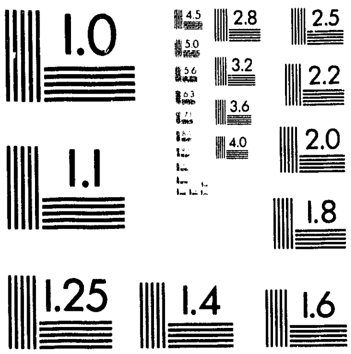

Centimeter
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
mm
1
2
3
4
5
Inches



1 of 1

PX56 Proceedings of the 10th International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions (Quark Matter 1993), Borlange, Sweden, June 20-24, 1993, in press.

BNL-49934

Conf-930636--15

Particle Spectra and Correlations from Experiment 814

Johanna Stachel Department of Physics, SUNY at Stony Brook, Stony Brook, NY 11794-3800, USA

for the E814 Collaboration:
J. Barrette[3], R. Bellwied[8], S. Bennett[8], P. Braun-Munzinger[6], W.E. Cleland[5], T.M. Cormier[8], G. David[6], J. Dee[6], G.E. Diebold[9], O. Dietzsch[7], J.V. Germani[9], S. Gilbert[3], S.V. Greene[9], J.R. Hall[8], T.K. Hemmick[6], N. Herrmann[2], B. Hong[6], K. Jayananda[5], D. Kraus[5], B. Shiva Kumar[9], R. Lacasse[3], Q. Li[8], W.J. Llope[6], T.W. Ludlam[1], S. McCorkle[1], R. Majka[9], S.K. Mark[3], R. Matheus[8], J.T. Mitchell[9], M. Muthuswamy[6], E. O'Brien[1], S. Panitkin[6], C. Pruneau[8], M.N. Rao[6], M. Rosati[3], F. Rotondo[9], N.C. daSilva[7], U. Sonnadara[5], J. Stachel[6], H. Takai[1], E.M. Takagui[7], C. Winter[9], G. Wang[3], D. Wolfe[4], C.L. Woody[1], N. Xu[6], Y. Zhang[6], Z. Zhang[5], C. Zou[6]

[1]BNL – [2]GSI – [3]McGill Univ.– [4]Univ. of New Mexico – [5]Univ. of Pittsburgh – [6]SUNY Stony Brook – [7]Univ. of São Paulo – [8]Wayne State Univ. – [9]Yale Univ.

1. INTRODUCTION

In this article we will summarize recent results from the E814 forward spectrometer on proton and pion distributions that give insight into the initial baryon (and energy) density achieved in central collisions as well as the temperature of the system at freeze-out. An independent measure for the latter, complementing the slope constants of particle spectra, is the population of nucleon excited states, in particular the $\Delta(1232)$ resonance. Besides its influence on the pion spectra it has also been identified directly in our experiment and we will discuss the first results. The first results from E814 on kaon spectra at low transverse momentum p_t will be presented here; the spectra show an unexpected very steep rise at the lowest p_t. The two pion correlation function has been studied for positive and negative pions and we will show that it is consistent with a large source size at freeze-out. Finally, we will show that the present data give a consistent picture of a system in thermal and chemical equilibrium at freeze-out.

The data presented here will be for central 14.6 A GeV/c Si + Al and Si + Pb collisions. The measure for centrality is always the multiplicity of charged particles N_c emitted into the pseudorapidity range $0.85 < \eta < 3.8$. Different centrality cuts will be quantified in terms of the trigger cross section σ in units of the geometric cross section $\sigma_{geo} \approx 3.6$ b (1.6 b) for the Pb (Al) target. The E814 experimental setup has been described previously (see e.g. [1]); all data presented here were taken in runs in spring 1991 and 1992 in the 'open spectrometer configuration' described in [2]. It covers in one fixed setting an angular range in the magnet bend plane of $-115 < \theta_x < 14$ mr and $-21 < \theta_y < 21$ mr perpendicular to it.

Work partially funded by the U.S. Department of Energy.

