Midrapidity $\Lambda$ and $\bar{\Lambda}$ Production in Au + Au Collisions at $\sqrt{s_{NN}} = 130$ GeV


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Ultrarelativistic nucleus-nucleus collisions provide a unique means to create nuclear matter of high energy density (temperature) and/or baryon density over an extended volume [1]. The first results from the Relativistic Heavy Ion Collider (RHIC) have shown that the large charged particle multiplicity, measured in Au + Au collisions at $\sqrt{s_{NN}} = 130$ GeV, corresponds to an energy density significantly higher than that previously achieved in heavy ion collisions [2–4]. The yield of baryons and antibaryons produced in relativistic nuclear collisions is very important because it is sensitive to two fundamental, not yet fully understood aspects of hadron production dynamics: baryon/antibaryon pair production and the transport of baryon number from beam rapidity to midrapidity. The nature of baryon/antibaryon production itself is the subject of much interest, with theoretical conjecture addressing a range of possible mechanisms from string fragmentation [5] to exotic mechanisms involving quantum chromodynamics (QCD) domain walls [6]. The physical nature of the entity which carries the baryon number and the means by which the baryon number is transported over a large rapidity gap into the midrapidity region are also subjects of considerable experimental and theoretical interest [7–9].

Strange baryon/antibaryon production is particularly interesting due to the increased sensitivity to the availability of strange/antistrange quarks, which is expected to be suppressed relative to light quarks in hadronic matter due to the strange quark mass. Strangeness production has long been predicted to be a signature of quark gluon plasma formation [10]. The strangeness production in previous generations of heavy ion experiments has been observed to be significantly increased compared to those from $p + p$, $p + A$, and light ion collisions [11–14], although questions remain about the exact strangeness production mechanism. In particular, the relative importance of strange baryon production from hadronic rescattering differs between calculations [15,16], depending on both the evolution of the system and the scattering cross sections assumed. Exotic dynamical mechanisms that have been proposed for strange baryon production include, for example, color string ropes [17], string fusion [18], and multimesonic reactions [19]. All require a high local energy density and therefore suggest that strangeness production occurs early in the collision.

In this Letter we report on midrapidity ($|y| < 0.5$) lambda ($\Lambda$) and antilambda ($\bar{\Lambda}$) production in Au + Au collisions at}
collisions at $\sqrt{s_{NN}} = 130$ GeV. The data were taken with
the STAR (Solenoidal Tracker At RHIC) detector. The
main components of the detector system for this analysis
have been described in detail elsewhere [20]. They in-
cluded a large volume time-projection chamber (TPC)
[21], a pair of zero-degree calorimeters located at
$\pm 18$ meters from the center of the TPC, and a central
trigger barrel constructed of scintillator paddles surround-
ing the TPC.

Data from both the minimum-bias trigger and the central
target have been used for this analysis. Similar to a
previous analysis [4], the collision centrality was defined
offline using the total charged particle multiplicity within a
pseudorapidity window of $|\eta| < 0.5$. The charged particle
multiplicity distribution was divided into five centrality
bins, corresponding to approximately the most central
5%, 5%–10%, 10%–20%, 20%–35%, and 35%–75%
of the total hadronic inelastic cross section of Au + Au
collisions.

The $\Lambda$ and $\bar{\Lambda}$ particles were reconstructed from their
weak decay topology, $\Lambda \rightarrow p \pi^- \bar{\nu}$ and $\bar{\Lambda} \rightarrow \bar{p} \pi^+$, using charged tracks measured in the TPC [22]. Particle assign-
ments for $p (\bar{p})$ and $\pi^-$ $(\pi^+)$ candidates were based on
charge sign and the mean energy loss, $\langle dE/dx \rangle$, measured
for each track. Candidate tracks were then paired to form
neutral decay vertices, which were required to be at least
5 cm in distance from the primary vertex. The recon-
structed momentum vector at the decay vertex was re-
quired to point back by a straight line to the primary
vertex within 0.5 cm.

