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large transverse flow in central collisions  
of Pb + Pb at 158 AGeV

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**Evidence for low freeze-out temperature and large transverse flow  
in central collisions of Pb + Pb at 158 AGeV**

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Utilizing a hydrodynamical model for the freeze-out stage in heavy-ion reactions, we extract from resolved transverse hadron spectra at midrapidity an inverse slope parameter (temperature)  $T_{Pb} = 120$  MeV and an averaged transverse flow velocity  $v_{\perp Pb}^{aver} = 0.43$  c in central collisions of Pb + Pb at 158 AGeV.

Recently the (yet preliminary) transverse momentum spectra of  $\pi^\pm$ ,  $\pi^0$ ,  $K^\pm$ ,  $K_s^0$ ,  $p^\pm$ ,  $\Lambda$ ,  $\bar{\Lambda}$  at midrapidity, resulting in central collisions of Pb + Pb at beam energy 158 AGeV, have been reported [1, 2, 3]. To analyze these spectra one can utilize a hydrodynamical description of the freeze-out stage. The concept of hydrodynamics for describing heavy-ion collisions has a long history, and quite sophisticated models have been proposed for modeling the hadron dynamics at freeze-out (for a survey cf. [4]).

The general interest in hydrodynamics is motivated by the fact that this approach is intimately related to the use of the equation of state of strongly interacting matter. Within such a framework the chiral symmetry restoration or the phase transition from hadron matter to a quark-gluon plasma appear as particularly interesting. It is still one of the ultimate goals in the realm of heavy-ion physics at relativistic energies to search for signals of deconfined matter. Now, it seems that only a combination of various observables can help to pin down information on the state of maximum density and excitation energy. Sometimes penetrating probes, like dileptons and photons, are considered as favorable signals for the diagnostic of the early stage in the course of colliding nuclei. Hadrons, otherwise, carry mainly information on the late stages of disassembling matter due to the strong interaction. However, if initially a state of hot and dense matter is formed, then the resulting strong pressure let the system rapidly explode, and a collective flow develops as a consequence.

Guided by such ideas one can try to elucidate whether experimental hadron spectra support the predictions of thermodynamical and hydrodynamical concepts. Indeed, in refs. [5, 6] it is claimed that in silicon and gold induced reactions at BNL-AGS energies the hadron abundances and the spectra point to thermal and hadrochemical equilibrium. Also in sulfur induced reactions at CERN-SPS energies this concept is anticipated with a freeze-out temperature of  $T_s = 160$  MeV [7], which is in the region where the deconfinement transition is expected.

Here we would like to point out that the available data set [1, 2, 3, 5] in central Pb + Pb reactions at CERN-SPS energy favors a freeze-out temperature of 120 MeV and an averaged transverse flow velocity of 0.43 c. Therefore, the puzzling situation arises that in the sulfur induced reactions a much higher freeze-out temperature appears than in lead reactions.

We base our analysis on the hydrodynamical model with linear velocity profile at freeze-out time  $\tau_{f.o.}$  [4]. The transverse momentum distributions then read in Boltz-

mann approximation

$$\frac{dN^i}{m_{\perp} dm_{\perp} dy} = \mathcal{N}_i \int_0^1 d\xi \xi m_{\perp} I_0 \left( \frac{p_{\perp} \text{sh}(\rho)}{T} \right) K_1 \left( \frac{m_{\perp} \text{ch}(\rho)}{T} \right), \quad (1)$$