2. BARYON RAPIDITY DISTRIBUTION

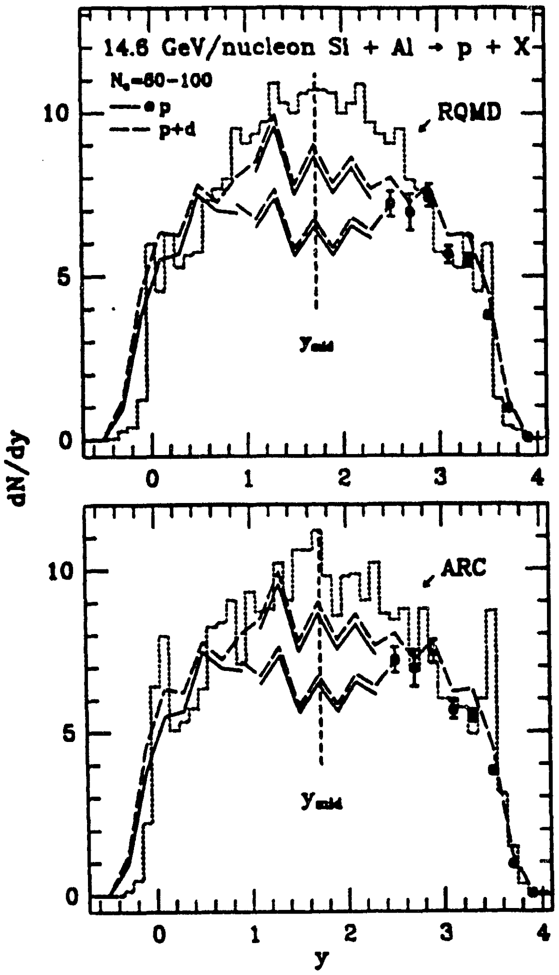


Figure 1: Proton rapidity distribution [2] (solid dots and lines) and sum of proton and deuteron distributions (long dashed lines) together with predictions from the event generators RQMD and ARC

The proton rapidity distribution for very central (σ/σ_{geo} = 0.2 %) Si + Al collisions is shown in Figure 1. As described in more detail in [2], in the rapidity range $2.4 \leq y \leq 4.0$ the experimental coverage in p_t is sufficiently large to complete the integral to $p_t = \infty$ without introducing a noticeable error in dN/dy (solid points in Fig. 1). The (near) symmetry of the colliding system requires the rapidity distribution to be symmetric about midrapidity and hence allows the reflection of the data points about midrapidity to obtain information for $y \leq 1.0$. In the interval y = 1.0 - 2.4 only the low p_t part of the spectrum is measured. To complete the integral to obtain dN/dy we have assumed a 'reasonable' range of slope constants in p_t leading to a range in dN/dy indicated by the band of solid lines in Fig. 1. The lower limit is to be viewed as such since it assumes that slope constants are constant for y = 0.8 - 2.6, while the upper limit reflects the expected and generally observed rapidity dependence of the slopes (see [2] and below).

The absence of a peak at beam rapidity indicates the large degree of stopping in the system. But the distribution is wider than expected for a fully stopped isotropic proton source with dN/dy $\propto 1/\cosh(y - y_f)^2 \approx \exp[-(y - y_f)^2/2 \cdot 0.88^2]$. The data show a mean rapidity shift (evaluated for the top half of the rapidity distribution) of $\Delta y = 0.90$ or 0.22 less than for an isotropic source at y_{mid}. Compared to the transverse motion, a proton has an excess kinetic energy longitudinally of 0.37 GeV. This could indicate either that the amount of stopping is about 80 % or that the protons were initially fully stopped and acquired the excess longitudinal kinetic energy by a collective longitudinal expansion with a velocity $\beta \approx 0.22$ relative to transverse motion. To compare the data to predictions of models we add the measured deuteron to the proton distributions (dashed lines in Fig. 1). Fig. 1 also shows results from the event generators RQMD [3] and ARC [4], both based on cascading and resonance production. The overall degree of stopping is reasonably described by both models. The mild discrepancy at midrapidity could indicate that the proton p_t slope constant is actually larger than we assumed for the evaluation of dN/dy. It could also indicate that an also experimentally observed trigger bias towards larger proton numbers for large N_c (triggering on charged particles selects charged partilce decays of neutral resonances) is too strong in the models.

