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ABSTRACT

The transverse momentum and rapidity distributions of negative hadrons, $K^o_s$, $\Lambda$, and participant protons have been measured in the target rapidity hemisphere for central $^{32}S + ^{32}S$ collisions at 200 GeV/nucleon. The measured mean rapidity shift $<\Delta y> \sim 1.5$ and mean transverse momentum $<p_t> \sim 600$ MeV/c of protons are higher than in pp collisions. These results suggest that there is significant rescattering in participant matter, the stopping is incomplete and that there is longitudinal expansion. The transverse mass ($m_t$) distributions of $K^o_s$, $\Lambda$, participant protons and high $m_t$ negative hadrons are consistent with thermal equilibrium at a temperature of T ~ 200 MeV.

## 1. Introduction

The primary objective of the initial experiments in relativistic and ultrarelativistic nucleus-nucleus collisions has been to determine whether conditions are favorable for the formation of the quark-gluon plasma. Measurements of produced particles and participant nucleons over a large rapidity interval provide important information on the reaction dynamics. Specifically, the degree of nuclear stopping, or the extent to which the initial longitudinal energy is transformed into other degrees of freedom, and the amount of thermalization can be extracted from these measurements. The stopping and thermalization are important dynamical quantities for determining whether sufficient particle and energy densities are attained in these collisions and whether conditions are favorable for formation of a quark-gluon plasma.

## 2. Experiment

In this experiment the rapidity and transverse momentum distributions of negatively- and positively-charged hadrons, $h^-$ and $h^+$, respectively, were measured in the target rapidity region $y < y_{cm} = 3$. In addition, the $K^0_s$ and $\Lambda$ were identified and measured in a separate analysis[1] of the same data. Beams of 200 GeV/nucleon $^{32}S$ were delivered from the CERN SPS accelerator complex onto a $^{32}S$ target in the NA35 detector system. For these experiments the NA35 detector configuration consisted of a 2.0 x 1.2 x 0.72 $m^3$ streamer chamber with associated midrapidity and forward calorimetry for triggering and measuring the energy flow. The streamer chamber was located in a 1.5 T magnetic field to facilitate momentum determination of the particles.

Data were accumulated for three types of trigger conditions: 1) a *central $E_t$ trigger* with high transverse energy deposition ($E_t$), primarily from produced particles at midrapidity, which corresponds to $\sigma(E_t) = 0.11\ \sigma_{reaction}$ or $b < 2.5$ fm in a geometrical model where $\sigma_{reaction} = 1.7$ barns; 2) a *central Veto trigger* with little forward energy ($E_{veto}$) remaining in fast spectators near beam rapidity, corresponding to $\sigma(Veto) = 0.02\ \sigma_{reaction}$ or $b < 1.0$ fm in the geometrical model; and 3) a peripheral trigger consisting of the most peripheral 600 mbarns of a minimum bias trigger.

The trajectories of charged particles in the streamer chamber were photographed with two independent imaging and data acquisition systems. One utilized the standard NA35 film cameras[2] and the second a charge-coupled device (CCD) electronic camera system.[3] The charged particle trajectories were measured, reconstructed in space and the momentum determined. From our analysis of the $K^-$ distributions it was determined that the $K^-$ contributes less than ten percent to the $h^-$ spectra. All data were corrected for hadrons resulting from misidentified $e^+$ and $e^-$, weak decays of $K^0_s$ and $\Lambda$ , and secondary hardon-nucleus interactions.

The participant proton distributions were determined[2,4] from the charge excess by subtraction of the $h^-$ distributions from those of $h^+$, assuming the proton mass. These data were further corrected for the excess of $K^+$ relative to $K^-$. [2,4]