where  $\rho = \text{arcth}(v_{\perp}(\xi))$ ,  $v_{\perp}(\xi) = \frac{3}{2} v_{\perp}^{\text{aver}} \xi$ , and  $v_{\perp}^{\text{aver}}$  is the averaged transverse flow velocity;  $m_{\perp} = \sqrt{m_i^2 + p_{\perp}^2}$  denotes the transverse mass of the hadron species  $i$ ;  $I_0$  and  $K_1$  are Bessel functions. The normalization constants  $\mathcal{N}_i = g_i R_{f.o.}^2 \tau_{f.o.} \lambda_i \exp\{\frac{\mu_i}{T}\} / \pi (\hbar c)^3$  depend on the chemical potentials  $\mu_i$ , phase space occupation factors  $\lambda_i$  and particle degeneracies  $g_i$ . This model relies on boost-invariant scaling hydrodynamics and a unique freeze-out time in both longitudinal and transverse directions. While the net proton rapidity density looks in Pb + Pb collisions quite flat in the interval  $1 < y < 5$ , the negative hadrons show a pronounced bell-shaped rapidity distribution [1]. Therefore the applicability of the model (1) is restricted to a sufficiently narrow interval at midrapidity. (The rapidity distributions could be adjusted by a suitable dependence  $\mu(y)$  [8] together with the selection of a finite rapidity range.)

With the model (1) one can easily describe the slopes of the resolved hadron spectra of pions, kaons, protons and lambdas [1] by a set of parameters  $T, v_{\perp}^{\text{aver}}$ , where  $T(v_{\perp}^{\text{aver}})$  can vary over a wide range for given slopes. In fitting the transverse spectra, which are parametrized in ref. [1] by  $\frac{dN^i}{m_{\perp} dm_{\perp} dy} = C_i \exp(-m_{\perp}/T_i)$ , one observes that, for the values  $T_i$  reported in table 1 in ref. [1] for Pb + Pb at 158 AGeV, all of the quoted hadron spectra measured by the NA49 collaboration are uniquely described by  $T_{Pb} = 120$  MeV and  $v_{\perp}^{\text{aver}} = 0.43$  c. This situation is different from S + S and S + W, Au, where such a focus of the curves  $T(v_{\perp})$  for the various hadrons does not occur [4]. In this respect the Pb + Pb data point to a clear flow signal for the first time. Our fitted spectra together with the data from ref. [1] are displayed in fig. 1 (for details of acceptance corrections, error bars and rapidity binning cf. [1]). Most remarkably is the change of the spectra's shapes when changing the hadron masses.

As cross check one can compare with the preliminary  $\pi^0$  spectrum of the WA98 collaboration [3] and finds very good agreement in the available transverse momentum range of  $p_{\perp} = 0.5 - 2.5$  GeV. We emphasize that our fit describes very well the data shown in ref. [5], namely all negatively charged hadrons for  $m_{\perp} - m_{\pi} = 0.015 - 1.85$  GeV,  $K^+$  for  $m_{\perp} - m_K = 0.015 - 1$  GeV, and the net baryons (+) - (-) for  $m_{\perp} - m_p = 0.015 - 1.42$  GeV. In addition, the preliminary NA44 data [2] of  $p^{\pm}$  and  $K^{\pm}$  in the ranges  $m_{\perp} - m_p = 0.01 - 0.87$  GeV and  $m_{\perp} - m_K = 0.01 - 1.12$  GeV, respectively, strongly support our values of  $T_{Pb}$  and  $v_{\perp}^{\text{aver}}$ . The situation is quite different for the preliminary NA44  $\pi^{\pm}$  data [2]. In the low  $m_{\perp}$  range, which is not covered by the NA49

data, there is a pronounced leveling off not described by our model. A careful analysis of feeding by resonance decays is required to decide whether a large chemical potential of pions [9] is needed for describing these details.

A possible interpretation of the values of  $T_{Pb}$  and  $v_{\perp Pb}^{aver}$ , with respect to the difference to the values  $T_S$  and  $v_{\perp S}^{aver} = 0.27 c$  extracted for sulfur induced reactions at CERN-SPS energies [6], could be that the larger system Pb + Pb develops more collectivity and stays for a longer time in contact up to freeze-out temperature, while the smaller systems S + W, Au disassemble earlier at lower transverse flow velocity but higher mean kinetic energy (temperature) of the hadrons. Interestingly, our dynamical code [10], which employs a linear transverse velocity profile and a resonance gas model equation of state and initial conditions appropriate for lead reactions, consistently results in  $v_{\perp}^{aver} = 0.45 c$ .