3. PARTICLE SPECTRA AND FREEZE-OUT TEMPERATURE

Figure 2 shows the π^- spectrum in transverse mass m_t divided by a Boltzmann spectrum $\sigma_{inv} \propto m_t \cdot \exp(-m_t/T_B)$ fitted to the range $p_t \geq 0.3$ GeV/c. The data are for central (top 2 %) Si + Pb collisions and are discussed in more detail in Hemmick's contribution [5]. They exhibit a significant enhancement at low p_t over a thermal distribution. We find the same enhancement for both pion charges and for the Al target. It has been proposed [6] that decays of the $\Delta(1232)$ resonance are the source of this enhancement and that this can actually be used as a quantitative measure of the nucleon resonance population at freeze-out and hence the true temperature of the system.
To show the sensitivity of the data, we also plot the distributions obtained for a thermal system with a ratio of pions from Δ decay to direct pions of 0.40 and 0.60. It can be seen that this range just brackets our experimental data. To fix the temperature, one has to know in addition the nucleon to pion ratio. Considering rapidities forward of y = 0.5 and the available experimental data, the rapidity average of this ratio is about 0.95. This implies that 30-40 % of all nucleons are in the $\Delta(1232)$ resonance, corresponding to a temperature of 140 ± 20 MeV. As discussed in [5], RQMD reproduces our pion spectra extremely well and there the rapidity averaged fraction of nucleons in the $\Delta(1232)$ resonance at freezeout is 35 % [7].

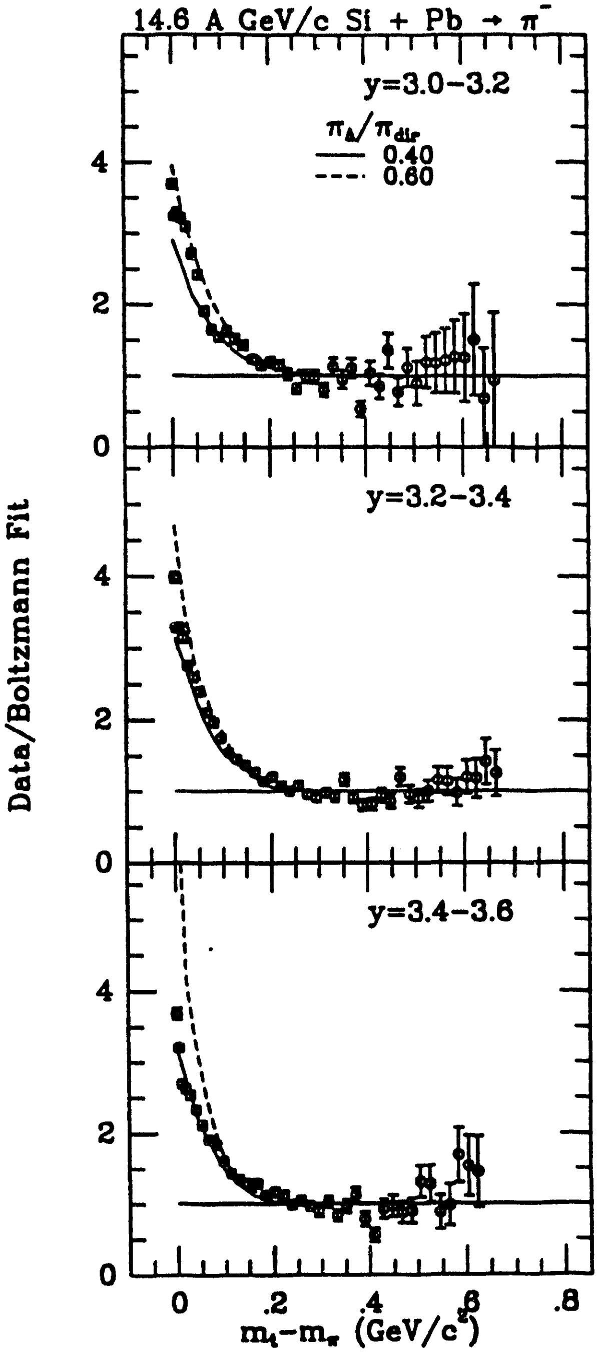


Figure 2: Experimental π^- spectra normalized to a Boltzmann distribution fitted to the data for $p_t \geq 0.3$ GeV/c. Solid and dashed lines: thermal model with different fractions of Δ decay vs. direct pions.