## 3. Data

Data from the Veto trigger were measured and analyzed using the CCD electronic camera/data-acquisition/computer system. All other data were analyzed using the film data and film scanning and measuring techniques. The analysis techniques of the two systems are different and are described in detail in Refs. 2 and 4. The rapidity distributions of $h^-$ are displayed in Fig. 1a for the $E_t$ and Veto triggers. Also displayed are data for minimum bias nucleon-nucleon interactions at the same energy derived from isospin averaging $p + p \rightarrow \pi^{+-} + X$ and $p + n \rightarrow \pi^- + X$ measurements.[5,6] The $h^-$ yield is highest for the most central trigger as is expected. The normalization of the NN data is arbitrary. The shapes of the three data sets are approximately the same, with rms widths of 1.22 +/- 0.03, 1.24 +/- 0.03 and 1.28 +/- 0.02 for the Veto, $E_t$ and NN minimum bias triggers, respectively. All are too broad to be purely thermal, since thermal distributions are typically about half the width of these for any thermal temperature. The elongation in the beam direction rules out any description in terms of an isotropic fireball or radial expansion, and suggest the presence of longitudinal expansion.

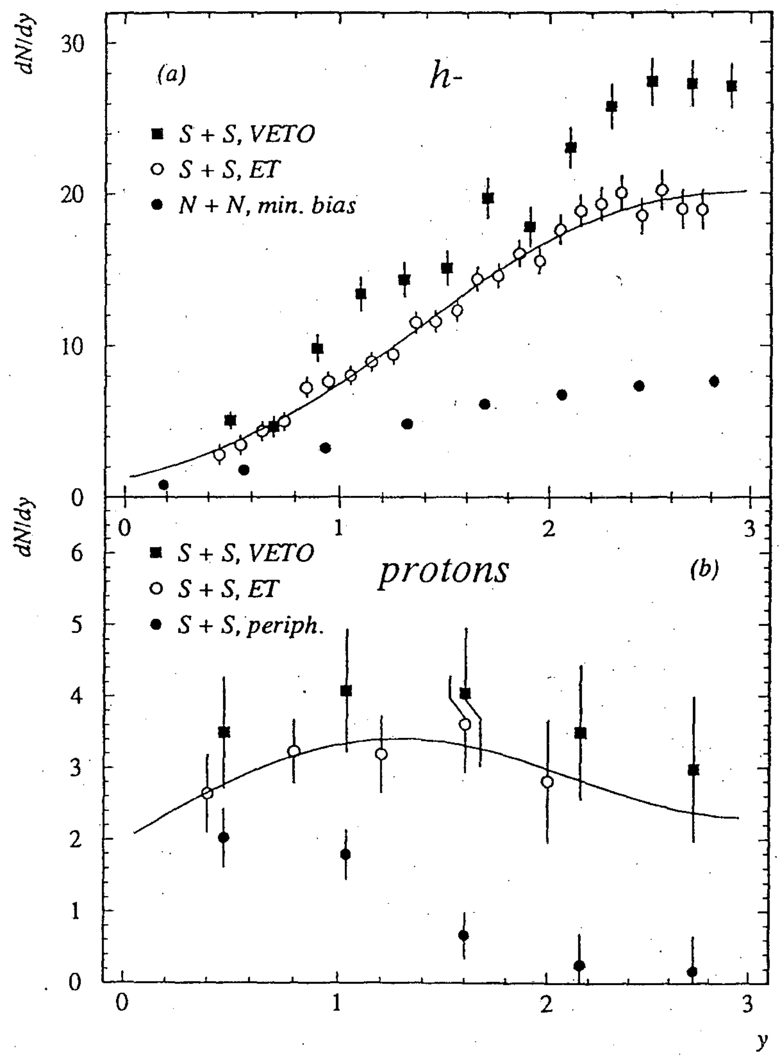


Fig. 1. Rapidity distributions normalized per event for a) $h^-$ and b) participant protons measured in 200 GeV/n interactions. The normalization for the NN minimum bias data is arbitrary. Error bars are statistical only. The acceptance is rectangular in y and $p_t$. The data in a) are integrated over $0.05 < p_t < 2.0$ GeV/c. All data in b) are extrapolated to $p_t = 0$ assuming factorization of the cross section into independent rapidity and transverse momentum terms. The solid curves correspond to a symmetric double Gaussian parametrization, described in Ref. 4 and used to illustrate a partial stopping scenario.

