Measurement of the $\Lambda$ and $\bar{\Lambda}$ particles in Au+Au Collisions at $\sqrt{s_{NN}} = 130$ GeV

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We present results on the measurement of Λ and ¯Λ production in Au+Au collisions at \( \sqrt{s_{NN}} = 130 \) GeV with the PHENIX detector at RHIC. The transverse momentum spectra were measured for minimum–bias and for the 5% most central events. The \( \bar{\Lambda}/\Lambda \) ratios are constant as a function of \( p_T \) and the number of participants. The measured net Λ density is significantly larger than predicted by models based on hadronic strings (e.g. HIJING) but in approximate agreement with models which include the gluon junction mechanism.

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In this paper we report on the measurement by the PHENIX experiment at the Relativistic Heavy Ion Collider (RHIC) of the production of Λ and \( \bar{\Lambda} \) particles and the ratio \( \Lambda/\bar{\Lambda} \) as a function of transverse momentum \( p_T \) and centrality in Au+Au collisions at \( \sqrt{s_{NN}} = 130 \) GeV. The production of strange baryons and of strange particles in general has been extensively studied in heavy ion collisions at the Alternating Gradient Synchrotron (AGS) and at the Super Proton Synchrotron (SPS) [1] to investigate the flavor composition of nuclear matter at high density and temperature. Furthermore, antibaryon–to–baryon ratios, or alternatively, a net baryon number such as \((\Lambda - \bar{\Lambda})\) at midrapidity provide insight into the baryon transport mechanism in these collisions [2,3].

The systematic study of baryon stopping (transport of baryon number in rapidity space) and hyperon production in proton–proton, proton–nucleus and nucleus–nucleus collisions has been done over the past decade at the AGS [6,7] and CERN SPS [8–10]. The results have shown a high degree of baryon stopping and enhanced hyperon production in heavy nucleus–nucleus collisions. Clearly the measurement of these quantities at RHIC, at the highest energies so far available in the laboratory, is of great importance for our understanding of the sources of these processes.

The results reported here were obtained using the west arm of the PHENIX spectrometer which covers an angular range of \( \Delta\phi = \pi/4 \) (during its first year of run-
ning) and a pseudorapidity range of $|\eta| < 0.35$. The detectors used were the drift chamber (DC), a set of multwire proportional chambers with pixel-pad read-out (PC1) \[12\], and a lead–scintillator electromagnetic calorimeter (EMCal) \[13\]. Signals from two sets of beam–beam counters (BBC) and two zero–degree calorimeters (ZDC) provided a trigger sensitive to 92 ± 4% of the 6.8 barn total Au+Au cross section \[4\]. The centrality selection was done using the correlation between the analog responses of the ZDC and BBC \[4\].

