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Publication Date

1998

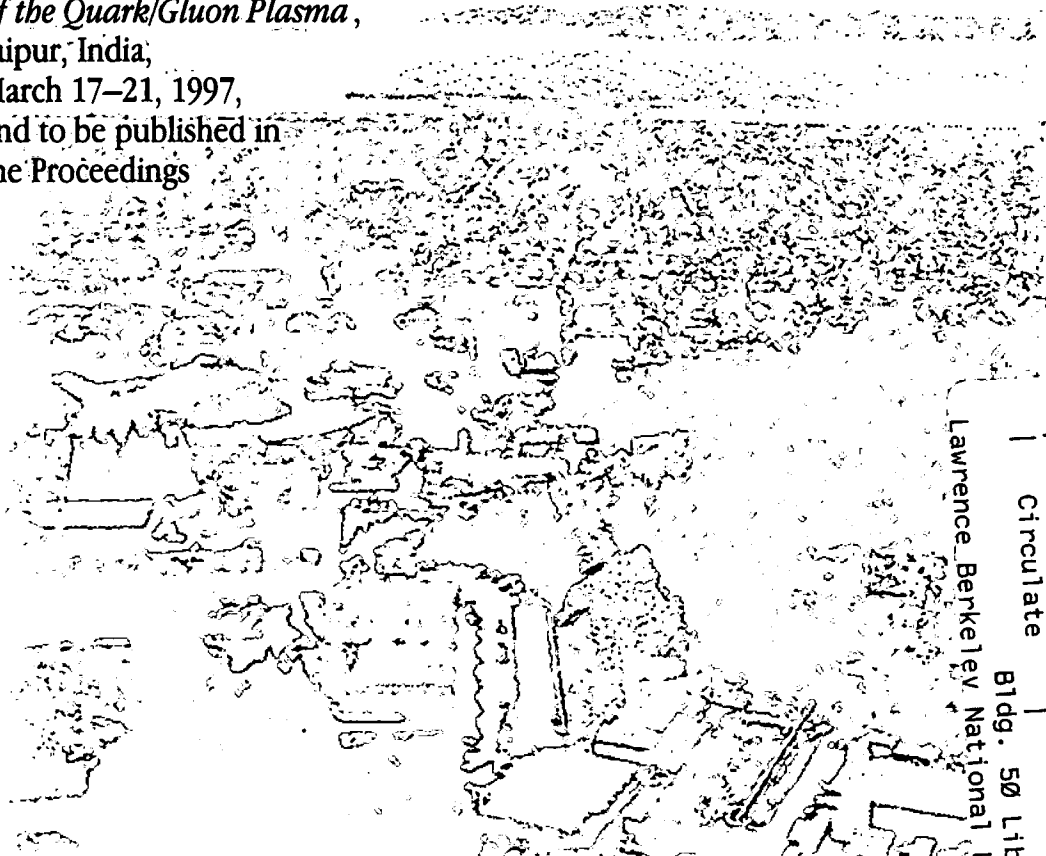


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Hadronic Spectra from Collisions of Heavy Nuclei

Peter Jacobs
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March 1997
Presented at the
*International Conference
on the Physics/Astrophysics
of the Quark/Gluon Plasma*,
Jaipur, India,
March 17-21, 1997,
and to be published in
the Proceedings



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LBNL-40258
UC-413

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March 1997

This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Nuclear Sciences Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

Hadronic Spectra from Collisions of Heavy Nuclei

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Abstract

Hadronic spectra from collisions of heavy ions at ultrarelativistic energies are discussed, concentrating on recent measurements at the SPS of central Pb+Pb collisions at 158 GeV/nucleon, which are compared to collisions of lighter ions and at lower beam energies. Baryon stopping is seen to be larger for heavier systems and lower energies. Total yields of pions and kaons scale with the number of participants in central collisions at the SPS; in particular, the K/π ratio is constant between central S+S and Pb+Pb at the SPS. Transverse mass spectra indicate significantly larger radial flow for the heavier systems. At midrapidity, an enhancement of $\langle\pi^-\rangle/\langle\pi^+\rangle$ and $\langle K^-\rangle/\langle K^+\rangle$ at low p_T are best explained by final state Coulomb interaction with the residual charge of the fireball.