The participant proton rapidity distributions are displayed in Fig. 1b for the Veto, $E_t$ and peripheral triggers. More protons participate and are observed as the trigger becomes more central. The data for both central triggers have similar shapes and are rather flat with a possible broad peak near y = 1.5. Both rapidity distributions of Fig. 1 can be reflected about $y = y_{cm} = 3$ because of the mass and isospin symmetry of the colliding system. The target fragmentation peak observed in the rapidity distribution of the peripheral data is not present in that of the central collision data. If the stopping were complete in the S + S central collision data, then a peak at midrapidity would be expected. The central collision rapidity distributions exhibit a significant, although incomplete, amount of stopping. The mean rapidity shifts are $\langle\Delta y\rangle = 1.58 \pm 0.15$ and $\langle\Delta y\rangle = 1.57 \pm 0.19$ for the Veto and $E_t$ triggers, respectively. This is larger than the $\langle\Delta y\rangle$ observed in central $\alpha\alpha$ collisions at the ISR[7] at a somewhat higher energy of $\sqrt{S} =$ 31 GeV.

The number of participant target protons $N_p$ is determined to be $N_p = 12.8 \pm 1.4$ and $N_p = 10.3 \pm 1.4$, respectively, for the Veto and $E_t$ triggers. This corresponds to 51 and 41 participant nucleons per event for these two triggers. The mean negatively-charged multiplicity per participant nucleon pair is $3.4 \pm 0.5$. Note that this is the same value within errors as that for the isospin averaged NN collisions at the same energy.[8] As reflected by the larger $\langle\Delta y\rangle$ the central S + S system has higher stopping than observed in the NN system. There is more energy per participant made available for particle production in S + S than in NN collisions. The energy must go into some other degree of freedom. Our previous observation[1,9] of an enhancement in strangeness production in central S + S collisions suggests that the incremental stopped energy results in preferential production of heavy hadrons rather than a further increase in the hadron production.

The h- transverse momentum distributions are displayed in Fig. 2a-b for two different rapidity intervals for each of the two central triggers. The shapes of the distributions are identical within errors for the two different triggers. The measured $p_t$ distributions are independent of rapidity within the statistics of this study. The distributions have a complicated shape and cannot be fit by a simple thermal model. A two component thermal fit $g(p_t) = f(A_1,T_1,p_t) + f(A_2,T_2,p_t)$ to the expression $f(A,T,p_t) = Am_t(p_t)\, K_1(m_t/T)$, with $m_t = \sqrt{(p_t^2 + m^2)}$ the transverse mass and $K_1$ the modified Bessel function. This equation is the exact result obtained from an ideal thermal distribution in the Maxwell-Boltzmann limit after integrating over phase space in the longitudinal degree of freedom. It is also a good approximation of the thermal model for limited rapidity intervals in the presence of longitudinal expansion. The data cannot be fit by a single-temperature function of $m_t$ over the entire $p_t$ acceptance of this experiment.

Since the fit parameters are correlated, the parameter R is fixed at R = 60 %, the relative yield of negative pions from direct thermal radiation and $\rho$ decay calculated for a thermally- and chemically-equilibrated hadron resonance gas.[10] The fitted parameters for the different triggers and rapidity intervals are the same within errors. For $1 < y < 2$, $T_1 = 84 \pm 21$ MeV, $T_2 = 181 \pm 18$ MeV for the Veto trigger and $T_1 = 83 \pm 6$ MeV, $T_2 = 188 \pm 8$ MeV for the $E_t$ trigger. For $2 < y < 3$, $T_1 = 82 \pm 10$ MeV, $T_2 = 197 \pm 14$ MeV for the Veto trigger and $T_1 = 85 \pm 11$ MeV, $T_2 = 191 \pm 7$ MeV for the $E_t$ trigger. This is clear evidence that a spherically symmetric thermal model does not apply at this energy.

