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HADRONIC TRANSVERSE MOMENTUM SPECTRA FROM NUCLEAR COLLISIONS AT CERN[1])

SCHNEDERMANN, E.,[2]) Regensburg

In an attempt to gain a phenomenological understanding of relativistic heavy-ion collisions, we analyse transverse momentum spectra from experiments at CERN with a thermodynamical model of an expanding fireball. We come to the conclusion that a model which describes the reaction zone as a locally equilibrated hadron gas exhibiting collective transverse flow is able to explain the qualitative features of transverse momentum spectra.

I. MOTIVATION

At the beginning I want to give the motivation for our work. Of course the ultimate goal of our research in relativistic heavy-ion physics is the search for the quark-gluon plasma[1]. In this paper I am not aiming that high, but nevertheless let me first outline what are believed to be the two possible approaches to the great answer:

1) Weakly (rarely) interacting "probes" like hard γ, lepton pairs, J/Ψ. These particles are produced in the collision and they leave the reaction zone without further interactions. This has the advantage of producing a very clean signal, but the disadvantage naturally comes with the small rates. For example in one central collision there is on average one lepton pair produced together with several hundred other particles. This gives serious problems for detection and background subtraction.

2) Strongly interacting particles like protons, antiprotons, pions, kaons, etc. They form the bulk of the matter which is produced in a collision, but they interact strongly with each other before they finally reach the detector. The interaction poses a problem as can be seen by considering the two following situations.

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[2]) Institut für Theoretische Physik. Universität Regensburg. Postfach 397, D-8400 REGENSBURG. Germany

Suppose we have a quark-gluon plasma. Particles will be produced in the plasma phase and go through a phase transition from plasma to hadron gas. After interactions in the hadron gas the particles will finally reach the detector. On the other hand suppose we do not have any plasma. Particles will be produced in the initial nucleon-nucleon collisions and in the subsequent hadron gas phase. After interactions in the hadron gas they will eventually reach the detector as well. In both cases we know what the detector tells us, but we do not know much about the hadronic gas before and even less about the plasma. If we knew better what is going on in between we could subtract these effects from the detector results and we would know more about a QGP.

Our aim is to obtain a better understanding of the hadronic gas phase by investigating collective flow effects inside a hadronic gas by looking at transverse momentum spectra. For this purpose we are building a phenomenological model of a heavy-ion collision[2], which consists of five parts (like any classical play).

II. DESCRIPTION OF THE MODEL

Part One: Colliding Pancakes

A heavy-ion reaction begins with a relativistic collision of two nuclei. At CERN one shoots, for example, ^{16}O onto ^{197}Au targets. When the small oxygen hits the big gold nucleus it will blow out a tube of hot nuclear matter. From purely geometrical considerations one finds that there are about 70 nucleons in this region which is, of course, highly compressed. Some compression comes already from the fact that we are sitting in the frame of the 70 participants and that we are dealing here with colliding nuclear pancakes instead of spheres because of the Lorentz contraction.

We do not know anything about how this area is formed and so we do not know the geometry of this object. We just know the following: At the Brookhaven energies there is full stopping[3], the projectile will get stuck in the target, whereas at the CERN energies we have some degree of transparency[4], so there will be the cold spectator pieces of the target nucleus left behind when the "real" interaction region flies on. At the CERN energies the directly participating nucleons and the spectators will have different longitudinal momenta or rapidities and can to a large extent be seperated whereas at the BNL energies full stopping mixes both types.

Part Two: Local Thermodynamics

In the collision region there will be high energy densities which are accompanied by high particle-number densities (not necessarily baryon-number densities), and both together will lead to quick local equilibration ($t \approx 1$ fm). So we can employ thermodynamics to give us the relations between the energy density ε, the baryon-number density ϱ_b, the pressure p, etc. at each point of the fireball.