1 Introduction

Single particle spectra of stable hadrons are a familiar tool for the study of high energy reactions. When heavy ions collide at ultrarelativistic energies, the observed single particle spectra reflect the state of the system at the time of their last interaction, commonly called freezeout. One can distinguish between kinetic and chemical freezeout, controlled by the elastic and inelastic hadronic cross sections for a given particle species. The natural question is whether these spectra carry messages from the earlier hot and dense phase of

the collision, which of course is what we aim to study. The only interesting answer to this question is affirmative, but this is not a foregone conclusion. Considerable theoretical effort over many years has gone into elucidating the information content of single particle spectra, within both hydrodynamical and cascade model frameworks (for a clear example of the former, see [1, 2]).

In this talk I will discuss recent measurements of hadronic spectra carrying information from four successive stages of the collision:

- Initial conditions: baryon stopping
- Hadrochemistry: negative hadron and kaon yields
- Expansion dynamics: transverse mass spectra at midrapidity
- Final state interactions: $\langle \pi^- \rangle / \langle \pi^+ \rangle$ and $\langle K^- \rangle / \langle K^+ \rangle$ at low p_T .

The data are from collisions of the heaviest ions at ultrarelativistic energies. Beams of 158 GeV/nucleon lead ions at the CERN SPS and 11 GeV/nucleon gold ions at the Brookhaven AGS have been available for several years. Analyses of hadronic spectra using these beams are now reaching maturity, and comparison with earlier results from lighter ion beams allows us to let the data speak for themselves to a considerable extent, requiring only occasional reference to theory. I will concentrate on recent results from the NA49 experiment at CERN, but will also present results from NA44 (CERN), E866(AGS), E877(AGS), and EOS(Bevalac). Unless reference is made to a publication, all data reported here should be understood to be preliminary.

2 Initial Conditions: Baryon stopping

Prior to the collision all of the energy is carried by the target and projectile baryons. After the collision, net baryon number is distributed across phase space in a fashion that reflects energy loss of the initial baryons during the collision. In an equilibrium picture the net baryon number is a crucial ingredient controlling the evolution of the chemical composition of the fireball, so that the final state distribution of the “primordial” baryons is an important gauge of the initial kinetic and chemical conditions in the collision. Note, however, that this energy loss is not equivalent, or simply related,

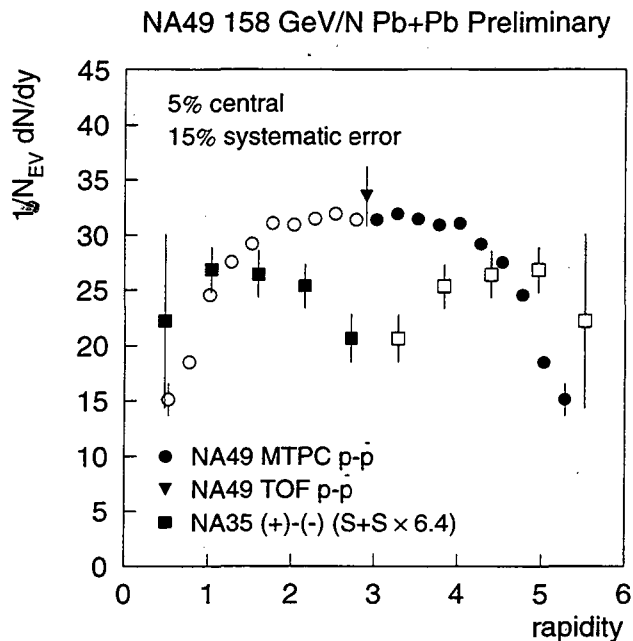


Figure 1: Net proton rapidity distribution for central Pb+Pb collisions at 158 GeV/nucleon from NA49: pid via dE/dx from TPC (circles) and Time of Flight (inverted triangle). Also shown is the equivalent “plus minus minus” for central S+S collisions at 200 GeV/nucleon from NA35 (squares), scaled by 6.4, the ratio of the number of participants in the two systems. Filled symbols are measured data, open symbols are data reflected about y_{cm} .

to the energy available for particle production at midrapidity. We will come back to this point.