Here we do not speculate on a possible chemical equilibrium. In this respect the normalization factors  $\mathcal{N}_i$  need still an interpretation by studying the chemical freeze-out, which does not need to be identical with thermal freeze-out [4]. By the above definition of  $\mathcal{N}_i$  one can try to deduce some combinations of chemical potentials and phase space occupation factors. However, at the present early stage of the data analyses one could come to less reliable results. For instance, the rapidity densities  $dN_i/dy$  obtained from a  $m_{\perp}$  integration of our fitted spectra and experimental data fits in ref. [1] differ up to a factor 2. Nevertheless in a first attempt [5] to interpret the hadron yield ratios, a chemical freeze-out temperature of 160 MeV is found. While this value, when identified with thermal freeze-out, is consistent with the transverse spectra of all negative hadrons,  $K^+$ , and net baryons for the model (1) with  $v_{\perp}^{aver} = 0.3 c$  [5], it is disfavored essentially by the proton and lambda data [1, 2].

In ref. [11] the dragging coefficient between pions and nucleons is calculated and is found to be too small that pions and nucleons are likely to flow with the same velocity. In this respect the circumstantial evidence for a common transverse flow of all hadrons could be traced back to emerge from an early overdense (and possibly deconfined) stage, which triggers the onset of the flow. But it should be emphasized that more accurate data, in particular in a wider transverse momentum range, are needed to come to firm conclusions. A finer rapidity binning is desirable to understand the longitudinal dynamics, too. Also feeding by resonance decays must be included in an advanced analysis.

In summary, within a hydrodynamical model we extract from the transverse mo-

momentum spectra of resolved hadrons a thermal freeze-out temperature  $T_{Pb} = 120$  MeV and averaged transverse flow velocity  $v_{1Pb}^{aver} = 0.43$  c in central Pb + Pb collisions at 158 AGeV.