We will use the formalism[5] of the grand canonical ensemble for a quantum gas of noninteracting particles which are in our case several meson and baryon resonances including the strange sector: pions, η, kaons, φ, ϱ, nucleons, Δ, Λ, Σ, Ξ, Ω, and their antiparticles. Expressing the state of the system in terms of the extensive variables, temperature T and chemical potentials μ_b and μ_s related to the baryon-number and the strangeness, respectively, we obtain the following formulas for the pressure p_i, the energy density ε_i, the baryon-number density $\varrho_{b,i}$ and the entropy density s_i for each particle species i. We have to add them all up to get the total values for the whole system.

$$-\frac{\Phi_i(T, \mu_b, \mu_s)}{V} = p_i = \frac{g_i}{6\pi^2}\int_{m_i}^{\infty} \frac{(\sqrt{e^2 - m_i^2})^3}{\exp((e - n_{b,i}\mu_b - n_{s,i}\mu_s)/T) \mp 1}\, de$$

$$\varepsilon_i = \frac{g_i}{2\pi^2}\int_{m_i}^{\infty} \frac{e^2\sqrt{e^2 - m_i^2}}{\exp((e - n_{b,i}\mu_b - n_{s,i}\mu_s)/T) \mp 1}\, de$$

$$\varrho_{b,i} = \frac{g_i}{2\pi^2}\int_{m_i}^{\infty} \frac{n_{b,i}e\sqrt{e^2 - m_i^2}}{\exp((e - n_{b,i}\mu_b - n_{s,i}\mu_s)/(T)) \mp 1}\, de$$

$$s_i = \frac{1}{T}(\varepsilon_i + p_i - \mu_b \varrho_{b,i})$$

We impose additionally $\varrho_s = 0$ for a locally strangeness neutral hadron gas.

In the equation above g_i is the spin/isospin degeneracy factor, $n_{b,i}$ the baryon-number and $n_{s,i}$ the strangeness of the particle under consideration. With this equation of state we can transfer back and forth from ε and ϱ_b (which are connected to conserved quantities) and the approporiate thermodynamical variables like T and μ_b which affect all particle species on the same footing and tell us something about the development of the system.

Instead of describing a hadron gas with the above formulas we could use them for a quark-gluon plasma as well. We just take quarks and gluons as constituents of a gas which is inside a big bag. Then we subtract the bag pressure from the computed pressure and increase the energy density by the same amount.

Part Three: Expansion

The highly compressed collision region will expand. As I mentioned earlier in Part One we do not know the initial geometry and other initial conditions like initial expansion velocity. To make up for this lack of knowledge we have to investigate several sensible possibilities. There are basically three simple ones:

a) *Fireball* — A geometry which lends itself to full stopping at BNL energies is a radially expanding sphere, where the radial motion is assumed to be generated by thermal pressure. Since this geometry is simple we have already done calculations for this case. I will comment on them later.

b) *Firestreak* — Another possibility which is more attractive for CERN energies might be a longitudinally expanding cylinder. The longitudinal expansion comes from partial transparency of the noclei, i.e. not all projectile nucleons are stopped equally by the target. The ones which are not so much stopped will be flying on faster than the others, so sitting in the centre-of-mass frame of the collision zone particles will be travelling away from each other in longitudinal direction. This scenario does not give rise to interesting transverse momentum spectra since the p_t-spectrum of the central slice alone (which is purely thermal) is identical to the p_t-spectrum of the whole cylinder assuming a frame independent velocity distribution.

c) *Firebarrel* — Hence we rather investigate currently the model of a cylinder which does both: frame invariant longitudinal expansion coming from partial transparency on the one hand and transverse expansion being caused by thermal pressure on the other hand.

The whole expansion of the highly compressed region (call it a fireball or a firebarrel) is governed by relativistic hydrodynamics and several conserved quantities. Besides the quite common conservation of the baryon-number, the total energy and the vanishing net-strangeness, hydrodynamics (which is based on local equilibrium) gives in particular conservation of entropy (or entropy per baryon, S/A).

Especially this constraint gives us useful information about the overall evolution. Suppose we prepare the system into some equilibrated initial state labelled by two values for temperature T and chemical potential μ_b in the phase diagram. (For the sake of simplicity we do not want to consider strangeness right now.) From this point (T_0, μ_{b0}) in the phase diagram the evolution will run down towards lower values of T and μ_b on a line which is fixed by S/A = const. From the equation of state we then know that the thermal energy per baryon number is decreasing along this curve. The initial energy, which is purely thermal, has to be continuously transformed into kinetic energy of a large-scale collective motion.