It is not possible to completely map the flow of baryon number in the collision by reconstructing all baryons, but we expect that the phase space distribution of *net protons* (i.e. the yield of protons minus that of antiprotons, to eliminate the effect of baryon production during the collision) is representative for the total net baryon number. Fig. 1 shows the net proton distribution measured by NA49 for central Pb+Pb collisions as a function of rapidity, together with the net proton distribution for central S+S collisions measured by NA35[3]. The TPC particle identification in NA49 does

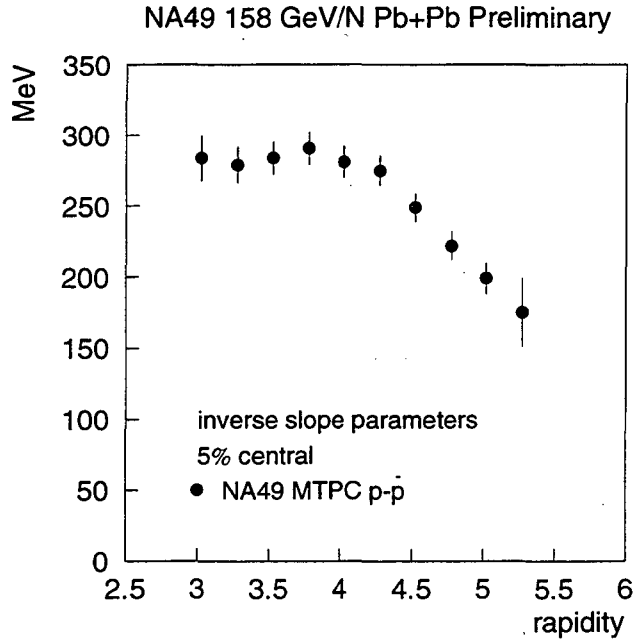


Figure 2: Transverse mass inverse slope parameters in GeV/c for net protons in central Pb+Pb collisions as a function of rapidity, for the data shown in Fig. 1.

not at present discriminate kaons from protons, so the displayed points have been corrected for the difference in charged kaon yields ($K^+ - K^-$), as well as protons from lambda decays that the tracking cannot distinguish from primary vertex tracks. Both kaon and lambda corrections are based upon NA49 measurements for these species. The TOF measurement is not corrected for lambda decays, but it is estimated that agreement with the TPC results will remain after this correction is applied. The integrated yield of measured net protons (within $2.9 < y_{lab} < 5.3$) is 65. A straight line extrapolation gives an estimate of 5 participant protons above the measured region, while model calculations estimate 10 spectator protons on average. Thus the net proton yield in the forward half of phase space is about 80. This is close to 82, the number of incoming projectile protons, and may be indicative of limited

baryonic equilibration.

The Pb+Pb system exhibits considerably greater stopping than S+S, indicated by the much larger fraction of protons at midrapidity. In fact, for Pb+Pb the rapidity distribution is uniform (boost-invariant) for two units about midrapidity. Fig. 2 shows the inverse slope parameters of the net proton transverse mass distribution for central Pb+Pb collisions as a function of rapidity. The same boost-invariant behaviour is seen up to $y_{lab}=4$.

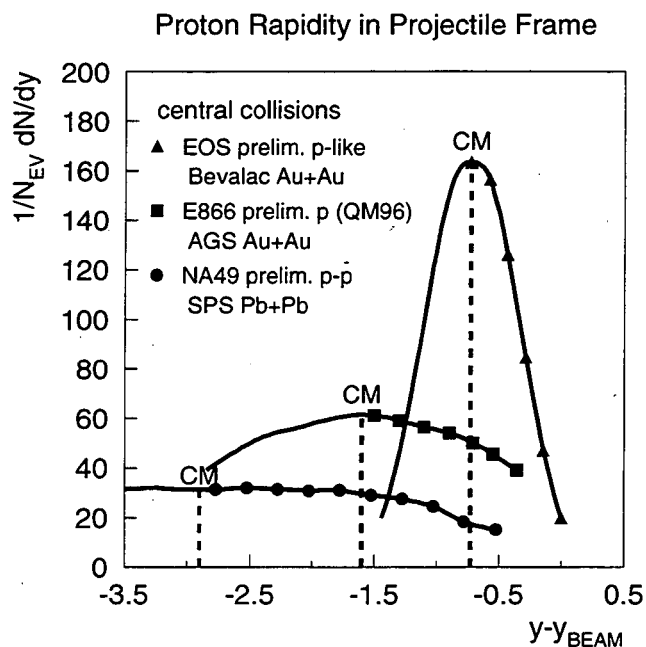


Figure 3: Energy dependence of net proton rapidity distribution for central collisions of heavy nuclei, seen in the rest frame of the projectile. NA49 data from Fig. 1 are compared to data from the AGS[4] and Bevalac[5]. Center of mass for each system is indicated.

