Kaon and Pion Production in Central Si + Au Collisions at 14.6A GeV/c

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Semi-inclusive spectra of $\pi^{\pm}$, $K^{\pm}$, and p have been measured near midrapidity for central collisions of 14.6A-GeV/c ^{28}Si with ^{197}Au nuclei. The invariant cross sections are all well fitted by exponential distributions in transverse mass, within the measured ranges. The π and K cross sections can also be fitted by Boltzmann distributions. From integrated yields, at midrapidity, the kaon/pion yield ratios are $(19.2\pm3)\%$ for K^+/π^+ and $(3.6\pm0.8)\%$ for K^-/π^-; the π^+/π^- ratio is 1.00 ± 0.04.

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Heavy-ion beams accelerated to highly relativistic energies provide an opportunity to study nuclear matter at a baryon density far greater than that of atomic nuclei. Measured transverse-neutral-energy distributions[1] indicate that at 14.6A GeV/c oxygen nuclei deposit essentially all their energy in central collisions with nuclei heavier than Cu. This stopping implies that an energy density of 3–5 times that of normal nuclear-matter density may be achieved. It has been suggested that under such extreme conditions enhanced strange-particle production might ensue.[2] Furthermore, calculations of the momentum spectra for different particle species have shown that a measurement of their shapes may provide evidence for outward hydrodynamic flow.[3] Thus, a measurement of the particle composition and momentum spectra could provide essential input for understanding the reaction dynamics of nucleus-nucleus collisions in this stopping regime. We report here the first results for momentum distributions of identified charged particles from such collisions in this energy range.

Beams of 14.6A-GeV/c ^{28}Si from the Brookhaven Alternating Gradient Synchrotron (AGS) have been used to bombard Au targets. Presented here are normalized momentum distributions of identified $\pi^{\pm}$, $K^{\pm}$, and p measured with the E-802 spectrometer.[4] The data are obtained from the study of 300000 interactions (central collisions only) of Si with an Au target of $\approx 3\%$ interaction length. The characterization of central collision events is obtained by requiring a high charged-particle multiplicity (upper 7% of the distribution) in the target-multiplicity array surrounding the target ($-1.3 \leq \eta \leq 3.0$).

The experimental apparatus consists of a rotatable magnetic spectrometer with 25 msr solid angle, covering about 0.6 unit of rapidity for pions at midrapidity at a given angle setting. Particle tracking is provided by projective drift chambers,[5] on each side of a bending magnet. Particle identification is provided by measuring particle flight time between a thin plastic-scintillator beam counter and a 160-slat plastic-scintillator arrray[6] located behind the particle-tracking system. The combined timing resolution of 75 ps (1σ) provides adequate K-π separation up to 2.2 GeV/c. The only contamination of particle types occurs between the pions and the electrons. The electrons are completely separable from the pions up to a momentum of 0.7 GeV/c; based on extrapolating the electron/pion ratio, the electron contamination at larger p is estimated to be no greater than 5%.

The compactness of the spectrometer allows a measurement of the kaon momentum spectra down to 0.5 GeV/c; below that, the fraction that survives decay is too small (20%). The track-reconstruction efficiency of $(85\pm5)\%$ has been determined from a manual reconstruction of 200 events and from Monte Carlo simulations. This efficiency is only weakly dependent on multiplicity, namely, a loss of $\leq 2.5\%$ for each additional track for the observed range of multiplicities (at midrapidity, the average multiplicity in the spectrometer for events where there is at least one track is 1.5). Decay and acceptance corrections for both pions and kaons have been performed on a track-by-track basis, assuming that a particle will be lost if it decays. Monte Carlo calculations, however, indicate that some muons from pion decay will be misidentified as pions, and thus be accepted as valid tracks. The data have not been corrected for this, but the inclusion of these particles in the pion spectra causes a negligible change in the slope of the pion momentum distribution and increases the pion integrated yield by no more than 10% from its correct value.