In principle we would know the time evolution of the collective flow completely from hydrodynamics if we knew the initial conditions. As I mentioned earlier we do not know the initial conditions, and again we are forced to assume some sensible form for the expansion velocity $\beta(t, \mathbf{r})$. For the fireball we have chosen a selfsimilar form in the spatial coordinate.

$$\beta(t, \mathbf{r}) = \beta_s(t)\left(\frac{|\mathbf{r}|}{R}\right)^n,$$

R is the radius of the sphere, $\beta_s(t)$ is the expansion velocity at the surface and n determines the shape of the velocity profile. We tried the values $n = \frac{1}{2}$, 1, 2 and achieved the best results for $n = 2$, so we fixed it there.

I have to mention here that this assumed velocity profile will not be stable under relativistic hydrodynamic evolution. But fortunately this is of no great importance because we are first and foremost interested in the velocity profile close to the freeze-out point and we do not need the whole time evolution of the system. I will come to this in more detail in the next section. Let me just mention here another point. There is a conflict arising now: the expansion is relativistic, it is described in the centre-of-mass coordinates of the fireball whereas the thermodynamics is done in the local comoving frame at each point in the fireball. So we always have to use Lorentz transformations to transfer back and forth from one frame to the other.

Part Four: Freeze-Out

Expansion of the fireball will lead to dilution and cooling, they both will affect local thermal equilibrium. Devoting our attention to this point we have to take a closer look at the thermal equilibration coming from individual collisions between particles[6]. We construct a mean time $\tau_{scatt,i}$ between collisions of one particle of species i hitting any other particle by simple geometrical considerations:

$$\tau_{scatt,i} = \frac{1}{\Sigma_j \langle \sigma_{ij} v_{ij} \rangle \varrho_j},$$

where $\sigma_{i,j}$ is the cross section if i hits a particle of species j, $v_{i,j}$ is the relative velocity of i and j, and ϱ_j is the density of j. We can (and have to) approximate the collision terms of the less common species of baryons and mesons by the values for nucleons or pions, respectively, since their densities are comparatively low and for most of them we don't even know their cross sections among each other. By imposing $\langle \sigma_{ij} v_{ij} \rangle \approx \langle \sigma_{ij} \rangle \langle v_i \rangle$ (where v_i is the thermal velocity of the lighter scattering partner) we arrive at this handy formula for the charecteristic scattering time:

$$\frac{1}{\langle v_i \rangle \tau_{scatt,i}} = \langle \sigma_{i,N} \rangle (\varrho_{baryon} + \varrho_{antibaryon}) + \langle \sigma_{i,\pi} \rangle \varrho_{mesons}.$$

On the other hand we can compute an expansion time τ_{exp} by using the

baryons as markers or flagpoles in the gas. It tells us the time interval during which the flagpoles have been diluted by a factor of e = exp(1):

$$\tau_{exp} = \varrho_{loc} \left(\frac{\partial \varrho_{loc}}{\partial t_{loc}} \right)^{-1}.$$

We can compute it by making use of the continuity equation $\partial_\mu (u^\mu \varrho_{loc}) = 0$ written here in terms of four-velocity u^μ and density ϱ_{loc}. u^μ is just a different notation for our old expansion velocity profile which is given in the centre-of-mass coordinates, whereas the index loc at ϱ_{loc} indicates that the density is measured in the local comoving frame.

If the time during which the particles typically scatter is larger than the time it takes to dilute them by a factor of e,

$$\tau_{scatt,i} > \varrho_{exp},$$

the particle species i will thermally decouple, that is freeze out from the collective flow.

The freeze-out condition has two consequences:

a) it predicts the freeze-out hypersurface, which will be dealt with in the next section and

b) it gives different freeze-out temperatures for different particles. In our case we have a baryon rich environment, so consider for simplicity just nucleons as interaction partners. Then looking at the cross sections of K^- and K^+ with nucleons, we find a substantial difference: $\sigma_{K^-} \approx 50$ mb is relatively high, so K^- will freeze out together with nucleons and pions. Since $\sigma_{K^+} \approx 10$ mb is rather low, K^+ will freeze out already at higher densities and temperatures.