Fig. 3 shows the energy dependence of the net proton rapidity distribution for central collisions of heavy nuclei, as seen in the projectile frame of reference. Data are from the Bevalac (1 GeV/nucleon [5]), AGS (11 GeV/nucleon [4]), and the SPS (158 GeV/nucleon, Fig. 1). The three distri-

butions are markedly different. The net proton distribution at the Bevalac shows clearly the limited phase space available and the complete stopping, resulting in a single fireball. The AGS distribution exhibits the relatively more extended phase space, but comparison with the SPS shows that the AGS is not in the asymptotic stopping regime. This is consistent with formation time arguments[6], which claim that the SPS is asymptotic in this respect. Likewise, the inverse slope parameters of the net proton transverse mass distribution at the AGS show a strong dependence on rapidity and no evidence of a plateau[7], unlike Fig. 2.

3 Hadrochemistry: Pion and Kaon Yields

One of the earliest signals predicted for a first order phase transition was an enhancement of the entropy, reflected in the total pion yield. An enhancement of total strangeness has been predicted for systems at high energy density, whether in the hadronic or the quark gluon plasma phase. We address these two questions through measurement of the yields of pions and kaons.

Collective effects may be revealed by comparing systems of different size at the same energy. For this we need a “hadronic baseline”, i.e. a rule determined from pA data for scaling produced particle yields[8]. This is given by the Wounded Nucleon Model scaling[9]: the produced particle 4π yield scales as the number of nucleon participants. This rule works to about 10% for 4π yields of negative hadrons. (Note that scaling with participant number is often used to compare yields within limited acceptance for asymmetric systems or yields of strange particles. Examination of the pA data at 200 GeV/c[8] shows that neither of these uses of the Wounded Nucleon Model scaling is justified.)

Fig. 4 shows the rapidity distribution of negative hadrons (π^- , K^- , \bar{p}) measured by NA49 for central Pb+Pb collisions. Also shown is the negative hadron rapidity distribution for central S+S at 200 GeV/nucleon measured by NA35[3] scaled by 6.4, the ratio of the number of participants in central Pb+Pb and S+S. The Wounded Nucleon scaling is respected to within 10%, leading to the conclusion that no anomalous entropy production occurs at this level. Note that the difference in bombarding energies alone should correspond to 4% greater multiplicity per baryon in S+S than Pb+Pb.

A complete accounting of the energy balance in Pb+Pb, as was done for

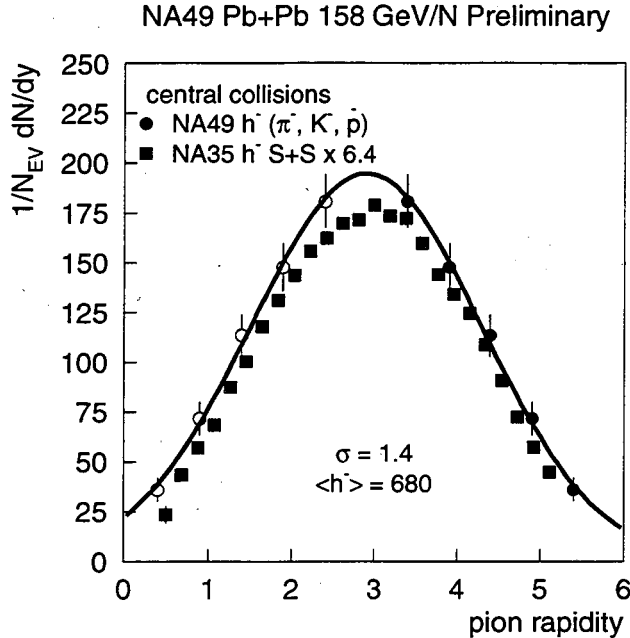


Figure 4: Negative hadron (π^- , K^- , \bar{p}) rapidity distribution for central Pb+Pb collisions from NA49 (measured data: filled circles, reflected data: open circles). Curve is a Gaussian fit ($\sigma = 1.4$, sum=680). Solid points are h^- for central S+S collisions at 200 GeV/nucleon from NA35, scaled by the ratio of the number of participants.