Figure 1 shows the invariant mass distributions for the
reconstructed $\Lambda$ and $\bar{\Lambda}$ candidates in $|y| < 0.5$ for two
typical $p_T$ bins from the data sample. The mass resolutions
($\sigma$) for reconstructed $\Lambda$ and $\bar{\Lambda}$ are typically about
3–4 MeV/c$^2$ based on a Gaussian fit to the peak. The
background beneath the $\Lambda(\bar{\Lambda})$ peak is dominated by com-
binatoric pairs of charged particles. Decays of $K^0 \rightarrow
\pi^+ \pi^-$ also contribute to the smooth background due to
pions misidentified as protons. The yield is obtained from
the invariant mass distribution in each transverse momen-
tum ($p_T$) and rapidity ($y$) bin, where the shape of the
background near the $\Lambda(\bar{\Lambda})$ peak is fit with a second order
polynomial function. Variations in the yield due to differ-
ent fits for the background have been included in the
estimate of systematic errors. The raw yield for each $p_T -
y$ bin was then corrected for finite detection efficiency,
which was calculated from simulated embedded simulated $\Lambda$ and
$\bar{\Lambda}$ particles in real collision events. Hadronic scatterings
and antiparticle annihilations are included in the simu-
atron. The combined acceptance and efficiency for $\Lambda$ and $\bar{\Lambda}$
ranges from 0.8% to 5.8% as a function of $p_T$ for the most
central collision sample.

The measured $\Lambda$ spectra contain contributions from
primordial $\Lambda$, $\Sigma^0$ decays, and feed-down from multiply
strange hyperons—notably $\Xi^0$ and $\Xi^-$. The primordial $\Lambda$
and the $\Sigma^0$ decay products cannot be separated in our
analysis and have been treated as primary $\Lambda$. We estimate
the contributions of feed-down from multiply strange hy-
perons, mostly $\Xi$ and $\Xi$ decays, to be approximately (27 ±
6)% of the measured $\Lambda$ and $\bar{\Lambda}$ yields, respectively. The
estimate was based on the fact that the distance of the
closest approach distribution of $\Lambda$ from $\Xi$ decays is differ-
ent from that of primary $\Lambda$ production, which we quantified
by extensive comparisons between simulations and real
data [22]. The spectra presented in this Letter include the
decay contribution.

Figure 2 presents the $m_T$ spectra (invariant distributions)
of $\Lambda$ and $\bar{\Lambda}$ for five selected centrality bins. Combined
systematic errors from various methods of yield extraction,
reconstruction efficiencies, and uncorrected sector by sec-
tor variations in the TPC performance are estimated to be
10%. Both exponential ($e^{-(m_T - m_0)/T}$) and Boltzmann
($m_T e^{-(m_T - m_0)/T}$) functions have been used to fit the data.
The slope parameter obtained from the exponential fit is
systematically higher than that for the Boltzmann by ap-
proximately 40–65 MeV. However, overall the integrated
yields from both fit functions are consistent within the
statistical errors. The slope parameters and the $dN/dy$
from these fits are presented in Table I. The Boltzmann
form was adopted in Fig. 2 because it typically provides a
better $\chi^2$ and gives a reasonable description of the $m_T$
spectra over the entire range of centrality and transverse
momenta investigated.

Within the systematic error, the slope parameters meas-
ured for the $\Lambda$ and $\bar{\Lambda}$ $m_T$ distributions are the same. There
is a systematic increase in the slope parameters from
approximately 254 MeV for the least central (35%–75%)
to 312 MeV for the most central (0%–5%) bin. Similar behavior as a function of centrality is found for the $\bar{p}$ transverse mass distributions [23]. Assuming the temperature at which particle interactions cease (the “freeze-out temperature” [24]) is constant independent of collision centrality, the increase in the slope parameter may be interpreted as an increase in the collective radial velocity [25,26].