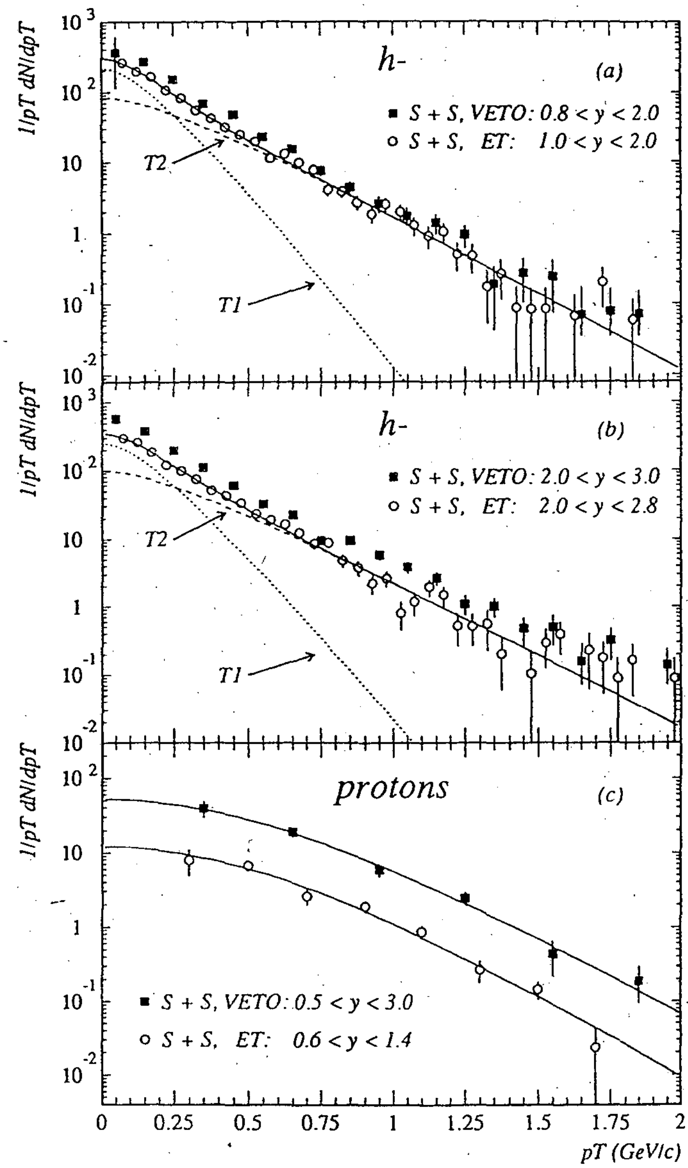


Fig. 2. Transverse momentum distributions for a) h- at low rapidity, b) h- near midrapidity and c) participant protons. The error bars are statistical only. The solid curves represent in a) and b) two-component fits and in c) a single temperature fit as described in the text.

The two-component spectra of the $h^-$ can be explained by considering resonances and their decay products in the final state.[10,11,12] Most resonances which have a $\pi^-$ in the final state undergo mass asymmetric or 3-body decays, e.g. $\Delta \rightarrow N\pi$ and $\eta \rightarrow \pi^+\pi^-\pi^0$. The kinematics of these decays focus the $\pi^-$ to low $p_t$. However, the mass symmetric twobody decays $\rho^{0,-} \rightarrow \pi^{+,0}\pi^{-}$ contribute significantly to the $\pi^-$ spectra at $p_t > 500$ MeV/c creating an $h^-$ spectrum which can be approximated by two temperature components.

The transverse momentum distributions of the protons are plotted in Fig. 2c. The mean transverse momenta of the proton distributions were found to be $<p_t> = 622 \pm 26$ MeV/c and $<p_t> = 595 \pm 26$ MeV/c for the Veto and $E_t$ triggers, respectively. Whereas the $<p_t>$ values measured for the $h^-$ data, $<p_t> \sim 360$ MeV/c, are approximately equal to those measured in pp interactions near midrapidity,[6,13] the values measured for the proton spectra in S + S collisions are considerably higher than those measured in pp data,[6,14] $<p_t>^{pp} \sim 400$ MeV/c.

As opposed to the $h^-$ distributions, the proton spectra can be fit with a single temperature thermal model fit with $T = 180 \pm 14$ MeV and $T = 168 \pm 10$ MeV for the Veto and $E_t$ triggers, respectively. These T values are close to the high temperature component $T_2 = 181$ - 197 MeV measured for the $h^-$ spectra.