S+S[3], must await measurement of strange mesons and hyperons over large acceptance. However, the constant number of pions per participant baryon does not contradict the stopping picture in Fig. 1, where the distributions of net protons in Pb+Pb and S+S are seen to be very different: for Pb+Pb about 20% and for S+S about 17% of the total energy available in the center of mass is carried as kinetic energy by the net protons and neutrons, so that the significant differences seen in the distributions in Fig. 1 correspond to few percent variations in the energy available for particle production.

NA49 has measured K^+ , K^- , and K_S^0 for central collisions of Pb+Pb, identified by topological techniques in the TPCs and by Time of Flight. The

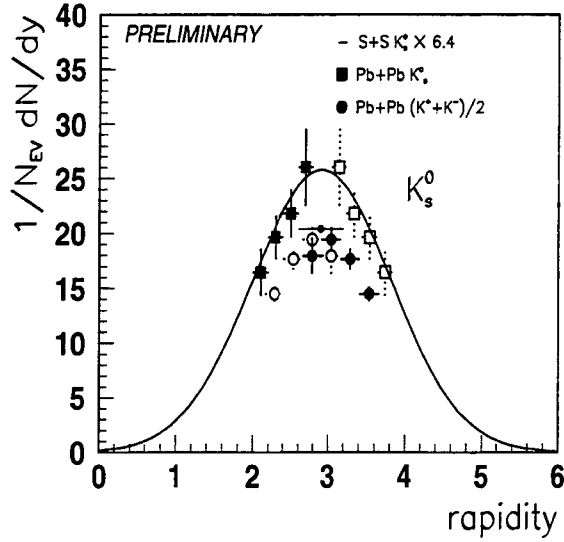


Figure 5: Rapidity distribution of yield of K_S^0 (squares) and the mean yield of K^+ and K^- from NA49 (large circles are TPC data, small circle is TOF datum), for central Pb+Pb collisions at 158 GeV/nucleon. Curve is parametrization of K_S^0 yield for central S+S collisions at 200 GeV/nucleon from NA35 scaled by the ratio of negative hadron yields from Fig. 4.

ratio of the yields of K^+ and K^- at midrapidity is measured to be 1.8. In combination with the yields of Λ and $\bar{\Lambda}$ measured by NA49[10], the baryochemical potential can be determined within a thermodynamic picture[11]: $\frac{\langle K^+ \rangle / \langle K^- \rangle}{\langle \bar{\Lambda} \rangle / \langle \Lambda \rangle} = e^{2\mu_B/T}$. At midrapidity, $\mu_B = 1.1T$ for Pb+Pb, whereas $\mu_B = 0.75T$ [12] for S+S.

Fig. 5 shows the yield as a function of rapidity for K_S^0 and $(K^+ + K^-)/2$, measured by NA49 for central Pb+Pb collisions. Also shown is the yield of K_S^0 from central S+S collisions[13], scaled by the same factor 6.4 that relates the yields of negative hadrons in the two systems (Fig. 4). The agreement of

the scaled yields is excellent, and from Fig. 4 it is seen that the ratio K/π is slightly larger in S+S than in Pb+Pb (the bombarding energy dependence should be a small effect in the ratio, below systematic effects). Thus, the strangeness enhancement observed in lighter nucleus–nucleus collisions relative to pp and pA[13] does not increase for the heavier system.

Also seen in Fig. 5 is that the ratio of yields at midrapidity is

$$\frac{\langle K_S^0 \rangle}{(\langle K^+ \rangle + \langle K^- \rangle)/2} = 1.3.$$

This ratio should be unity for an isospin symmetric system. It should deviate from unity for Pb+Pb collisions, but simple quark counting models, considerations of associated production mechanisms, or standard cascade models[15, 16], cannot explain the measured magnitude of the ratio, and it remains a challenge to explain. However, it must also be noted that these data are preliminary, and that instrumental reasons for this effect cannot be ruled out at present.