A synopsis of the Boltzmann temperature for different particle species and central collisions of Si(S)+Au(Pb) at 14.6 and 200 A GeV/c is shown in Figure 3 as a function of rapidity normalized to the beam rapidity. For AGS energies, all data points backward of 0.6 are from E802/E859, the points forward of 0.6 from E810 (K,Λ) and E814 (p,π). There is now enough overlap in the

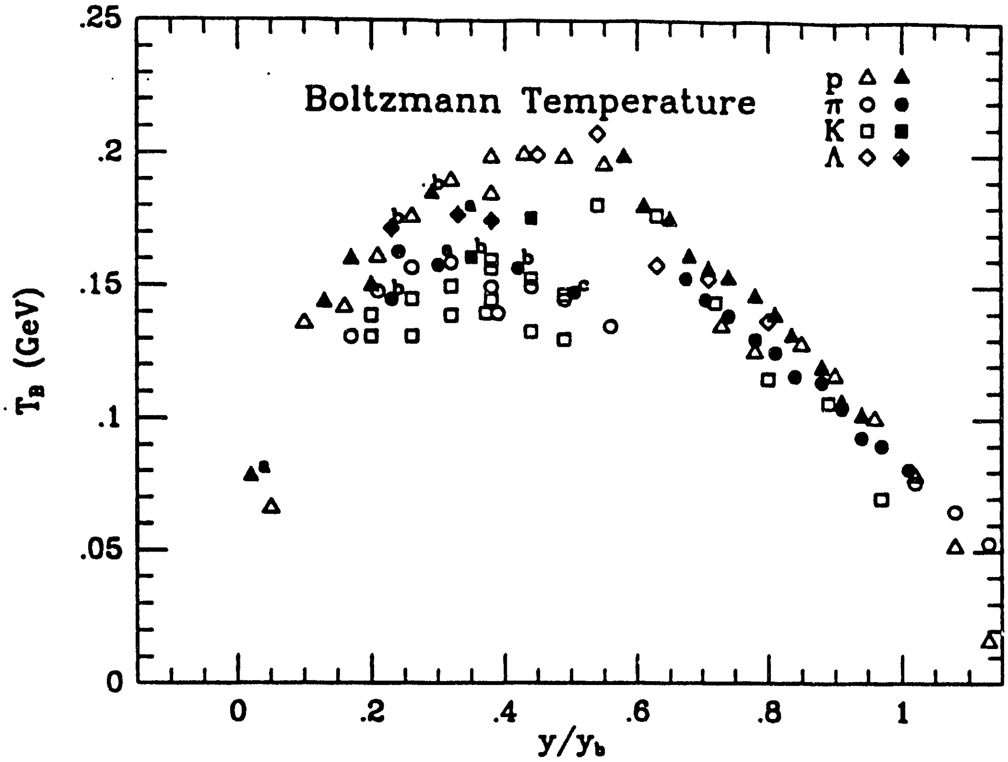


Figure 3: Boltzmann temperatures of different particle species for central Si(S)+Pb(Au) collisions at the AGS (open symbols) and SPS (200 A GeV/c, closed symbols) as a function of the rapidity normalized to the beam rapidity. New data points from E802/E859 [8, 9], E810 [10], E814 [2, 5] and NA35 [11] have been added to a figure from [12]. See [12] for details and other references.

data from the AGS and SPS for the individual particle species to see that there is no noticeable difference in the slopes of the particle spectra, i.e. the final state of the system appears not to depend on the intial condition in support of the idea of an equilibrated system at freeze-out. There are, however, significant differences in the values of T_B for the different particle species in the midrapidity range. With the exception of K^-, which always shows a relatively steep slope, more massive particles systematically exhibit larger slope constants. This could be an indication of transverse collective flow. The observed spread can be accounted for with an approximate flow velocity of $\beta = 0.15$.

In Figure 3 of [5] it is shown that the $\Delta(1232)$ resonance is also seen directly in E814 by reconstructing the $p\pi^+$ invariant mass in central (top 2 %) Si + Pb collisions. In Figure 4 we show a first attempt to give an acceptance corrected yield of Δ^{++}. Together with the rapity density of Δ^{++} from RQMD [7] we show the geometrical acceptance in the E814 spectrometer using p_t spectra for the Δ as measured for protons. For such an input distribution our acceptance is $1.5 \cdot 10^{-3}$ for the rapidity interval y = 1.9 - 3.1. This leads to a Δ^{++} multiplicity of 2.1 ± 0.7 for this interval as compared to 5.9 protons in the same rapidity interval. RQMD predicts 1.8 Δ^{++} for this interval in good agreement with our preliminary experimental number.