Part Five: Transverse Momentum Spectra

The freeze-out will probably not occur over the whole fireball volume at the same time. Outer shells and inner shells might freeze out at different times, so we have to construct a three dimensional freeze-out hypersurface σ_f in four--dimensional space-time which seperates thermal equilibrium from free travelling. The invariant cross section Ed^3n/dp^3 is then given[7] by an integral over σ_f with volume element $d\sigma_\mu$, which is orthogonal on the surface:

$$\frac{Ed^3n}{dp^3} = \int_{\sigma_f} f(x, p) p^\mu d\sigma_\mu.$$

Forming the product with the momentum vector we arrive at the invariant volume element $p^\mu d\sigma_\mu$. $f(x, p)$ is the invariant distribution function, e.g. in the local comoving frame it is an isotropic Boltzmann distribution $f(\bar{x}, \bar{p}) =$

$= N \exp(-\bar{E}/T)$, with N as normalization factor. For usual purposes one can neglect quantum-statistical effects because we have rather low densities around the freeze-out.

We have chosen σ_f to be at equal local times since the freeze-out occurs in the local comoving frame. For the spherical case we can evaluate the integral for every value of p by using spherical coordinates, taking as the polar axis the direction of $\boldsymbol{p}$.

$$\frac{E\mathrm{d}^3 n}{\mathrm{d}p^3} = N \int_V (E - \boldsymbol{\beta}.\boldsymbol{p}) \exp(-\gamma(E - \boldsymbol{\beta}.\boldsymbol{p})/T)\, \mathrm{d}^3 x.$$

Since our interest focuses on signatures of transverse flow, we will be looking at the transverse momentum spectra. We can get them easily by integrating the full cross section over all longitudinal momenta (along the beam axis) and making use of $\mathrm{d}p_L = \mathrm{d}(\sqrt{m^2 + p_t^2}\sinh y) = \sqrt{m^2 + p_t^2}\cosh y \mathrm{d}y = E\mathrm{d}y$, by which we can shift to the rapidity y as an integration variable:

$$\frac{\mathrm{d}n}{p_t \mathrm{d}p_t} = 2\pi \int_{y_{lo}}^{y_{hi}} E \frac{\mathrm{d}^3 n}{\mathrm{d}p^3} \mathrm{d}y.$$

We have put the limits y_{lo} and y_{hi} to account for a limited detector range, otherwise the y-integral would extend from $-\infty$ to $+\infty$.

Carrying out again the computation for the spherical case, we can perform two integrals analytically, but are still left with another two integrals to be done numerically. I have already dropped some normalization factors because we are not (yet) interested in the absolute height of the spectra; the reason is that the normalization for each particle species (which will be reflected in the measured particle ratios) crucially depends on the degree of chemical equilibration reached at the freeze-out. While thermal equilibration (which only enters in the shape of the spectra) until the freeze-out is a valid concept by definition of the freeze-out point, chemical equilibrium will break down much sooner[8]. Since our model also assumes chemical equilibrium until the very end, it is bound to predict unreasonable particle ratios.

Up to a normalization factor, the p_t-spectrum is then given by

$$\frac{\mathrm{d}n}{p_t \mathrm{d}p_t} \propto \int_{y_{lo}}^{y_{hi}} \mathrm{d}y \int_0^1 \left(\frac{r}{R}\right)^2 \mathrm{d}\left(\frac{r}{R}\right) E \mathrm{e}^{-\gamma E/T} \left[\left(1 + \frac{T}{\gamma E}\right) \frac{\sinh \alpha}{\alpha} - \frac{T}{\gamma E} \cosh \alpha\right],$$

where $\beta = \beta\left(t, \frac{r}{R}\right) = \beta_s(t)\left(\frac{r}{R}\right)^n$, $\gamma = \gamma\left(t, \frac{r}{R}\right) = 1/\sqrt{1-\beta^2}$ and $\alpha = \gamma\beta p/T$. One sees that even the dependency on the radius R of the fireball can be absorbed into the normalization factor by introducing the relative radius $\frac{r}{R}$ as the integration variable, leaving only dependencies on β_s and T. (n is fixed as $n = 2$.) Information about R is available from two-pion interferometry[9].

