GeV} \) collisions at the AGS (Alternating Gradient Synchrotron) showed \( K^+ \) and \( K^- \) yields to be higher in lighter systems compared to the respective values in heavy systems at a given number of participants [5]. Measurements at the SPS showed higher \( K/\pi \) ratios for the light systems also at a given number of participants [6]. Whether these trends continue up to RHIC energies, and what new information can be learned from strangeness enhancement as a QGP signature at RHIC, will be central issues in this Letter.

The new data presented are from approximately \( 20 \times 10^6 \text{ Au} + \text{Au} \sqrt{s_{NN}} = 200 \text{ GeV} \) and \( 40 \times 10^6 \text{ Cu} + \text{Cu} \sqrt{s_{NN}} = 200 \text{ GeV} \) collisions recorded at RHIC in 2004 and 2005, respectively. In order to extract the \( \Lambda, \bar{\Lambda}, \Sigma^0, \Xi^-, \bar{\Xi}^+, \Omega^-, \bar{\Omega}^+ \) yields as a function of transverse momentum, \( p_T \), STAR’s [7] time projection chamber (TPC) [8] is utilized to identify these particles via their dominant weak decay channels. The channels are \( \Lambda \rightarrow p + \pi^- \), \( \bar{\Lambda} \rightarrow \bar{p} + \pi^+ \), \( \Sigma^0 \rightarrow \pi^+ + \pi^- + \pi^- \), \( \Xi^- \rightarrow \Lambda + \pi^- \), \( \bar{\Xi}^+ \rightarrow \bar{\Lambda} + \pi^+ \), \( \Omega^- \rightarrow \Lambda + K^- \), and \( \bar{\Omega} \rightarrow \bar{\Lambda} + K^+ \). These particles usually decay before the TPC’s inner radius (50 cm), so the decay products enter the TPC. Daughter tracks are then reconstructed using STAR’s tracking software. The raw particle yields are then calculated from the respective invariant mass distributions formed by the daughter track candidates. A combination of topological, energy loss, and kinematic restrictions are placed to ensure the combinatorial background is minimal, while preserving the statistical significance of the signal. We fit the regions adjacent to the respective peaks with a second order polynomial, to determine the background beneath the respective peaks. This is then subtracted to obtain the signal. The signal to background ratio varies from 1 to 50, and depends on particle type, \( p_T \), and the average charged particle multiplicity. To calculate the reconstruction efficiency, Monte Carlo particles are generated, embedded in the real events, and propagated through a detector simulation. The \( \Lambda \) and \( \bar{\Lambda} \) yields have contributions from weak decays of charged and neutral \( \Xi \) and their antiparticles, which can be subtracted up to \( p_T \sim 5 \text{ GeV}/c \). This contribution is \( \sim 15\% \) and independent of \( p_T \). Feed-down contributions from \( \Omega \) hadrons are negligible. More detailed descriptions of the strange particle spectra extraction can be found elsewhere [9,10]. The systematic uncertainties are due to: (1) slight mismatches in the real and embedded particle distributions which leads to an uncertainty in the reconstruction efficiency (2\%–11\%), and (2) small variations in raw particle yields with respect to the magnetic field setting and day (\( \sim 2\% \)). Some of these uncertainties are common for \( \text{Cu} + \text{Cu} \) and \( \text{Au} + \text{Au} \) spectra. Finally, for each colliding system, data are partitioned in centrality bins, based on the charged hadron multiplicity in the pseudorapidity range \( |\eta| < 0.5 \).

Figure 1 shows the \( p_T \) spectra for the singly strange and multistrange particles. A Lévy function is used in this analysis to fit the spectra in order to extrapolate to the unmeasured region [11], so that the yield, \( dN/dy \), can be extracted (see Table I). Uncertainties resulting from the extrapolation procedure, based on the above fit function, are included in the systematic uncertainties. Fits to the spectra for a selection of centralities are shown in Fig. 2 on a linear scale. The \( \text{Au} + \text{Au} K^0 \bar{\Lambda} \) spectra were found to be consistent with published STAR \( K^{\pm} \) spectra [12]. We also found the \( \text{Au} + \text{Au} K^0 \bar{\Lambda} \) spectra to be consistent with PHENIX and BRAHMS \( K^{\pm} \) spectra, apart from the very peripheral PHENIX data [13–15].