4. KAON SPECTRA

For the 1992 run a time-of-flight telescope was implemented 12 m downstream from the target immediately after the last tracking chamber in order to obtain kaon spectra at low p_t. This hodoscope had appropriate granularity for Si + A collisions and a time resolution of 260 ps. For E877 it will be replaced by a new hodoscope with much finer granularity and better timing. Figure 5 (left) shows time spectra for different momentum bins and positively charged particles. Here, the time has been calculated relative to the time-of-flight of a particle with a mass of 494 MeV (kaon) so that kaons should lead to Gaussians centered about zero with a momentum independent width determined by the time resolution only. Other particle species lead to (near Gaussian) distributions with a momentum dependent but calculable shape. On the right hand side of Fig. 5 we show the leftover distribution after subtraction of the pion and proton distributions and a constant background fitted to the region between kaon and proton. In order to obtain kaon spectra free from contamination only the finely hatched region of the kaon peaks was used later on. This way the background subtraction never amounts to more than 10 %. We have studied both from the data and in simulations the shape in m_t of the subtracted proton and pion background. Data and simulations agree well and show that the observed shape of the kaon spectra cannot be explained in terms of the background and is in fact very insensitive to the precise amount of background subtracted.

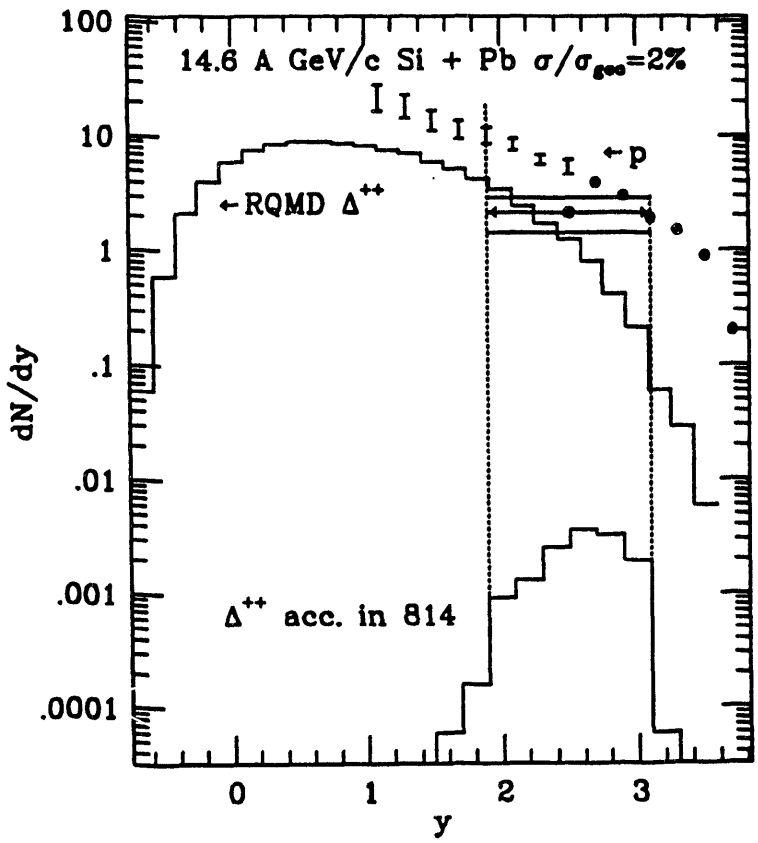


Figure 4: Rapidity distribution of protons from E814[2], of Δ^{++} from RQMD[7], of Δ^{++} into the 814 acceptance and acceptance corrected experimental yield of Δ^{++} (open circle).

The resulting preliminary spectra vs. $m_t - m_K$ for both kaon charges are shown in Figure 6 for two rapidity bins and central Si + Pb collisions (σ/σ_{geo} = 2%). Note, that the invariant multiplicity has been divided by an additional factor m_t so that Boltzmann distributions are represented by exponentials with the temperature T_B as inverse slope constant. The dashed lines indicate exponentials fitted to the data. The resulting values of T_B are 12 MeV for K^+ and 10 MeV for K^-. The spectra at low m_t are obviously much steeper than what is observed at $m_t - m_K \geq$ 0.02 GeV/c^2 by the E802/ E859 collaboration (see e.g. Fig. 3 and [9]). This effect is not reproduced by the current event generators. As an example we also show in Fig. 6 the results from RQMD as well as fits of the RQMD spectra at larger m_t ($m_t - m_K \geq 0.1$GeV/c^2). Our data, although currently measured only over a small p_t interval, show a significant low p_t kaon enhancement for both kaon charges. The source of this enhancement is currently not known, although it has been conjectured that a collective potential of a depth of 50 MeV or larger or an equivalent drop of the kaon mass in the dense medium could account for the data [13]. More data will be taken with Au beams by E877 to further study and establish this effect.