The present analysis is based on 1.3 M minimum–bias events with a vertex position of $|z| < 20$ cm. To reconstruct the $\Lambda$ and $\bar{\Lambda}$ particles, their weak decays $\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\pi^+$ are used. The tracks of the charged particles from the decay of $\Lambda$ and $\bar{\Lambda}$ are reconstructed using DC and PC1, and their momentum is determined by the DC with a resolution of $\delta p/p \simeq 0.6\% \oplus 3.6\% \, (\text{GeV/c})$. Although these tracks do not point back to the primary vertex position their momentum is calculated assuming that they come from the interaction point, hence there is in general a shift in the momentum of the reconstructed $\Lambda$ and $\bar{\Lambda}$ particles. A Monte Carlo (MC) study shows that the difference is of the order 1–2% over the measured momentum range, within the measured momentum resolution, and thus neglected in the present study. The absolute momentum scale is known to better than 2\% \[12\]. In order to reduce background the tracks are confirmed by requiring a matching hit in the EMCal within ±3$\sigma$. For the particle identification (PID) of the daughter charged particles the time–of–flight signal of the EMCal with a timing resolution of ~700 ps is used. Using the momentum measured by the DC and the flight–time, the particle mass is calculated and a 2$\sigma$ momentum–dependent cut is applied to the mass–squared distribution to identify protons, antiprotons and pions. An upper momentum cut of 0.6 GeV/c and 1.4 GeV/c for pions and protons respectively provides clean particle separation. Then each proton is combined with each pion in the same event and the invariant mass is calculated. If $\Lambda$ or $\bar{\Lambda}$ are produced a peak appears in the mass distribution on top of a background from random combinations of particles. In order to determine the number of $\Lambda$'s and $\bar{\Lambda}$'s from such a distribution an estimation of the background is essential. For this, the mass distribution with combinations of protons and pions from different events with the same centrality class (event mixing) is used. In order to reduce the combinatorial background the decay proton energy is required to be within $E_{p}^{\text{min}} < E_p < E_{p}^{\text{max}}$ where $E_{p}^{\text{min}}$ and $E_{p}^{\text{max}}$ are calculated from the two–body decay kinematics in the $\Lambda$ center–of–mass system. A similar cut is used for the pions. This cut gives an improvement of the signal–to–background ratio by a factor of two and results in the final value of $S/B = 1/2$ for both $\Lambda$ and $\bar{\Lambda}$. We obtain ~12000 $\Lambda$ and ~9000 $\bar{\Lambda}$ particles in the mass range 1.05 < $m_{\Lambda}$ < 1.20 GeV/c$^2$ with mass resolution $\delta m/m \simeq 2\%$ obtained from a Gaussian fit.

Fig. \[2\] shows the invariant mass spectra for the $\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\pi^+$. The results represent the primary $\Lambda$ and $\bar{\Lambda}$ and contributions from the feed–down from heavier hyperons (mainly $\Sigma^0$ and $\Xi$). The reconstructed number of $\Lambda$ and $\bar{\Lambda}$ particles is corrected for the acceptance, pion decay–in–flight, momentum resolution and reconstruction efficiency. For this, single–particle MC events were generated over the full azimuth $0 < \phi < 2\pi$ and one unit of rapidity $-0.5 < y < 0.5$. The simulated particles were passed through the entire PHENIX GEANT \[14\] simulation. The correction function is defined as the ratio of the input (generated) transverse momentum distribution to the $p_T$ distribution of the particles reconstructed in the spectrometer. However this correction does not take into account the decreasing track reconstruction efficiency due to the high multiplicity environment in more central events. A well established method to obtain this efficiency drop is the embedding procedure \[12\]. We use single–particle MC tracks embedded into real events and analyze the merged events with the same analysis code as used for the reconstruction of the data set. The track reconstruction efficiency decreases from 90\% for minimum–bias to 70\% for central events. The $\Sigma^0$ and $\Xi$ hyperons decay to $\Lambda$ with a branching ratio of essentially 100\%. We have verified, using HIJING, that the kinematic properties ($p_T$ and $y$ distributions) of primary $\Lambda$ and those produced by $\Sigma^0$ and $\Xi$ decay are the same (within a few percent). We conclude that the correction function determined for primary $\Lambda$ is valid for all $\Lambda$. Since there are no reliable data available for the yields of those hyperons at RHIC energies, we cannot quantitatively state the contributions from those heavier hyperons to our $\Lambda$ production. Therefore, our data include the primordial $\Lambda$ and $\bar{\Lambda}$, as well as the feed–down from the heavier hyperons.