It would also be possible to calculate the rapidity distribution by integrating over all transverse momenta.

$$\frac{\mathrm{d}n}{\mathrm{d}y} = 2\pi \int_0^\infty E \frac{\mathrm{d}^3 n}{\mathrm{d}p^3} p_t \mathrm{d}p_t.$$

This gives basically information on longitudinal motion and the longitudinal freezeout geometry. A closer analysis might be interesting at some later time.

III. RESULTS

We are using our above model in the following way: By assuming some initial conditions ε and ϱ and following the fireball until the freeze-out we obtain a p_t-spectrum for say, pions, which is characterized by β_s and T. Varying ε and ϱ we try to get a good fit to the data points, and indeed, we succeed very well in this respect. Using then β_s and T from this fit we can predict p_t-spectra for other particle species.

For the fit of figure 1 we used data from the WA80 collaboration[10, 10a] at CERN. The experimental events have been separated into two classes, central and peripheral, by considering the amount of energy which goes right through (E_{ZDC}) compared to the total beam energy (E_{proj}). For the central data ($E_{ZDC} < 30\%\ E_{proj}$) you can see that a nice fit over the whole p_t-range is obtained. By using the values of $\beta_s = 0.78c$ and $T = 101$ MeV we can now predict spectra for other particle species: Kaons, protons, η for example. Their slopes are in general flatter than π-spectra because heavier particles profit more from the underlying transverse flow by their bigger masses. Aside from this effect there is another coming in when one is considers kaons. K^+ and K^- have the same mass, their spectra should be alike if it were not for their different cross sections which in turn lead to higher temperatures = flatter slopes for K^+ because of the freeze-out criterion. As you can see in the plots the change in slope from this effect is relatively small compared to the mass effect. We have also computed η-spectra, their uncertainty originates in uncertainties in the cross section $\sigma_{N\eta}$.

In the peripheral system (more than 40% of beam energy in zero-degree calorimeter) the number of participating nucleons is much smaller (we set $A = 28$) than in central collisions ($A = 68$). The size of the system enters into our formulas through the freezeout condition, so imposing the same initial con-

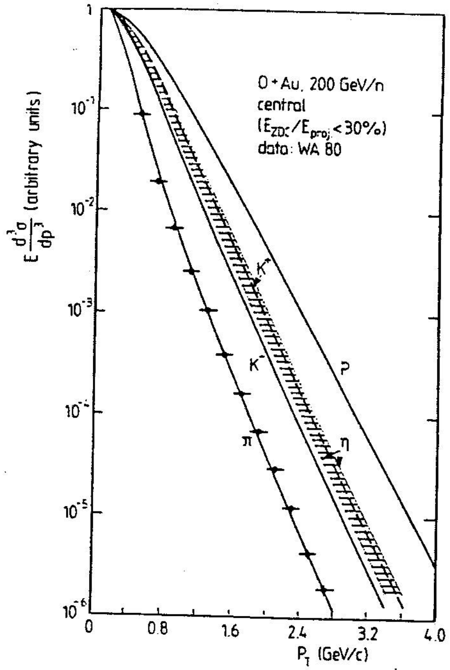

Fig. 1. Transverse momentum spectra for pions, kaons, and protons in central O + Au collisions at 200 GeV/n. The data points are π^0 data from WA80 [10a] with a central trigger. All the curves are arbitrarily normalized at $p_t = 0.1$ GeV/c. For details on the parameter sets for this fit see Lee and Heinz [2].

