Kaon Production and Kaon to Pion Ratio in Au+Au Collisions at $\sqrt{s_{NN}} = 130$ GeV

C. Adler$^{11}$, Z. Ahammed$^{23}$, C. Allgower$^{12}$, J. Amonton$^{14}$, B.D. Anderson$^{14}$, M. Anderson$^{5}$, G.S. Averichev$^{9}$, J. Balewski$^{12}$, O. Bariannikova$^{23}$, L.S. Barnby$^{14}$, J. Baudot$^{31}$, S. Bekele$^{20}$, V.V. Belaga$^{9}$, R. Bellwied$^{31}$, J. Berger$^{11}$, H. Bichsel$^{30}$, A. Billemin$^{31}$, L.C. Bland$^{2}$, C.O. Blyth$^{3}$, B.E. Bonner$^{24}$, A. Boucham$^{26}$, A. Brandin$^{18}$, A. Bravara$^{2}$, R.V. Cadman$^{1}$, H. Caines$^{35}$, M. Calderón de la Barca Sánchez$^{2}$, A. Cardenas$^{14}$, J. Carroll$^{15}$, J. Castillo$^{26}$, M. Castro$^{31}$, D. Cebra$^{5}$, P. Chaloupka$^{20}$, S. Chattopadhyay$^{31}$, Y. Chen$^{6}$, S.P. Chernenko$^{9}$, M. Cherney$^{8}$, A. Chikanian$^{43}$, B. Choi$^{28}$, W. Christie$^{2}$, J.P. Coffin$^{13}$, T.M. Cormier$^{31}$, J.G. Cranmer$^{30}$, H.J. Crawford$^{4}$, W.S. Deng$^{2}$, A.A. Derevschikov$^{22}$, L. Didenko$^{2}$, T. Dietel$^{11}$, J.E. Draper$^{1}$, V.B. Dunin$^{9}$, J.C. Dunlop$^{33}$, V. Eckardt$^{16}$, L.G. Efimov$^{9}$, V. Emeljanov$^{18}$, J. Engelmod$^{4}$, G. Eppley$^{24}$, B. Erazmus$^{26}$, P. Fachi$^{2}$, V. Faine$^{2}$, J. Faire$^{13}$, K. Filimonov$^{15}$, E. Fitch$^{33}$, Y. Fisyak$^{2}$, D. Flierl$^{11}$, K.J. Foley$^{2}$, J. Fu$^{15,32}$, C.A. Gaulier$^{27}$, N. Gagamashvili$^{23}$, J. Gans$^{13}$, L. Gauchet$^{26}$, M. Germain$^{13}$, F. Geurts$^{24}$, V. Ghazikhanian$^{9}$, O. Grachov$^{31}$, V. Grigoriev$^{18}$, M. Guedon$^{13}$, E. Gushin$^{18}$, T.J. Hallman$^{2}$, D. Hardtke$^{15}$, J.W. Harris$^{33}$, T.W. Henry$^{27}$, S. Heppelmann$^{21}$, T. Herston$^{23}$, B. Hippolyte$^{13}$, A. Hirsch$^{23}$, E. Hjort$^{15}$, G.W. Hoffmann$^{28}$, M. Horsley$^{33}$, H.Z. Huang$^{6}$, T.J. Humanic$^{20}$, G. Igo$^{6}$, A. Ishihara$^{28}$, Yu.I. Ivanishin$^{10}$, P. Jacobs$^{15}$, W.W. Jacobs$^{12}$, M. Janik$^{29}$, I. Johnson$^{15}$, P.G. Jones$^{3}$, E.G. Judd$^{11}$, A.S. Konstantinov$^{3}$, E.G. Judd$^{11}$, O. Barannikova$^{22}$, A. Billmeier$^{22}$, A.S. Konstantinov$^{2}$, D. Reichhold$^{3}$, L. Gaudichet$^{2}$, B. Choi$^{28}$, I. Savin$^{10}$, V. Emelianov$^{18}$, J. Marx$^{31}$, G. Igo$^{6}$, G. Paic$^{12}$, Y.V. Zanevski$^{9}$, A. Stolpovsky$^{31}$, J. Marx$^{31}$, G. Igo$^{6}$, G. Paic$^{12}$, Y.V. Zanevski$^{9}$, A. Stolpovsky$^{31}$, J. Marx$^{31}$, G. Igo$^{6}$, G. Paic$^{12}$, Y.V. Zanevski$^{9}$, A. Stolpovsky$^{31}$, J. Marx$^{31}$, G. Igo$^{6}$, G. Paic$^{12}$, Y.V. Zanevski$^{9}$, A. Stolpovsky$^{31}$, J. Marx$^{31}$, G. Igo$^{6}$, G. Paic$^{12}$, Y.V. Zanevski$^{9}$, A. Stolpovsky$^{31}$, J. Marx$^{31}$, G. Igo$^{6}$, G. Paic$^{12}$, Y.V. Zanevski$^{9}$, A. Stolpovsky$^{31}$, J. Marx$^{31}$, G. Igo$^{6}$, G. Paic$^{12}$, Y.V. Zanevski$^{9}$, A. Stolpovsky$^{31}$, J. Marx$^{31}$, G. Igo$^{6}$, G. Paic$^{12}$, Y.V. Zanevski$^{9}$, A. Stolpovsky$^{31}$, J. Marx$^{31}$, G. Igo$^{6}$, G. Paic$^{12}$, Y.V. Zanevski$^{9}$, A. Stolpovsky$^{31}$, J. Marx$^{31}$, G. Igo$^{6}$, G. Paic$^{12}$, Y.V. Zanevski$^{9}$, A. Stolpovsky$^{31}$, J. Marx$^{31}$, G. Igo$^{6}$, G. Paic$^{12}$, Y.V. Zanevski$^{9}$, A. Stolpovsky$^{31}$, J. Marx$^{31}$, G. Igo$^{6}$, G. Paic$^{12}$, Y.V. Zanevski$^{9}$, A. Stolpovsky$^{31}$, J. Marx$^{31}$, G. Igo$^{6}$, G. Paic$^{12}$, Y.V. Zanevski$^{9}$, A. Stolpovsky$^{31}$, J. Marx$^{31}$, G. Igo$^{6}$, G.
Mid-rapidity transverse mass spectra and multiplicity densities of charged and neutral kaons are reported for Au+Au collisions at \( \sqrt{s_{NN}} = 130 \) GeV at RHIC. The spectra are exponential in transverse mass, with an inverse slope of about 280 MeV in central collisions. The multiplicity densities for these particles scale with the negative hadron pseudo-rapidity density. The charged kaon to pion ratio is lower than the same ratio observed at the SPS and while the \( K^-/\pi^- \) ratio is higher than the SPS result. Both ratios are enhanced by about 50% relative to p+p and \( \bar{p}+p \) collision data at similar energies.