Using the correction function determined from single–particle MC and multiplicity–dependent track reconstruction efficiency derived from the embedding procedure we correct the transverse momentum distributions of $\Lambda$ and $\bar{\Lambda}$. The invariant yields as a function of the transverse momentum $p_T$ for $\Lambda$ and $\bar{\Lambda}$ are shown in Fig. \[2\] for minimum–bias events (circles). Over the measured transverse momentum range (0.4 < $p_T$ < 1.8 GeV/c) both the $\Lambda$ and $\bar{\Lambda}$ spectra can be described by a distribution of the form $dN/dp_T \propto p_T e^{-p_T/T}$ as shown in Fig. \[2\] by the solid line. The total yield $dN/dy$ is obtained by integrating the functional fit from zero to infinity. In the same Fig. \[4\] we show the invariant yield for the 5\% most central events (squares). In Table \[1\] the total yields $dN/dy$ together with the average transverse momentum $<p_T>$ and the slope parameters $T$ are listed for both minimum–bias and for the 5\% most central events.

There are several sources which contribute to the systematic uncertainties of the total yield $dN/dy$ and average transverse momentum $<p_T>$ determination. One of the sources, the uncertainty in the correction function de-
termination, is found to be 13%. A second contribution is due to the fitting function used for the extrapolation beyond the measured \( p_T \) range: the fraction of the extrapolated yield is 29 ± 9%. There is also an additional contribution to the systematic error which originates from the combinatorial background subtraction which is 3%. Combining the above uncertainties in quadrature gives a total systematic error in the yield of 16% (see Table I).

The \( \bar{\Lambda}/\Lambda \) yield ratio determined in the mass window defined above versus \( p_T \) is shown in Fig. 3 (top panel). The ratio is constant over the whole \( p_T \) range \( 0.4 < p_T < 1.8 \text{ GeV/c} \). There is also no significant variation of the \( \bar{\Lambda}/\Lambda \) ratio as a function of the number of participants (bottom panel) which is calculated using a Glauber model together with a simulation of the ZDC and BBC responses [2]. The average \( \bar{\Lambda}/\Lambda \) ratio is 0.75 ± 0.09 (stat). Both the \( p_T \)–dependence and the integral \( \bar{\Lambda}/\Lambda \) ratio are consistent with statistical thermal model calculations [7] at RHIC energies.

The present measurement of the total yield of \( \Lambda \) and \( \bar{\Lambda} \) enables us to take the previously reported inclusive \( p \) and \( \bar{p} \) spectra [8], and construct a feed–down correction for \( \Lambda \) decays. As the \( \Sigma \) yield has not been measured, we do not include feed–down from \( \Sigma^\pm \) decays, but this is expected to be < 5%, based on HIJING calculations. The feed–down corrections were done bin by bin on the proton (antiproton) \( p_T \) spectrum by the following method:

\[
\frac{dN^p}{dydp_T}(i) = \frac{dN^m}{dydp_T}(i) - \sum_{j=1}^{N_{bins}} \frac{dN^\Lambda}{dydp_T}(j) \times BR \times w(j,i)
\]

(0.1)

where \( dN^p/dydp_T \) is the total yield of the primary protons, \( dN^m/dydp_T \) – the total yield of the measured protons, \( dN^\Lambda/dydp_T \) – the total yield of the measured \( \Lambda \), BR – branching ratio of the \( \Lambda \) decay \( \Lambda \rightarrow p\pi^- \), \( i \) is the \( p_T \) bin number, \( N_{bins} \) is the number of bins, \( w(j,i) \) is the fraction of protons from \( \Lambda \) decay from bin number \( j \) which fall into the proton bin number \( i \). These fractions were extracted from MC. The feed–down corrected proton and antiproton \( p_T \) spectra are shown in Fig. 4. We calculated the total yield, \( dN/ dy \), for protons and antiprotons by fitting them to the same distribution as used for the \( \Lambda \) and integrating from zero to infinity. The results for the total yields \( dN/ dy \), the average transverse momentum \( <p_T> \) and the slope parameters \( T \) for minimum–bias and for the 5% most central events are also listed in Table I. The measured \( \Lambda/p \) and \( \bar{\Lambda}/\bar{p} \) ratios after feed–down corrections are found to be 0.89 ± 0.07 (stat) and 0.95 ± 0.09 (stat).