A possible indication of hydrodynamic flow is the increase of the observed mean transverse momenta for various species with increasing particle mass. The transverse momentum distributions of negatively charged hadrons, as well as $\bar{p}$ and $\bar{\Lambda}$, are shown in Fig. 3. The $\bar{p}$ and $\bar{\Lambda}$ $p_T$ distributions are similar in shape in the region where they can be compared (below 1 GeV/c), even though the data sets cover somewhat different ranges in $p_T$. Both distributions are qualitatively different from and much less steep than the corresponding $h^-$ distribution, which is dominated by pions. Qualitatively similar behavior was observed in heavy ion collisions at the CERN Super Proton Synchrotron (SPS) [25–27]. As predicted, the slope parameters for all species are observed to be larger at RHIC [28]. The increase was also described by thermal model fits, e.g., [29].

Figure 3 indicates that at higher $p_T$ ($p_T > 1$ GeV/$c$) the ratio of $\bar{\Lambda}$ to negative hadrons increases rapidly. The baryon to meson ratio at RHIC for $p_T > 1$ GeV/$c$ exceeds expectations from perturbative QCD inspired string fragmentation models which were tuned to fit $e^+e^-$ collision

![Figure 2](image1.png)

**FIG. 2.** Transverse mass distributions of $\Lambda$ (left) and $\bar{\Lambda}$ (right) at midrapidity ($|y| < 0.5$) for selected centrality bins. The dashed lines are Boltzmann fits. Note that multiplicative factors have been applied to data from the two most central data sets for display.

![Figure 3](image2.png)

**FIG. 3.** The midrapidity $\bar{\Lambda}$ ($|y| < 0.5$) transverse momentum distribution from the top 5% most central collisions. For comparison the distributions for negative hadrons [d$^2N/(2\pi p_T)dp_Td\eta$, $|\eta| < 0.1$] and antiprotons ($|y| < 0.1$) for the similar centrality bin are included. Statistical errors are less than the size of the data points.

**TABLE I.** Fit parameters from Boltzmann and exponential fits of the $m_T$ spectra for $\Lambda$ and $\bar{\Lambda}$ at midrapidity ($|y|<0.5$). Only statistical errors are presented. The systematic errors on $dN/dy$ and $T$ are estimated to be 10%.

<table>
<thead>
<tr>
<th>Centrality</th>
<th>0%–5%</th>
<th>5%–10%</th>
<th>10%–20%</th>
<th>20%–35%</th>
<th>35%–75%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$dN/dy$</td>
<td>$\Lambda$</td>
<td>17.0 ± 0.4</td>
<td>13.0 ± 0.3</td>
<td>10.1 ± 0.2</td>
<td>5.9 ± 0.2</td>
</tr>
<tr>
<td>(Boltz)</td>
<td>$\bar{\Lambda}$</td>
<td>9.6 ± 0.3</td>
<td>7.4 ± 0.2</td>
<td>4.6 ± 0.1</td>
<td>1.26 ± 0.04</td>
</tr>
<tr>
<td>$T_\parallel$</td>
<td>$\Lambda$</td>
<td>298 ± 5</td>
<td>304 ± 6</td>
<td>303 ± 6</td>
<td>289 ± 6</td>
</tr>
<tr>
<td>(MeV)</td>
<td>$\bar{\Lambda}$</td>
<td>312 ± 6</td>
<td>310 ± 6</td>
<td>305 ± 6</td>
<td>280 ± 6</td>
</tr>
<tr>
<td>$dN/dy$</td>
<td>$\Lambda$</td>
<td>17.4 ± 0.4</td>
<td>13.3 ± 0.3</td>
<td>10.4 ± 0.2</td>
<td>6.1 ± 0.2</td>
</tr>
<tr>
<td>(exp fit)</td>
<td>$\bar{\Lambda}$</td>
<td>12.3 ± 0.3</td>
<td>9.8 ± 0.3</td>
<td>7.6 ± 0.2</td>
<td>4.7 ± 0.1</td>
</tr>
<tr>
<td>$T_\parallel$</td>
<td>$\Lambda$</td>
<td>355 ± 8</td>
<td>364 ± 9</td>
<td>362 ± 8</td>
<td>343 ± 8</td>
</tr>
<tr>
<td>(MeV)</td>
<td>$\bar{\Lambda}$</td>
<td>374 ± 9</td>
<td>373 ± 8</td>
<td>366 ± 8</td>
<td>331 ± 8</td>
</tr>
</tbody>
</table>
data and are the basis for modeling particle production in hadronic collisions as well [5,30,31]. For example, the $\Lambda$ to $h^-$ ratio is approximately 0.35 at $p_T$ of 2 GeV/$c$. Data from $e^+e^-$ collisions and calculations from string fragmentation models, however, indicate that, although the baryon to meson ratio from quark and gluon fragmentation increases as a function of Feynman $x$, the ratio never exceeds 0.2 [32]. As mentioned above, a natural explanation for the increase at high $p_T$ would be a large collective radial flow at RHIC [24,27]. Alternatively, it has also been suggested that the energy loss of high $p_T$ partons could modify the baryon to meson ratio [30].