Lattice QCD predicts that at sufficiently high energy density, matter will be in a state of deconfined quarks and gluons \([1]\). It has been suggested that strangeness production is a sensitive probe of a deconfined state: for example, strangeness production may be enhanced by the fast and energetically favorable process of gluon-gluon fusion into strange quark-antiquark pairs \([2]\). A systematic investigation of strangeness production is therefore needed to understand different production mechanisms.

Strangeness production has been studied in heavy-ion collisions at the AGS \([3, 4, 5]\), SPS \([6, 7, 8]\), and more recently at RHIC \([9, 10, 11, 12]\). In this letter, we report measurements by the STAR experiment at RHIC on charged and neutral kaon production. The measurements were made at mid-rapidity in Au+Au collisions at a nucleon-nucleon center-of-mass energy of \( \sqrt{s_{NN}} = 130 \) GeV. The measurements were carried out during the summer of 2000 and details of the STAR experiment are described elsewhere \([9, 10, 11, 12]\). The primary tracking device in the experiment is a Time Projection Chamber (TPC). It sits in a magnetic field of 0.25 Tesla. Tracks were reconstructed from three-dimensional hits measured in the TPC and the primary vertex of the interaction was found by fitting the reconstructed tracks to a common point of origin. Corrections were made for the energy loss of the charged kaons in the detector material. The momentum resolution was found to have negligible effect on the kaon spectra and so no correction was applied.