The enhancement factor \( E \) is defined as \( dN/dy \) (yield) per mean number of nucleon participants \( \langle N_{\text{part}} \rangle \) in heavy-ion collisions, divided by the respective value in \( p + p \) collisions [10]. It characterizes the deviation in participant scaled yields relative to \( p + p \). Monte Carlo Glauber calculations are used to calculate \( \langle N_{\text{part}} \rangle \) for each centrality bin in heavy-ion collisions [13]. The top panels of Fig. 3 show the enhancement factor for singly (anti-) strange particles in \( \text{Cu} + \text{Cu} \) and \( \text{Au} + \text{Au} \) collisions as a function of \( \langle N_{\text{part}} \rangle \). In addition to the rising enhancements...
exhibited by all particles for both Cu + Cu and Au + Au collisions, at a given value of $\langle N_{\text{part}} \rangle$ above $\sim 60$, the production of strange hadrons is higher in Cu + Cu collisions than in Au + Au collisions. Similar patterns are observed for the multistrange particles in the bottom panels of Fig. 3. The Cu + Cu and Au + Au difference also applies to the nonstrange sector, as shown in Fig. 4.

Finally, as shown in Fig. 2, the higher yields per $\langle N_{\text{part}} \rangle$ in Cu + Cu apply across the measured $p_T$ range, $p_T > 0.5$ GeV is assumed in the canonical framework that the observed strangeness enhancement actually results from a suppression of strangeness production in $p + p$ collisions [3]. This suppression arises from the need to conserve

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{$K_0^0$, $\Lambda$, $\bar{\Lambda}$, $\Xi$, $\bar{\Xi}$, and $\Omega + \bar{\Omega}$ invariant mass spectra from Cu + Cu and Au + Au $\sqrt{s_{NN}} = 200$ GeV collisions, where $|y| < 0.5$. The $\Lambda$ and $\bar{\Lambda}$ yields have not been feed-down subtracted from weak decays. The uncertainties on the spectra points are statistical and systematic combined.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{$K_0^0$, $\Lambda + \bar{\Lambda}$, $\Xi + \bar{\Xi}$, and $\Omega + \bar{\Omega}$ spectra divided by $\langle N_{\text{part}} \rangle$ for Cu + Cu 0%–10% ($\langle N_{\text{part}} \rangle \sim 99$) and Au + Au 20%–40% ($\langle N_{\text{part}} \rangle \sim 141$) $\sqrt{s_{NN}} = 200$ GeV collisions, where $|y| < 0.5$. The Au + Au multistrange data have been previously published [25]. The $\Lambda$ and $\bar{\Lambda}$ yields have been feed-down subtracted from weak decays. The uncertainties on the spectra points are statistical and systematic; for clarity the uncertainty on $\langle N_{\text{part}} \rangle$ has not been included. The curves show the functions described in the text used to extract $dN/dy$.}
\end{figure}

TABLE I. Midrapidity $dN/dy$ for strange hadrons in Cu + Cu and Au + Au $\sqrt{s_{NN}} = 200$ GeV collisions. Combined statistical and systematic errors are shown.

| Cu + Cu | $\langle N_{\text{part}} \rangle$ |
|---------|-------------------------------|
| 0%–10%  | 10%–20%                      |
| 20%–30% | 30%–40%                      |
| 40%–60% | 50%–60%                      |

| Cu + Cu $K_0^0$ | $\bar{\Omega}$ |
|-----------------|----------------|
| 0%–10%          | 10%–20%        |
| 20%–30%         | 30%–40%        |
| 40%–60%         | 50%–60%        |

| Cu + Cu $\Lambda$ | $\bar{\Lambda}$ |
|-------------------|-----------------|
| 0%–5%             | 10%–20%         |
| 20%–30%           | 30%–40%         |
| 40%–60%           | 50%–60%         |