The measured momentum distributions for $\pi^{\pm}$, $K^{\pm}$, and p in the rapidity interval $1.2<y<1.4$ are shown in Fig. 1. The distributions are shown in terms of the invariant cross section, per trigger, as a function of the transverse kinetic energy $T_{\perp}=m_{\perp}-m_0$, where $m_{\perp}=(p_{\perp}^2+m_0^2)^{1/2}$ is the transverse mass, $p_{\perp}$ is the transverse momentum, and m_0 is the rest mass. For each rapidity interval, we have performed fits using three possible types of distributions: $A_0\exp(-m_{\perp}/T_0)$, the Boltzmann form $A_B m_{\perp}\exp(-m_{\perp}/T_B)$, and $A_p\exp(-p_{\perp}/T_p)$, where the parameters A and T are determined for each interval. The inverse slopes T_0 and T_B obtained from these fits for the rapidity interval shown in Fig. 1 are listed in Table I. For our data, as for p-p collisions,[7] the momentum distributions are found to be better described by exponentials in $m_{\perp}$ than in $p_{\perp}$, especially for $p_{\perp}\leq m_0$.

The rapidity dependences of T_0 and T_B for π^- are shown in Fig. 2. The data appear to indicate a variation in inverse slope of about 40 MeV with y. However, the fits to the momentum distributions are made in different ranges of $m_{\perp}$ for the different rapidity intervals, the range being shown in the upper panel of Fig. 2. From fits to different $m_{\perp}$ intervals at several rapidities, it is estimated that a systematic change in slope of 10–20 MeV may occur over the full rapidity range as a result of this restriction in $m_{\perp}$ range. This restriction has the effect of decreasing the T_B (or T_0) in Fig. 2 at larger y. If the data were fitted with the same $m_{\perp}$ range for each rapidity interval, it would likely lead to a flatter rapidity distribution of the inverse slopes. For reference, indicated in Fig. 2 are two values of rapidity: $y_{\text{c.m.}}^{NN}$, the rapidity of the nucleon-nucleon c.m. system; and $y_{\text{c.m.}}^{\text{geom}}=1.25$, the rapidity of a system of ≈ 103 nucleon participants, composed of the incident Si and a core of 75 Au nucleons swept out by the Si nucleus in a head-on collision.

The measured values of T_0 (or T_B) at midrapidity are similar for the different particle species, but progressive-

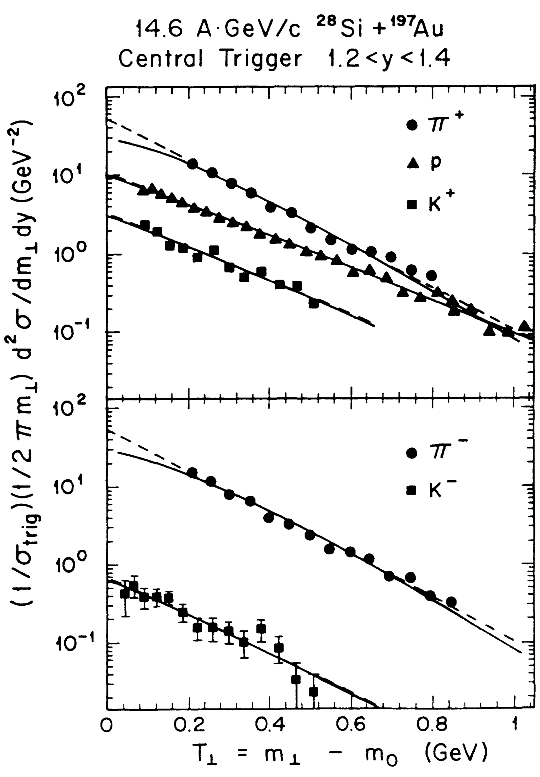

FIG. 1. Invariant cross section per central trigger for $\pi^{\pm}$, $K^{\pm}$, and protons. The dashed lines show the exponential fits to the data; the solid curves show fits to Boltzmann distributions. The uncertainties (statistical only) in the data are either shown or are of the size of the drawn points. There is an additional uncertainty of $\pm 10\%$ in the overall normalization.

TABLE I. Slope parameters and dN/dy for $\pi^{\pm}$, $K^{\pm}$, and proton distributions, at midrapidity $1.2<y<1.4$, from central collisions of 14.6A-GeV/c ^{28}Si with Au. Values are given for fits to the invariant cross sections as exponential and Boltzmann distributions in $m_{\perp}$. The error estimates in the slope parameters include systematic uncertainties. The error estimates in dN/dy are for the relative values only.