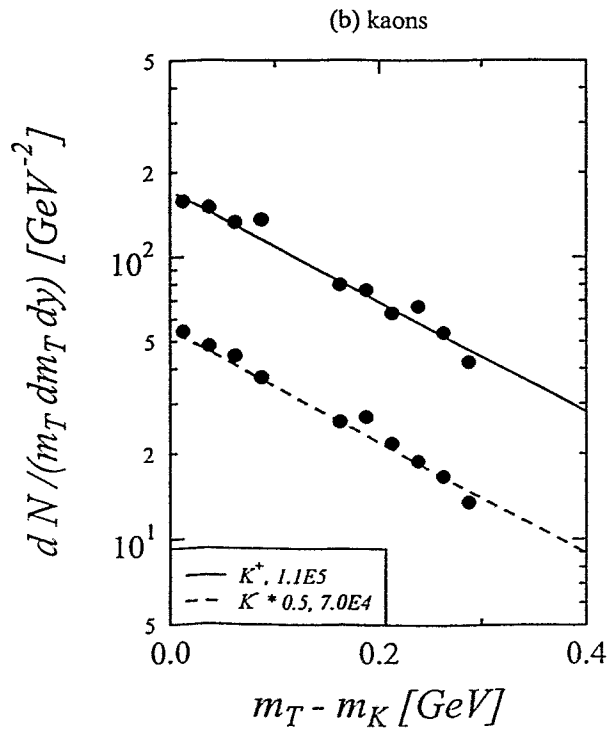
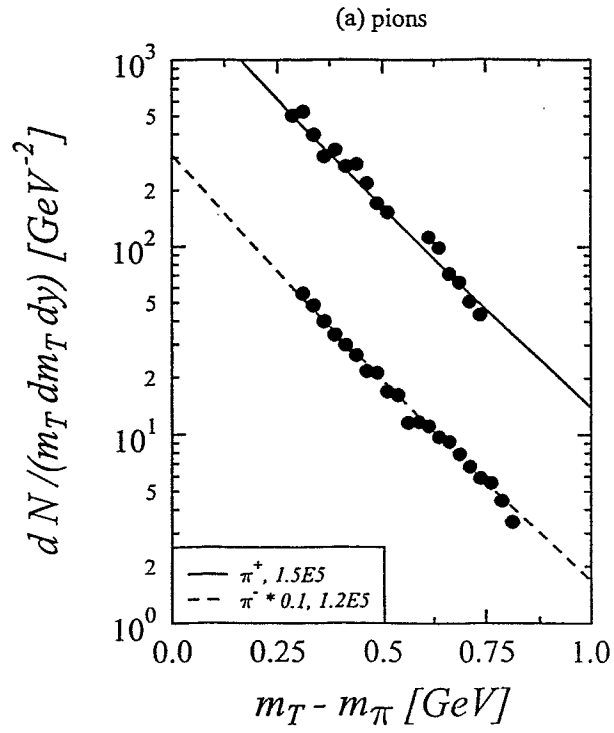
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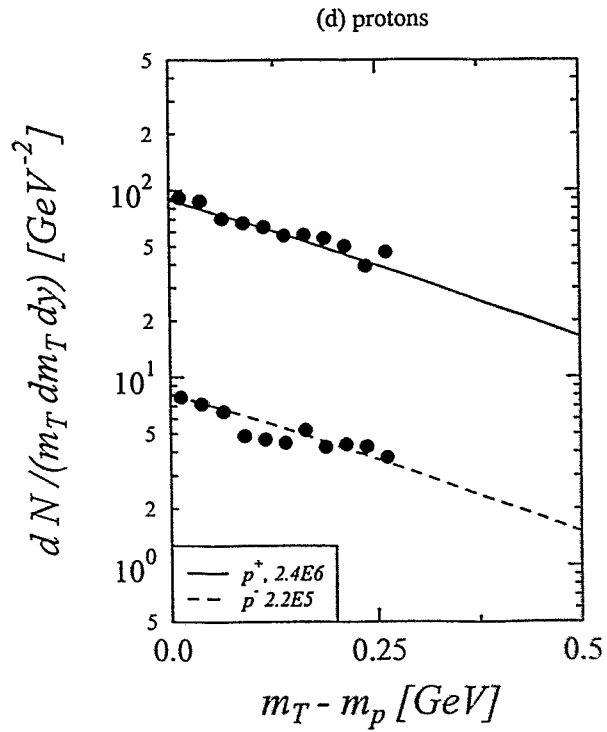
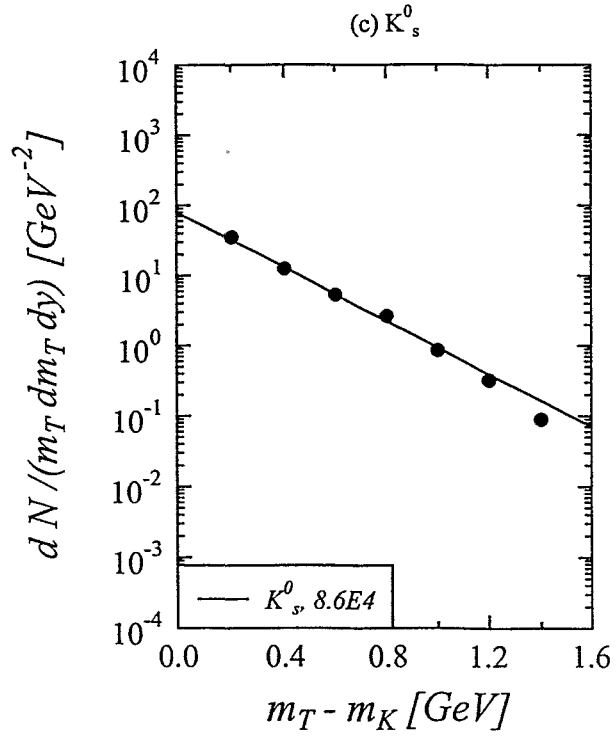
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### Figure caption

Fig. 1: Fits of the resolved transverse momentum spectra of hadrons (a:  $\pi^\pm$ , b:  $K^\pm$ , c:  $K_s^0$ , d:  $p^\pm$ , e:  $\Lambda$ ,  $\bar{\Lambda}$ ). The preliminary data are from ref. [1]. Our normalization factors  $\mathcal{N}_i$  are given in the keys.







(e) Lambdas