| Cu + Cu $\Lambda$ | $\bar{\Lambda}$ |
|-------------------|-----------------|
| 0%–10%            | 10%–20%         |
| 20%–30%           | 30%–40%         |
| 40%–60%           | 50%–60%         |
strangeness within a small, local volume, which limits strangeness production in p + p relative to A + A collisions. The correlation volume is a parameter in the canonical model which dictates the region to which strangeness conservation applies. Assuming the system’s correlation volume is proportional to $\langle N_{\text{part}} \rangle$, the canonical framework predicts yields per $\langle N_{\text{part}} \rangle$ which should rise with increasing $\langle N_{\text{part}} \rangle$ as phase space restrictions due to strangeness conservation are lifted. At the grand canonical limit where $\langle N_{\text{part}} \rangle \sim 100$, yields per $\langle N_{\text{part}} \rangle$ are constant as a function of $\langle N_{\text{part}} \rangle$. The extracted chemical freeze-out temperature ($T_{\text{ch}}$) and baryochemical potential ($\mu_B$) values for Cu + Cu and Au + Au which are explicitly used for the framework’s predictions, have been shown to be consistent and independent of system size [16]. Therefore, the higher yields in Cu + Cu and the rising Au + Au enhancements with $\langle N_{\text{part}} \rangle > 100$ in Fig. 3 appear inconsistent with the canonical framework as the sole description of strangeness enhancement. There are other canonical predictions which assume the correlation volume may scale with $\langle N_{\text{part}} \rangle^{1/3}$ or $\langle N_{\text{part}} \rangle^{2/3}$ and these give slower rises of $E$ as a function of $\langle N_{\text{part}} \rangle$ [17]. Although these match the Au + Au data better, they also predict the enhancement should just depend on $\langle N_{\text{part}} \rangle$ which is again inconsistent with the Cu + Cu and Au + Au data. If the canonical formalism is valid in describing strangeness enhancement, these failures may relate to the validity of the assumption that the correlation volume is proportional to $\langle N_{\text{part}} \rangle$.

The curves in Fig. 3 correspond to the following parametrization:

$$E_i(N_{\text{part}}) = B_i f(N_{\text{part}}) + 1$$  \hspace{1cm} (1)

which Becattini and Manninen (BM) propose as a core-corona description of strangeness production in heavy-ion collisions [18]. The variable $f$ is the fraction of participants that undergo multiple collisions obtained from the Glauber model, and $B_i$ is a particlewise normalization factor. In this case, it is chosen to fit the Cu + Cu and Au + Au data simultaneously and, therefore, independent of collision species. Participants that undergo multiple collisions produce a core that expands and freezes out to produce hadrons. The resulting strange hadron yields follow thermal expectations for the reasons stated in the introduction of this Letter, namely, that $s + \bar{s}$ equilibrate in the core’s QGP stage, then the core hadronizes to produce strange hadrons in chemical equilibrium. $B_i$ depends linearly on the particle density in the core. Participants with just one collision act like nucleons in $N + N$ collisions with respect to strangeness production.

FIG. 3. The enhancement factor for (multi-) strange particles in Cu + Cu and Au + Au $\sqrt{s_{NN}} = 200$ GeV collisions, where $|y| < 0.5$. The $\Lambda$ and $\bar{\Lambda}$ yields have been feed-down subtracted in all cases. The Au + Au multistrange data have been previously published [25]. The black bars show the normalization uncertainties, and the uncertainties for the heavy-ion points are the combined statistical and systematic errors. Curves described in the text, where $B_K = 2.0$, $B_\Lambda = 2.4$, $B_\Xi = 5.0$, and $B_\Omega = 12.1$.