	Exponential in $m_{\perp}$		Boltzmann in $m_{\perp}$	
Particle	T_0 (MeV)	dN/dy	T_B (MeV)	dN/dy
π^+	162 ± 10	16.0 ± 1.0	126 ± 10	13.8 ± 0.8
π^-	161 ± 10	16.0 ± 1.0	126 ± 10	13.8 ± 0.8
K^+	203 ± 15	2.9 ± 0.2	160 ± 15	2.8 ± 0.2
K^-	175 ± 25	0.53 ± 0.08	140 ± 25	0.52 ± 0.08
p	215 ± 5	16.2 ± 0.3	187 ± 5	16.0 ± 0.3
K^+/π^+		$(18.1\pm1.7)\%$		$(20.3\pm1.9)\%$
K^-/π^-		$(3.3\pm0.5)\%$		$(3.8\pm0.6)\%$

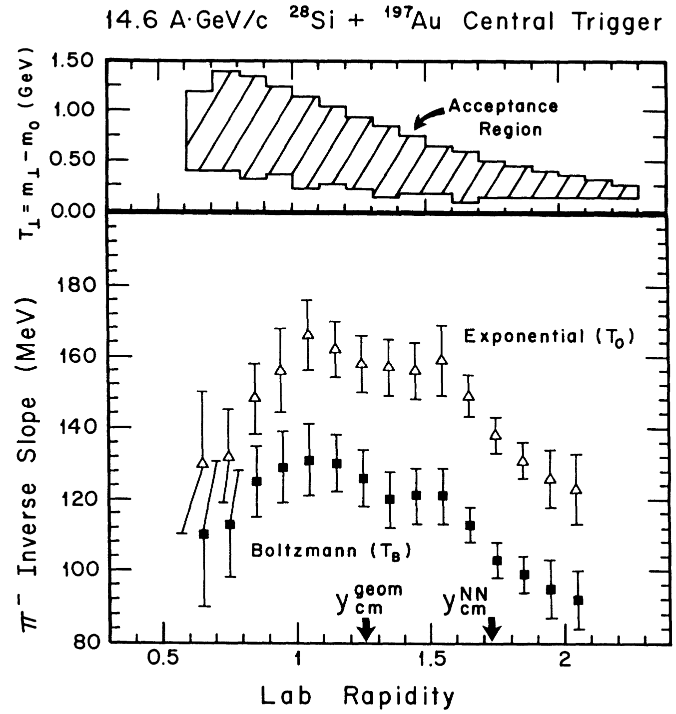

FIG. 2. The upper panel shows the range in $T_\perp$ for which the pion data are fitted to obtain inverse slope parameters in each rapidity interval. The lower panel shows the inverse slope parameters for the π^- distributions. The uncertainties include an estimate of the systematic errors.

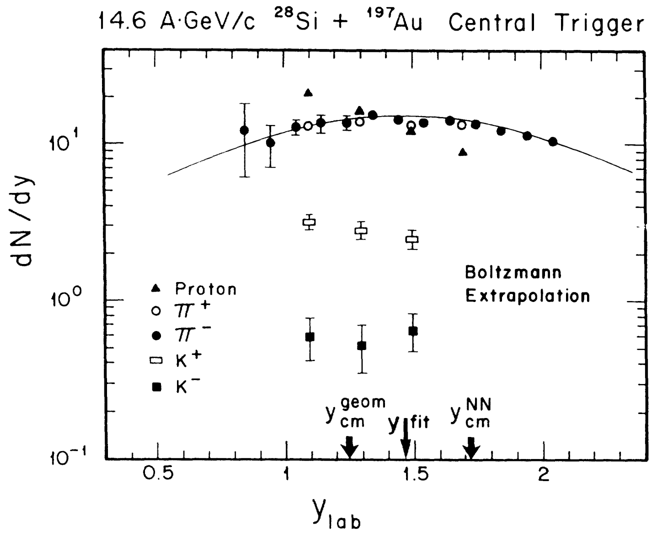

FIG. 3. Rapidity distributions dN/dy per trigger. The errors shown are relative errors only; there is an overall uncertainty of $\pm 10\%$ due to the absolute normalization. The solid curve shows the fit with Eq. (1), for a source located at $y_{fit} = 1.46$ and $T = 125$ MeV.