5. PION CORRELATIONS AND SOURCE SIZE AT FREEZE-OUT

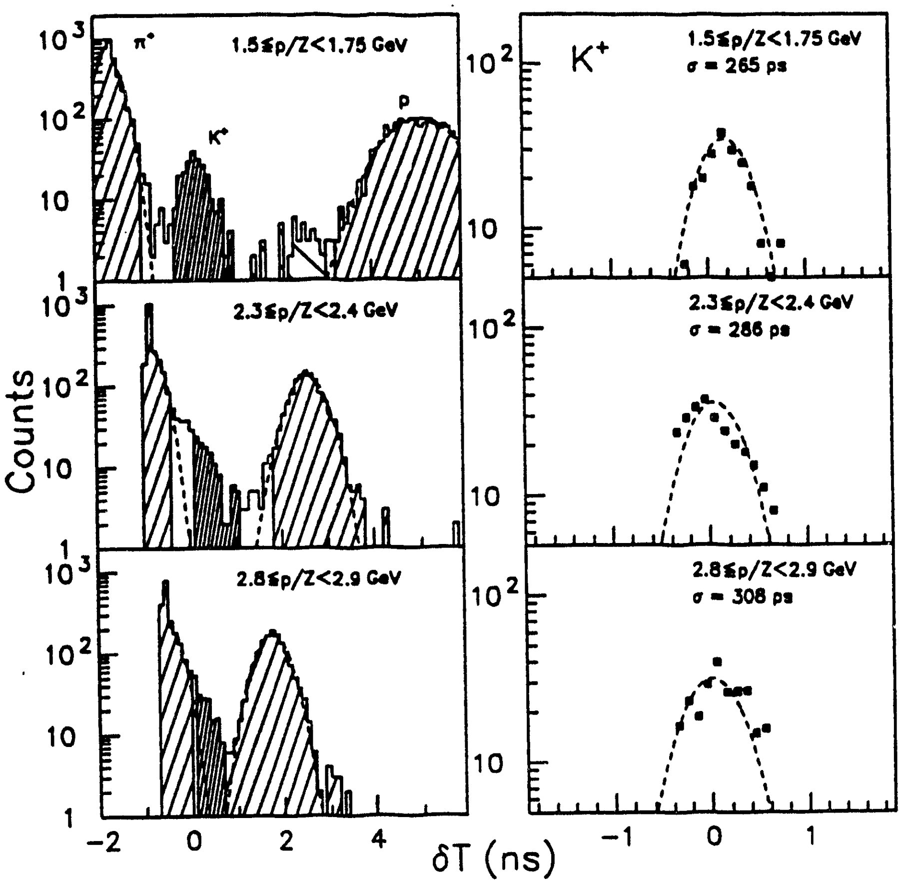


Figure 5: Left: Distributions in time-of-flight relative to that of a kaon for positively charged particles. Right: After background subtraction (see text).

The $\pi^+\pi^+$ and $\pi^-\pi^-$ correlation function measurement for central Si + Pb collisions (top 10 %) has been discussed in [14] and the 814 data are again presented in Figure 7. Because of the arguments given in [14] we prefer to obtain a correlation function from an event generator with known space time extent of the souce of particles (e.g. pions) and compare this to the experimental correlation function over fitting the data with certain functional forms. Fig. 3 shows in comparison to our data the correlation function obtained for RQMD events and excellent agreement is found for both pion charges. Going back to the original RQMD events, one finds that on average the pions are emitted from a source of transverse radius R_T = 6.7 fm and of longitudinal radius (in the c.m. frame) R_L = 5.0 fm. This source is nearly spherical with a rms radius of R = 8.3 fm and we conclude that our data are consistent with such a source. The transverse radius has to be compared to e.g. the initial transverse size of the system of R_T(Si) = 2.9 fm yielding a transverse expansion of the sytem by a factor 2.3. If the expansion proceeds with $\beta = 0.3$ the timescale of the expansion is 10 fm/c. We saw above that more realistic estimates of the collective expansion velocity give $\beta \approx 0.2$ leading to a time of about 15 fm/c. A very similar radius of the system is obtained from the deuteron to proton ratio in central Si + Pb collisions and its interpretation in a thermal model [15].