FIG. 4. Ratio of particle yields in central Cu + Cu and mid-central Au + Au collisions when $\langle N_{\text{part}} \rangle = 99$ in each case for $|y| < 0.5$. $\pi$ yields are from elsewhere [16]. Boxed uncertainties are from the Glauber calculations and are correlated for every particle. $N_{\text{part}}$ refers to the parametrization shown by Eq. (1), while the EPOS and AMPT models are described in the text. The default settings are used for each model. The vertical lines show the remaining independent statistical and systematic uncertainties.
The parametrization describes the two main qualitative aspects of the data: the rising enhancements with \( \langle N_{\text{part}} \rangle \) in a given system over the full range of \( \langle N_{\text{part}} \rangle \), and a higher enhancement factor for central 
\( Cu + Cu \) collisions compared to 
\( Au + Au \) collisions with the same \( \langle N_{\text{part}} \rangle \). The higher \( E \) for 
\( Cu + Cu \) at a given \( \langle N_{\text{part}} \rangle \) simply results from 
\( f(\langle N_{\text{part}} \rangle) \) being higher for the lighter system. This in turn is 
due to the differing geometries of the respective collision zones; i.e., 
\( Cu + Cu \) is more spherical at a given \( \langle N_{\text{part}} \rangle \). Although not implicit 
in the Glauber model, differing nuclear shadowing in 
\( Cu + Cu \) compared to 
\( Au + Au \) could also lead to larger multiple interactions in 
\( Cu + Cu \) at a given \( \langle N_{\text{part}} \rangle \) [19]. \( f(\langle N_{\text{part}} \rangle) \) increases with centrality 
for a given system because the participant densities in the 
collision zone increase. Its important to note deviations 
from the curves are observed for the singly strange 
particless in central 
\( Au + Au \) and multistrange particles in peripheral 
\( Au + Au \) multistrange particles. Since for a given 
particle, since we adjust 
\( B_i \) in Eq. (1) to best fit the 
\( Cu + Cu \) and 
\( Au + Au \) enhancements simultaneously, this sometimes 
leads to a poorer description of the 
\( Au + Au \) enhancements in relation to what is shown by BM where the 
\( Au + Au \) data alone is fit [18]. As will be shown in Fig. 4, 
the relative differences in central 
\( Cu + Cu \) and midcentral 
\( Au + Au \) collisions at the same \( \langle N_{\text{part}} \rangle \) are also underpredicted 
by the curves in Fig. 3.

In Fig. 4 we show the ratio of 
\( Cu + Cu \) and 
\( Au + Au \) particle yields where 
\( \langle N_{\text{part}} \rangle = 99 \). Since the 
\( Au + Au \) yields lack a data point at this value we linearly interplate 
between \( \langle N_{\text{part}} \rangle = 67.5 \) and \( \langle N_{\text{part}} \rangle = 147 \). Taking into account 
the uncertainties, no significant dependence with 
respect to strangeness content is observed for the measured 
data. In addition to the relation in Eq. (1), we make 
comparisons to two other models, EPOS [20] and AMPT [21]. EPOS is also a core-corona model; however, the core-corona splitting is based on the initial energy density, 
rather than participants that undergo multiple collisions. 
Other core-corona descriptions have been investigated 
elsewhere [22]. The AMPT model is based on HIJING [23], and thus describes particle production in heavy-ion 
collisions via string excitation and breaking (soft), and 
mini-jet fragmentation (hard) where the excited nucleons 
fragment independently. The ratios in the data are better 
reproduced by EPOS than by AMPT or the parameterization 
in Eq. (1). However, neither EPOS nor AMPT are able to 
reproduce individual strange hadron yields in 
\( Au + Au \) and 
\( Cu + Cu \), as opposed to the ratios of yields between 
those systems. EPOS is slightly closer to the measured 
data [24].

In summary, we have presented the enhancement factors 
for midrapidity strange particles as a function of centrality 
for 
\( Cu + Cu \) and 
\( Au + Au \) \( \sqrt{s_{NN}} = 200 \) GeV collisions. We have found that the enhancement factors for central 
\( Cu + Cu \) collisions are higher than for midcentral 
\( Au + Au \) collisions with similar numbers of participants. We also

found that the qualitative trends for the enhancement 
factors can be described by a relation that assumes the 
enhancement factor is proportional to the fraction of participants that undergo multiple collisions. We thank Klaus Werner, Joerg Aichelin, Francesco Becattini, and Bin Zhang for discussions, the RHIC Operations Group and RCF at BNL, the NERSC Center at LBNL, and the Open Science Grid consortium for providing resources and support. This work was supported in part by the Offices of NP and HEP within the U.S. DOE Office of Science, the U.S. NSF, the Sloan Foundation, the DFG cluster of excellence “Origin and Structure of the Universe” of Germany, CNRS/IN2P3, STFC, and EPSRC of the U.K., FAPESP CNpq of Brazil, Ministry of Ed. and 
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