Displayed in Fig. 3 are transverse mass $m_t = \sqrt{(p_t^2 + m^2)}$ distributions for the $h^-$, $K^o{}_s$, protons and $\Lambda$ measured in the rapidity intervals $0.8 < y(h^-) < 2.0$, $1.5 < y(K^o{}_s) < 3.0$, $1.4 < y(p) < 2.7$ and $1.5 < y(\Lambda) < 3.5$ for central $^{32}S + {}^{32}S$ collisions at 200 GeV/nucleon in the same experiment. Plotted is the variable $m_t^{-3/2}dn/dm_t$ as a function of $m_t$. Using relativistic thermodynamics as developed by Hagedorn[15] for a single isotropic fireball, a Boltzmann distribution after integration over rapidity gives $dn/dm_t = \kappa\, m_t^{3/2} \exp(-m_t/T)$ for large $m_t/T$, where $\kappa$ is a constant. Thus at large $m_t$, $m_t^{-3/2}dn/dm_t$ plotted as a function of $m_t$ should be a negative exponential with a single slope and temperature T for all particles. This appears to be the case for the measured $\Lambda$, $K_o$ and proton distributions as well as the larger $m_t$ regime of the $h^-$ spectra. The straight lines in Fig. 3 correspond to $dn/dm_t = \kappa\, m_t^{3/2} \exp(-m_t/T)$ with T = 200 MeV. Can this be a transition temperature that we are seeing?

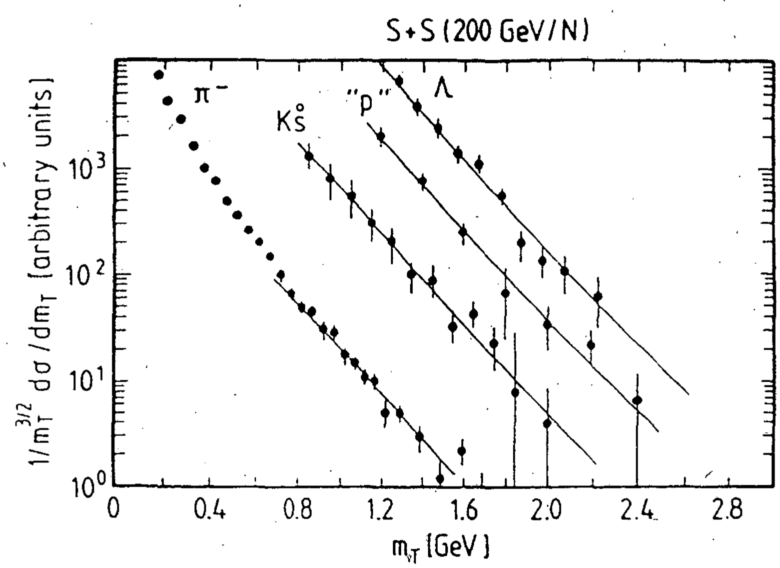


Fig. 3 Transverse mass distributions for particles in central collisions of 200 GeV/n S + S central interactions. The rapidity intervals are described in the text. The straight lines correspond to a temperature of 200 MeV in the Hagedorn fireball model.

## 4. Summary and Conclusions

Transverse momentum and rapidity distributions of negative hadrons, $K^{\circ}_{s}$, Λ, and participant protons have been measured in the target hemisphere for 200 GeV/nucleon central $^{32}S + ^{32}S$ collisions. The mean rapidity shift $<\Delta y> \sim 1.5$ and mean transverse momentum $<p_t> \sim 600$ MeV/c of participant protons are larger than observed in pp collisions suggesting that successive scattering in participant matter plays a significant role in nucleus-nucleus (AA) collisions. This leads to increased stopping in AA collisions relative to pp interactions. The rapidity and transverse momentum distributions of $h^-$ and participant protons can be accomodated in a simple picture of partial stopping followed by longitudinal expansion. The transverse mass distributions of $K^{\circ}_{s}$, Λ, participant protons and high $m_t$ negative hadrons are consistent with thermal equilibrium at a temperature T ~ 200 MeV. The $h^-$ per participant nucleon and measurements of the particle and strangeness production over a large fraction of the available phase space suggest that the increased stopping of S + S compared to pp interactions is directed preferentially into the production of heavy hadrons.

## 5. Acknowledgements

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