The pion interferometry data as well as the d/p ratio are consistent with a volume at freeze-out of V = 2400 fm^3. One can explore whether this is a reasonable result in terms of the known pion nucleon cross section. For a freeze-out temperature T_f = 0.14 GeV one finds a thermal and isospin averaged value of $\sigma_{\pi n}$ = 62 mb. Defining that freeze-out occurs when the average distance from a given nucleon to the nearest pion is $d = \sqrt{\sigma_{\pi n}/\pi}$ the freeze-out volume is $V = 2750$ fm^3, close to the above result. For this volume, the densities of nucleons and pions are $\rho_n = 0.045/\mathrm{fm}^3$ and $\rho_\pi = 0.055/\mathrm{fm}^3$, leading to a baryon chemical potential $\mu_B = 0.48$ GeV. The strangeness chemical potential can be evaluated from the K^+/K^- ratio [9] and is found to be comparatively small, $\mu_S = 0.105$ GeV. To test whether the system at freeze-out is in chemical equilibrium, one can use the values of μ to predict the production ratios $\bar{p}/p = 1 \cdot 10^{-3}$ and $\bar{\Lambda}/\Lambda = 4.7 \cdot 10^{-3}$. Both are close to the experimental values of $0.6(3)\cdot 10^{-3}$ (from E802, E859, E814 and E858 [16]) and $2.0(8)\cdot 10^{-3}$ (E859, preliminary [17]). In summary, we find that there is good evidence from the experimental data on particle spectra, correlations and ratios to support the assumption of a hadron gas in thermal and chemical equilibrium at freeze-out. This, however, also implies that the system at this stage has preserved no 'memory' of the hot intial stage, may it be a hadron gas or a quark-gluon plasma. It also explains why rather simple events generators based just on hadronic cascading can explain the present data so successfully, although their treatment of the system in the high density phase may well not be appropriate. An indication that a system with a large number of degrees of freedem was created comes from evaluating from the data the entropy per baryon $S/N_n = 3.95 - \ln(d/p) + S_\pi/N_n = 12.2$, which is large. In light of this, future experiments will have to search for observables which reflect the early hot and dense stage of the collisions, as e.g. electromagnetic probes, which have not been explored yet at the AGS.

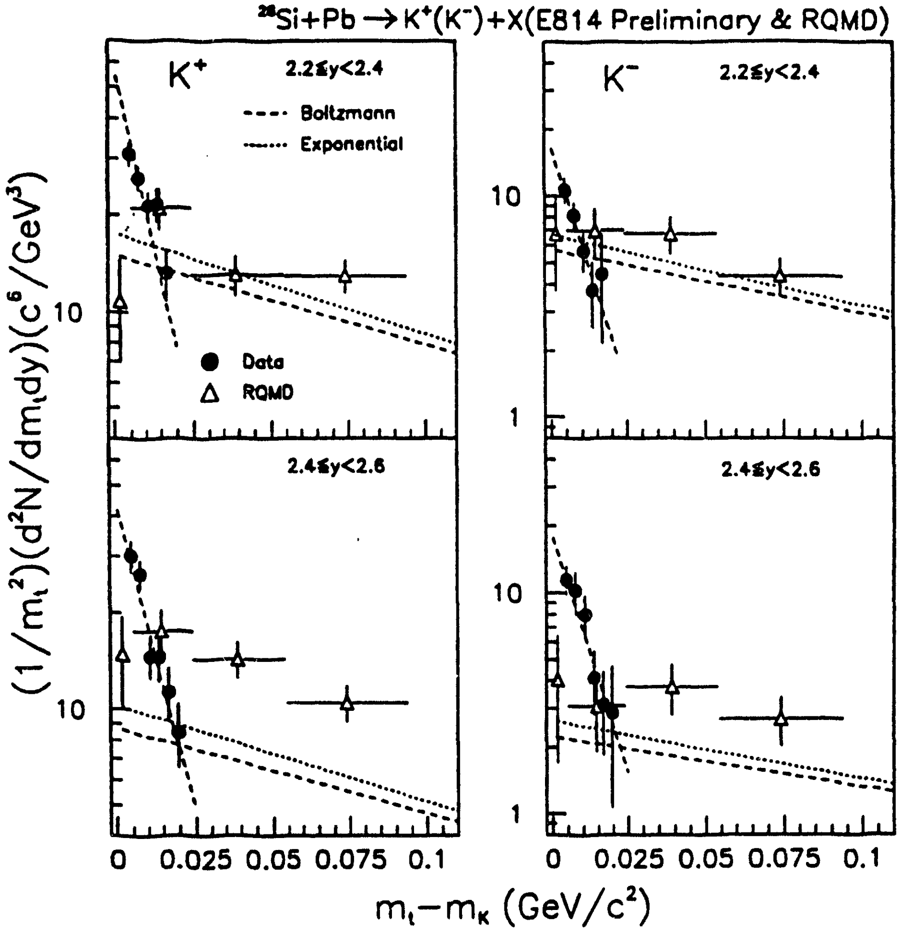


Figure 6: Experimental kaon spectra compared to predictions from RQMD and fits to RQMD at $m_t - m_K \geq 0.1$ GeV/c^2.