Two methods were used to identify the kaons:

(I) The Energy loss method \((dE/dx)\): Particle identification was done by measuring the mean specific energy lost by the charged particles, \((dE/dx)\), in the TPC gas. The \((dE/dx)\) resolution was approximately 11%. The tracks were required to come from within 3 cm of the primary vertex and every track had at least 25 hits, out of 45 possible hits, on the TPC pad plane. Using a method that is described in \([9]\), the distribution in \(n[(dE/dx)/(dE/dx)_{BB}]\) (where \((dE/dx)_{BB}\) is the expected Bethe-Bloch value) was fit by a sum of four Gaussians corresponding to \(\pi^\pm\), \(K^\pm\), \(e^\pm\), and \(p\), \(\bar{p}\). The fit was done for each centrality and transverse momentum \(p_\perp\) bin. The raw kaon yield was extracted from the fit parameters. In the range where the kaons are well separated from other species, \(p_\perp \lesssim 0.5\) GeV/c, we estimate a point-to-point systematic error of 5% on the extracted kaon yields. In the range where the kaons and the \(e^\pm\) overlap in \((dE/dx)\), \(0.5 \lesssim p_\perp \lesssim 0.7\) GeV/c, we parameterized the \(e^\pm\) yield using data from lower \(p_\perp\) and
move a majority of the contribution from $\Lambda$ on the from the primary vertex by more than 6 cm. A cut at least 1.5 cm, and the decay vertex had to be separated that the daughter tracks miss the primary vertex by at least 0.5 cm. The majority of the $K$ the order of 15% is corrected for in the kaon spectra. Eliminating charged pions because they have a limited longitudinal range near the center of the TPC. The event centrality was determined off-line and is based on measured charged particle multiplicities in the TPC. A correction factor was applied to account for losses due to limited acceptance, decay, tracking inefficiency, and hadronic interactions. The overall efficiency ($\epsilon$), including all these effects, was obtained from a full MC simulation by embedding MC tracks into real events on the raw data level. For the most central collisions, the $dE/dx$ method yielded $\epsilon \simeq 20\%$ at $p_\perp = 0.2$ GeV/c and 60\% at 0.7 GeV/c. For the Kink method, $\epsilon \simeq 15\%$ at $p_\perp = 1$ GeV/c and 6\% at 2 GeV/c. For the $K^0_S$ method, $\epsilon \simeq 4.5\%$ at $p_\perp = 1$ GeV/c and 7\% at 2 GeV/c. The efficiency increases with decreasing event multiplicity by about 20\% of its value, from the most central to the most peripheral bins, for the $dE/dx$ and Kink methods and by 70\% for the $K^0_S$ method.

Figure 1 shows the transverse mass spectra for the invariant yields of $K^+$, $K^-$, and $K^0_S$, respectively; the data are plotted in order of decreasing centrality from top to bottom. See Table 3 for the legend and the systematic errors to range from 10\% to 20\%. In the region including all these effects, was obtained from a full MC simulation by embedding MC tracks into real events on the raw data level. For the most central collisions, the $dE/dx$ method yielded $\epsilon \simeq 20\%$ at $p_\perp = 0.2$ GeV/c and 60\% at 0.7 GeV/c. For the Kink method, $\epsilon \simeq 15\%$ at $p_\perp = 1$ GeV/c and 6\% at 2 GeV/c. For the $K^0_S$ method, $\epsilon \simeq 4.5\%$ at $p_\perp = 1$ GeV/c and 7\% at 2 GeV/c. The efficiency increases with decreasing event multiplicity by about 20\% of its value, from the most central to the most peripheral bins, for the $dE/dx$ and Kink methods and by 70\% for the $K^0_S$ method.

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primordial $K_S^0$ yield is most likely equal to the average of the primordial charged kaon yields. However, our measurements include decay products of $\phi$ mesons which decay into charged kaons and neutral kaons with different branching ratios. The effect is estimated using the measured $\phi$ spectra to be 1-3% between the measured charged and neutral kaons in the $0.2 < p_T < 1.0$ GeV/$c$ range.