ly increase with the mass of the emitted particle: $T_0(\pi) \leq T_0(K^+) \leq T_0(p)$. This order is different from the LBL Bevalac results[8] with beams at 2.1A GeV/c, namely, $T_0(\pi) \leq T_0(p) \leq T_0(K^+)$. For p-p collisions at 12 GeV/c at midrapidity,[9] $T_0(\pi)$ and $T_0(p)$ are both equal to 150 MeV to within the 2% statistical uncertainty. For a thermal distribution one expects a common temperature T for all species of emitted particles, provided they freeze out at the same time. A variety of possible mechanisms have, however, been proposed to postulate different effective temperatures for different species: outward radial flow,[3] mean-free-path differences among emitted particles,[10] resonance decay,[11] and formation of a quark-gluon plasma.[12]

By using either the exponential or Boltzmann dependence in $m_\perp$ to integrate the cross sections over all $T_\perp$, one can obtain the rapidity distribution dN/dy. The values depend on the chosen method of extrapolation, but agree within 15%. The dN/dy distributions, obtained by integrating the Boltzmann form, are shown in Fig. 3 for $\pi^\pm$, $K^\pm$, and p. The summed yields for charged particles are consistent with previously reported[13] pseudorapidity distributions. Listed in Table I are the results for both extrapolations averaged over the midrapidity interval $1.2 < y < 1.4$. The results are shown with only the uncertainties in the relative values; there is an additional overall uncertainty of $\pm 10\%$ due to the absolute normalization. The distributions for π^+ agree with those for π^- within the statistical uncertainty of 4% and are broadly peaked. The distribution for protons rises dramatically near the target rapidity, consistent with the expected contribution of target protons.

A simple prediction for the rapidity distribution can be obtained from the single source Boltzmann distribution:[14]

$$dN/dy \propto (x^{-2} + x^{-1} + 0.5)\exp(-x)\,, \qquad (1)$$

with $x = (m_0/T)\cosh(y - y_0)$, where m_0 is the rest mass of the emitted particle and T is the temperature of the source with rapidity y_0. A satisfactory fit with Eq. (1) for the pion data in Fig. 3 is possible for $y_0 = 1.46$ and any $T > 125$ MeV. The solid curve in Fig. 3 is a fit to dN/dy for the pion data with $T = 125$ MeV, consistent[15] with the measured values of T_B shown in Fig. 2.

By comparing the integrated spectra one also obtains the particle yield ratios. For the midrapidity interval $1.2 < y < 1.4$, averaging the similar results given in Table I from the two different extrapolation methods described above, the integrated ratios are $(19.2 \pm 3)\%$ for K^+/π^+ and $(3.6 \pm 0.8)\%$ for K^-/π^-. These values are somewhat smaller than those given in a preliminary report;[13] the difference arises solely from the extrapolation to $T_\perp = 0$ used here, instead of the low-p cutoff of 0.5 GeV/c used in Ref. 13. The value for K^+/π^+ is much larger than the corresponding ratio of (4–8)% measured in p-p reactions.[16] Analysis of data for p-A collisions indicates a K^+/π^+ ratio that is intermediate between the p-p and Si+Au results, albeit for a somewhat different kinematic range.[16] An enhancement of K^+ production, called the K^+ distillation effect,[17] has been predicted to occur if either very high baryon density matter or a quark-gluon plasma is formed.[2] However, more mundane mechanisms are also possible. For example, the rescattering of the reaction products $\pi^+ n \rightarrow K^+ \Lambda$ could provide a mechanism for the K^+ enhancement.[13,18]

The K^-/π^- ratio for *p-p* collisions at the same rapidity is $\approx (2.4 \pm 2.0)\%$, the large uncertainty arising from the low yield of K^-. Because of this large uncertainty one cannot determine whether this ratio is different in heavy-ion collisions. The π^+/π^- ratio is 1.00 ± 0.04, whereas it is ≈ 1.6 for *p-p* reactions.[7] This result presumably reflects the contribution of *n-n* and *n-p* interactions as well as *p-p* interactions in Si+Au collisions.

In summary, we have measured the first momentum distributions for identified charged particles produced in high-energy nucleus-nucleus collisions. We find that the invariant cross sections for the produced particles within a given rapidity interval for central collisions can be described as having an exponential or Boltzmann dependence in transverse mass. The integrated pion distributions have a rather broad dependence in rapidity, but are peaked about a rapidity intermediate between the participant $y_{\text{c.m.}}^{\text{geom}}$ and $y_{\text{c.m.}}^{NN}$. The observed ratio of K^+/π^+ is considerably enhanced compared with ratios observed in similar kinematic regions in *p-p* collisions.

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