Financial support by the US DoE, the NSF, the Canadian NSERC, and CNPq Brazil is gratefully acknowledged.

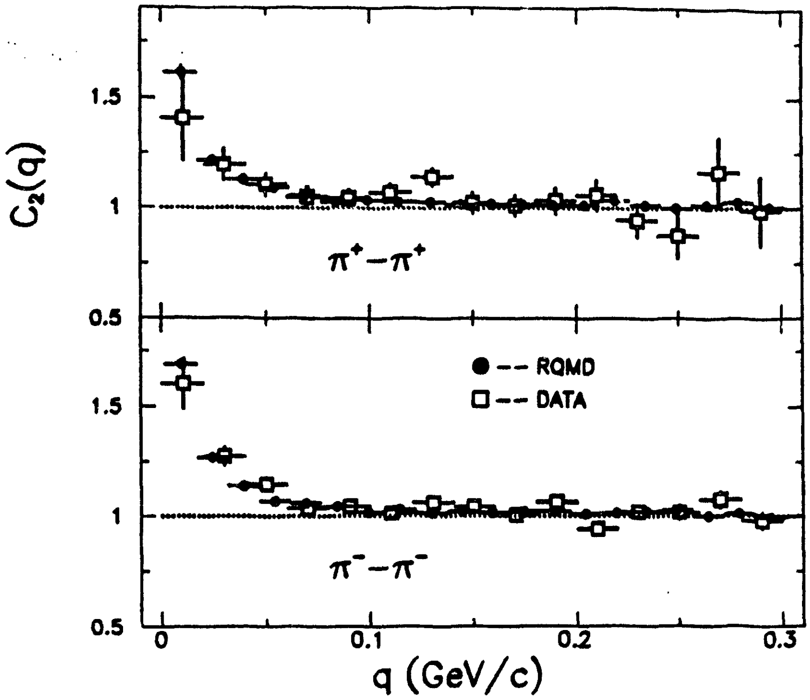


Figure 7: Experimental 2 pion correlation function together with the corresponding correlation function constructed from RQMD events (see [14])

References

[1] J. Barrette et al., E814 Coll., Phys. Rev. Lett. **64** (1990) 1219; Phys. Rev. **C45** (1992) 819; Phys. Rev. **C46** (1992) 312.

[2] J. Barrette et al., E814 Coll., Z. Physik **C59** (1993) 211.

[3] H. Sorge, H. Stöcker, W. Greiner, Ann. Phys. (NY) **192** (1989) 266; A. Jahns, H. Sorge, H. Stöcker, W. Greiner, Z. Physik **A341** (1992) 243.

[4] T. J. Schlagel, S. H. Kahana and Y. Pang, Phys. Rev. Lett. **69** (1992) 3290.

[5] T.K. Hemmick, these proceedings.

[6] G.E. Brown, J. Stachel, and G.M. Welke, Phys. Lett. **B253** (1991) 19.

[7] M. Hofmann and R. Mattiello, private communication.

[8] C. Parsons, proceedings Workshop HIPAGS '93, MITLNS-2158.

[9] T. Sung, proceedings Workshop HIPAGS '93, MITLNS-2158.

[10] A. Saulys, proceedings Workshop HIPAGS '93, MITLNS-2158.

[11] J. Mitchell, these proceedings.

[12] J. Stachel and G.R. Young, Annu. Rev. Nucl. Part. Sci. **42** (1992) 537.

[13] V. Koch, G.E. Brown, E.V. Shuryak, private communication.

[14] N. Xu, these proceedings.

[15] J. Germani, Ph.D. thesis, Yale Univ., July 1993.

[16] see e.g. overview by H.J. Crawford, proceedings Workshop HIPAGS '93, MITLNS-2158 and refs. there.

[17] G.S.F. Stephans, these proceedings.

DATE
FILMED
8/25/94

END