4 Transverse Expansion Dynamics: Transverse Mass Spectra

Within a hydrodynamic picture, transverse mass spectra exhibit the effects of transverse flow. This is best seen by looking at the inverse slope parameters as a function of mass of the particle, where the heaviest particles are the most sensitive: if all particles are emitted from a fluid having a common transverse velocity profile, the same boost will result in a larger increase in p_T for a heavier particle than a lighter one.

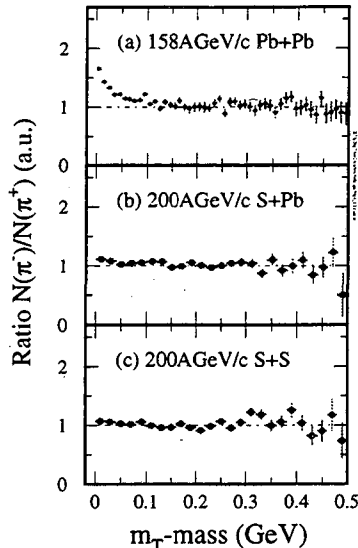
Table 1 shows inverse slope parameters measured at midrapidity for central collisions of S+S and Pb+Pb by the NA35, NA44 and NA49 collaborations. The general trend of increasing slope parameter with increasing mass is stronger in Pb+Pb than S+S, indicating enhanced transverse flow for the heavy system, but detailed conclusions can only be obtained within a model framework. An alternative explanation for the observed p_T broadening in the heavy system, already seen in pA data[17], invokes initial state scattering, commonly called the Cronin effect[18, 19]. However, the existing pA data for particle species other than pions are too poor at present to resolve this issue decisively.

Particle	Pb-Pb		S-S	
	NA49 (preliminary)	NA44 [20]	NA35	NA44 [20]
π^+	185 ± 15	156 ± 6		148 ± 4
π^-	175 ± 15	154 ± 8	197 ± 14 [3]	148 ± 4
K^+	215 ± 15	234 ± 6	227 ± 15 [13]	180 ± 8
K^-	215 ± 15	235 ± 7	190 ± 22 [14]	180 ± 7
K_s^0	220 ± 15		210 ± 16 [13]	
p	300 ± 15	289 ± 7	180 ± 14 [3]	208 ± 8
\bar{p}	290 ± 20	278 ± 9	184 ± 14 [22]	190 ± 7
Λ	290 ± 15		204 ± 17 [13]	
$\bar{\Lambda}$	290 ± 15		180 ± 24 [22]	

Table 1: Inverse slope parameters in MeV at mid-rapidity for a variety of species in central S+S and Pb+Pb collisions, from NA35, NA44 and NA49. Disagreement between experiments of pion slopes for the same system is due in part to different fitting procedures.

5 Final State Interactions: Charge Dependence of p_T Distributions

Fig. 6 shows the ratio of yields of charged pions as a function of transverse mass, measured by NA44 for central collisions of S+S, S+Pb and Pb+Pb[21]. The ratio is normalized to unity at high $m_T - m_\pi$. An enhancement in the ratio is seen at low $m_T - m_\pi$ for Pb+Pb. This phenomenon was first reported by the E866 collaboration[23]. Possible explanations for the enhancement of negative over positive pion yield at low m_T include the contribution of Δ resonances and Λ decays. However, the most attractive explanation is that of final state Coulomb interaction modifying the transverse momentum distributions[23, 21, 24]. Preliminary results from the NA49 Time of Flight detector show a similar enhancement below $p_T=200$ MeV/c in the yield of K^- over that of K^+ , for which the contribution of resonance decays should be negligible. However, again it must be stressed that these kaon data are preliminary, and instrumental reasons for the observed enhancement cannot



NA44. Phys. Lett. B, in press.

Figure 6: Ratio of yields of π^+ and π^- at midrapidity as a function of m_T for central collisions of systems as indicated, measured by NA44 [21].

be ruled out at present.

6 Conclusions

Hadronic spectra from light and heavy projectiles at the AGS and SPS yield important, model-independent information. Baryon stopping is seen to increase with increasing mass and decrease with increasing energy. Yields of pions and kaons at the SPS are seen to scale with the number of participating nucleons. The increased stopping in the heavier nuclei is correlated with a mass-dependent p_T broadening, though whether this is due to collective expansion or initial state scattering is not yet resolved. Final state Coulomb effects appear to modify the spectra of pions and kaons at low p_T .

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