The average ratio of $p_T$ integrated yield $\Lambda$ to $\Lambda$ is $0.74 \pm 0.04$ (stat) $\pm 0.03$ (syst) with no significant variation over the measured range of centrality. Given that there is a net excess of baryons at midrapidity, it is reasonable to conclude that there is more than one process contributing to $\Lambda$ production and that significant baryon number from the colliding beams is transported to $\Lambda$ at midrapidity. A question in this regard is why the shapes of $m_T$ spectra for $\Lambda$ and $\Lambda$ are the same within errors. It has been suggested that significant rescattering of $\Lambda$ and $\Lambda$ during the evolution of the collision can lead to equilibration [16,33]. Our measurement provides important constraints for modeling the mechanism of baryon number transport, which itself requires further study.

Figure 4 shows the $dN/dy$ of $\Lambda$ and $\Lambda$ from the Boltzmann fit as a function of the $h^-$ pseudorapidity density [4]. At midrapidity the hyperon production is approximately proportional to the primary $h^-$ multiplicity in Au + Au collisions at RHIC. The dashed lines in the figure correspond to $\Lambda = 0.054h^-$ and $\Lambda = 0.040h^-$ from a linear fit to the data. The systematic errors on the hyperon yields and the $h^-$ are 10% and 6%, respectively. Similar centrality dependence of the lambda production was observed at the SPS energies. The $\Lambda$ to $h^-$ ratio at RHIC is much larger than that at the SPS while the $\Lambda$ to $h^-$ ratio is smaller at RHIC [13]. This may be understood from the fact that at the SPS most of the observed $\Lambda$ hyperons carry baryon number transported from the colliding nuclei through associated production, rescattering, and fragmentation processes. In this case, the yield of $\Lambda$ to $h^-$ ratio is larger than that at RHIC due to the relatively high fraction of the $\Lambda$ yield not resulting from pair production. Conversely, the increased importance of baryon pair production at RHIC energies must contribute to the observed increase of the $\Lambda$ to $h^-$ ratio relative to the SPS measurement.

In conclusion, we have presented the first inclusive midrapidity ($|y| < 0.5$) $\Lambda$ and $\Lambda$ spectra as a function of centrality from Au + Au collisions at the $\sqrt{s_{NN}} = 130$ GeV energy. Salient features of the data include (i) large slope parameters of transverse mass spectra probably resulting from increased collective radial velocity at RHIC, (ii) similar shapes for $\Lambda$ and $\Lambda$ spectra despite the fact that a significant fraction of the $\Lambda$ hyperons at midrapidity carry a baryon number from the incoming nuclei while the $\Lambda$ hyperons are primarily pair produced, and (iii) a significant increase in the $\Lambda$ yield relative to negatively charged primary hadrons at moderate $p_T$ above 1 GeV/$c$ which cannot be described by existing perturbative QCD inspired string fragmentation models alone. Collective dynamics and/or modified string particle production schemes are needed. The $p_T$ integrated rapidity densities of $\Lambda$ and $\Lambda$ are approximately proportional to the number of negative hadrons at midrapidity.

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