The net baryon numbers are indicative of the baryon transport mechanism in relativistic heavy ion (RHI) collisions. In Table I we compare our results for minimum–bias and for the 5% most central events with the predictions of the HIJING [9] model which assumes that the primary mechanism for baryon transport in RHI is due to quark–diquark hadronic strings. Vance et al. [10] implemented a non–perturbative gluon–junction mechanism in a new version of HIJING (called HIJING/B) to explain the enhanced baryon stopping at CERN SPS energies. The predictions of this model are also shown in Table I. For a valid comparison with the experimental data, the HIJING and HIJING/B results for \( \Lambda \) and \( \bar{\Lambda} \) also include the feed–down from the heavier hyperons, and the results for protons and antiprotons the feed–down from \( \Sigma^\pm \). The Table shows a clear difference (by a factor of ~4) between HIJING and HIJING/B for the net \( \Lambda \) number, with the HIJING/B predictions in much better agreement, in particular for the minimum–bias data, where the experimental errors are relatively small. The difference between the two models for the net proton number is less obvious and although the data seem to favor HIJING/B the present accuracy does not allow for a clear preference between the two models.

In conclusion, we have measured the transverse momentum spectra of the of \( \Lambda \) and \( \bar{\Lambda} \) particles in the \( p_T \) range \( 0.4 < p_T < 1.8 \text{ GeV/c} \) in minimum–bias and the 5% most central Au+Au collisions at \( \sqrt{s_{NN}} = 130 \text{ GeV} \) at RHIC with the PHENIX experiment. The absolute yields of \( dN/ dy \), at mid–rapidity, of \( \Lambda \) hyperons are determined by extrapolating to all values of \( p_T \). The average \( \bar{\Lambda}/\Lambda \) ratio is found to be 0.75 ± 0.09. The ratio is constant over the whole \( p_T \) range and there is also no significant variation of the \( \bar{\Lambda}/\Lambda \) ratio as a function of the number of participants. Using the measured \( \Lambda \) and \( \bar{\Lambda} \) yields, the \( p \) and \( \bar{p} \) yields corrected for feed–down from \( \Lambda \) decays are determined. The \( \Lambda/p \) and \( \bar{\Lambda}/\bar{p} \) ratios after feed–down corrections are found to be 0.89 ± 0.07 and 0.95 ± 0.09. The measured net \( \Lambda \) number is substantially larger than predicted by HIJING as already seen at CERN SPS and which may indicate enhanced baryon stopping at RHIC energies. The newly available high statistics data at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) will allow us to further study baryon transport and strangeness production in RHI collisions.

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[1] 5th International Conference on Strangeness in Quark Matter 2000, J. Phys. G 27, 255 (2001) and references therein.
FIG. 1. Invariant mass spectra of $p\pi^−$ (solid squares) and $\bar{p}\pi^+$ (open squares) pairs. The histograms show the background for $p\pi^−$ (solid) and $\bar{p}\pi^+$ (dashed). For clarity the $\bar{p}\pi^+$ data are scaled up by a factor of two. The insert shows the background–subtracted spectra of $\Lambda$ (solid circles) and $\bar{\Lambda}$ (open circles). The lines are Gaussian fits to the $\Lambda$ (solid line) and $\bar{\Lambda}$ (dashed line) mass spectra.

FIG. 2. Transverse momentum spectra of $\Lambda$ and $\bar{\Lambda}$ for minimum–bias and for the 5% most central events. For clarity of presentation the data points for minimum–bias are scaled down by a factor of ten.

FIG. 3. The ratio $\bar{\Lambda}/\Lambda$ as a function of $p_T$ (top) and as a function of the number of participants (bottom).
FIG. 4. Spectra of inclusive $\Lambda$ ($\bar{\Lambda}$) and feed–down corrected protons (antiprotons) for minimum–bias events. The data points for antiprotons and $\bar{\Lambda}$ are scaled down by a factor of two.