The kaon spectra exhibit an exponential shape in $m_\perp$. We fit the spectra of charged kaons (combined from $dE/dx$ and Kink) and $K_S^0$, respectively, to an $m_\perp$ exponential with the inverse slope, $T$, and the integrated rapidity density, $dN/dy$, as free parameters. The fit results are shown as solid lines in Fig. 1. The fit parameters are listed in Table I together with $dN_{h^-}/dy$, the negative hadron multiplicity within $|\eta| < 0.5$. Systematic errors on $dN/dy$ and $T$ are both about 8% for charged kaons, and 10% and 6%, respectively, for $K_S^0$. The systematic errors are partially correlated between $K^+$ and $K^-$. An additional 5% systematic error applies to the $dN/dy$ and it is correlated between all three particle species. Our charged kaon $dN/dy$ results are in agreement with the recent PHENIX publication\cite{T5} and the point-by-point spectra agree within two standard deviation of systematic errors.

Figure 2(a) shows $T$ as a function of $dN_{h^-}/dy$. No difference is observed between the $K^+$, $K^-$ and $K_S^0$. There is an indication of a systematic increase in $T$ from $\sim 240$ MeV in the most peripheral collisions to $\sim 280$ MeV in the most central collisions. For comparison, the kaon inverse slope is about 240 MeV for central heavy ion collisions at the SPS (\(\sqrt{s_{NN}} \approx 17\) GeV)\cite{T2,T3,T6} and 200 MeV at the AGS (\(\sqrt{s_{NN}} \approx 5\) GeV)\cite{T2,T3}. Note, however, that inverse slopes may measure a combined effect of thermal temperature and transverse radial flow\cite{T21} and the larger $T$ values suggest stronger radial flow at RHIC energies. For the most central collisions, the measured kaon $T$ is smaller than that of the lambda and the lambda $dN/dy$\cite{T22} is about 1/3 of the kaon $dN/dy$. As a result, the lambda yield approaches, and may even exceed the kaon yield for $p_T \gtrsim 1.5$ GeV/$c$. A similar behaviour was observed for non-strange particles (pion and proton) in a similar $p_T$ region\cite{T11}.

Figure 2(b) shows the ratio of kaon $dN/dy$ to $dN_{h^-}/dy$ as a function of $dN_{h^-}/dy$. No strong centrality dependence is observed for the ratios, suggesting no significant change in strangeness production mechanisms from peripheral to central collisions at this RHIC energy. In contrast, kaon production at lower AGS and SPS energies roughly doubles from peripheral to central collisions.

### TABLE I: The mid-rapidity kaon multiplicity densities ($dN/dy$) and $m_\perp$ exponential inverse slopes ($T$ in MeV) as a function of negative hadron multiplicity within $|\eta| < 0.5$ ($dN_{h^-}/dy$). Quoted errors are uncorrelated errors (first) and correlated systematic errors (second). See text for details. Systematic error on $dN_{h^-}/dy$ is 7%. The centrality bins are as same as in Ref. 3.

| Centrality bin | $dN_{h^-}/dy$ | $dN/dy$ | $T$ | $dN/dy$ | $T$ | $dN/dy$ | $T$ |
|---------------|---------------|---------|-----|---------|-----|---------|-----|
| 58-85%        | 17.9          | 2.46±0.07±0.32 | 241±7±19 | 2.32±0.06±0.30 | 238±7±19 | 1.82±0.04±0.27 | 253±4±15 |
| 45-58%        | 47.3          | 7.23±0.18±0.95 | 242±6±19 | 6.48±0.17±0.84 | 257±7±21 | 5.40±0.10±0.81 | 268±3±16 |
| 34-45%        | 78.9          | 11.8±0.3±1.5  | 265±6±21 | 10.4±0.2±1.4  | 250±6±20 | 9.57±0.17±1.4  | 274±3±16 |
| 26-34%        | 115.          | 17.2±0.4±2.3  | 281±7±22 | 15.5±0.4±2.0  | 268±7±21 | 14.0±0.2±2.1  | 273±3±16 |
| 18-26%        | 154.          | 23.1±0.5±3.0  | 275±7±22 | 20.8±0.5±2.7  | 271±7±22 | 18.8±0.3±2.8  | 287±3±17 |
| 11-18%        | 196.          | 28.8±0.7±3.8  | 269±6±22 | 26.4±0.6±3.4  | 274±7±22 | 23.3±0.4±3.5  | 287±3±17 |
| 6-11%         | 236.          | 38.0±0.6±5.0  | 284±4±23 | 34.5±0.5±4.5  | 283±4±23 | 31.4±0.5±4.7  | 277±3±17 |
| 0-6%          | 290.          | 46.2±0.6±6.1  | 277±4±22 | 41.9±0.6±5.4  | 277±4±22 | 36.7±0.6±5.5  | 285±3±17 |

![Figure 2](image-url)
sions 8, 9. On the other hand, the $K^+/K^-$ ratio remains constant as a function of centrality at all energies 8, 10, 24).

$K/\pi$ ratios are often used to study strangeness production enhancement. In order to evaluate $K/\pi$, we deduce the mid-rapidity pion $dN_\pi/dy$ in central collisions from our measurements of negative hadrons 8, antiprotons 15, and $K^-$ spectra. The deduced mid-rapidity value is $dN_\pi/dy = 287 \pm 20$, consistent with our preliminary measurement of pion spectra cited in 23. For the most central collisions, $K^+/\pi^- = 0.161 \pm 0.002(\text{stat}) \pm 0.024(\text{syst})$ and $K^-/\pi^- = 0.146 \pm 0.002(\text{stat}) \pm 0.022(\text{syst})$. The systematic errors are a quadratic sum of those on the kaon and the pion $dN/dy$.

Figure 3 is a compilation of $K/\pi$ results for central heavy ion collisions. Since mid-rapidity $\pi^+/\pi^- \approx 1$ at RHIC 24, we can readily compare our $K^+/\pi^-$ results to $K^+/\pi^-$ results from lower energies. The $K/\pi$ ratio steadily increases with $\sqrt{s_{NN}}$, while the $K^+/\pi^-$ ratio in heavy ion collisions sharply increases at low energies and the maximum value of $K^+/\pi^+$ occurs at $\sqrt{s_{NN}} \approx 10$ GeV. This value is determined by the interplay between the dropping net-baryon density with $\sqrt{s_{NN}}$ and an increasing $K\bar{K}$ pair production rate, as previously noted (e.g. in 23, 24).

Figure 3 also shows parameterized p+p data (curves) and data from p+p 23 and $\bar{p}+p$ 26 at higher energies. Our measurement indicates a 50% enhancement over $(K^++K^-)/2(\pi)$ in p+p and $\bar{p}+p$ at similar energies. The enhancement in $K^-/\pi$ is similar at SPS and RHIC, while that in $K^+/\pi$ is larger at lower energies due to the effect of a changing net-baryon density.

In conclusion, we have reported invariant yield transverse mass spectra and multiplicity densities of charged and neutral kaons at mid-rapidity in Au+Au collisions at $\sqrt{s_{NN}}=130$ GeV at RHIC. The spectra are described by an exponential in transverse mass. The inverse slope parameters are found to increase slightly with collision centrality, with a value of about 280 MeV in central collisions. No strong centrality dependence is found in the ratio of kaon rapidity densities to negative hadron pseudo-rapidity densities. For the most central collisions, the mid-rapidity kaon to pion ratios are $K^+/\pi^- = 0.161 \pm 0.002(\text{stat}) \pm 0.024(\text{syst})$ and $K^-/\pi^- = 0.146 \pm 0.002(\text{stat}) \pm 0.022(\text{syst})$. For central heavy ion collisions, the $K^+/\pi$ ratio is found to increase rapidly with the collision energy and then to decrease, while the $K^-/\pi$ ratio increases steadily. This behavior is consistent with the increasing pair production rate as the collision energy increases, and the decreasing net-baryon density at mid-rapidity. The measured $K/\pi$ ratios at RHIC show an enhancement of about 50% over p+p and $\bar{p}+p$ collisions at similar energies.

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