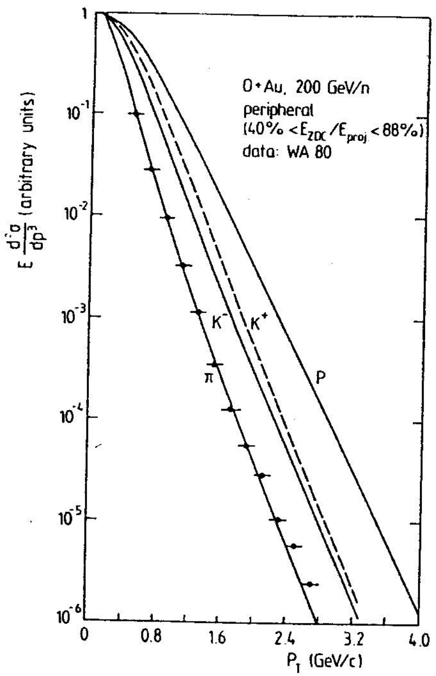

Fig. 2. Transverse momentum spectra for pions, kaons, and protons in peripheral O + Au collisions at 200 GeV/n. The data points are π^0 data from WA80 [10a] with a peripheral trigger. All the curves are arbitrarily normalized at $p_t = 0.1$ GeV/c. For details on the parameter sets for this fit see Lee and Heinz [2].

ditions ε_0, ϱ_0 as in central collisions we arrive at slightly different values for β_s(0.72c instead of 0.78) and T(108 MeV vs. 101 MeV). For details see again Lee and Heinz[2]. Since the decrease in β_s is just partly compensated by the increase in T the peripheral spectra are a bit steeper than the central ones, but give an equally good fit to the data except for deviations at high p_t. We believe that they show up here rather than in the central data because a peripheral collision leads to a much smaller system and deviations from thermodynamics have a much better chance to last.

We used the same parameter pair extracted from the central collision π^0-data from WA80 for the plot in figure 3 where the datapoints are π^- from NA35 O + Au collisions[11]. One can see that the curve matches the datapoints fairly well, though there is some indication of underestimating the higher part of the p_t-spectrum.

A follow-up analysis has been performed by R. Renfordt[12] (NA35) with more recent data from 200A GeV^{32}S on ^{32}S and 200A GeV ^{16}O on ^{197}Au collisions, considering just the few percent of most central events. He used a rapidity window ($2 \leq y \leq 3$) which is slightly backwards in the centre-of-mass system of S + S whereas it contains the centre-of-mass of the O + Au reaction zone. Proton identification is to some degree possible for the sulphur system by the following trick: Because S + S is an isospin O system one should obtain as many π^+ as π^-, then counting all negative tracks as π^- the excess of positive tracks should be protons. The theoretical curves are computed with three different assumptions:

a) Taking our parameter pair $\beta_s = 0.78$c, $T = 100$ MeV which we obtained from the WA80 π^0 data through our model which takes the freeze-out properly into account, one gets reasonable agreement of computed p_t-spectrum and data points for π^-, protons and Λ^0. Major deviations are found only for pions in the high p_t region and may be due to neglecting a possible 5—10% K^- contamination.

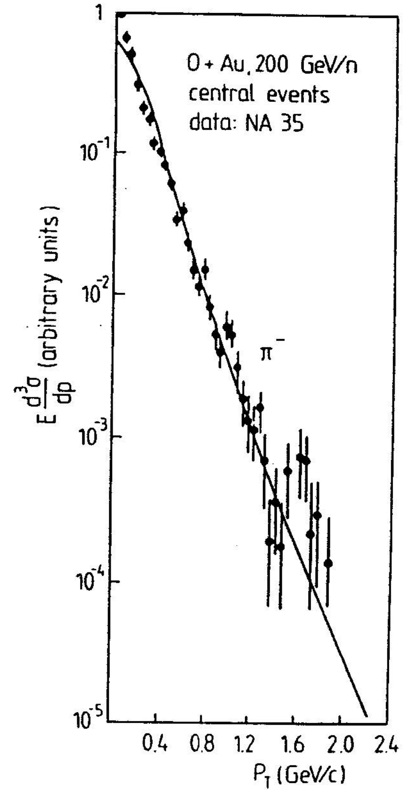

Fig. 3. π^- transverse momentum spectra for central O + Au collisions by NA35 [11]. The curve is obtained using the same parameter set as in Figure 1, with a different rapidity integration interval $2 < y_{lab} < 3$ ($-0.5 < y_{cm} < 0.5$).

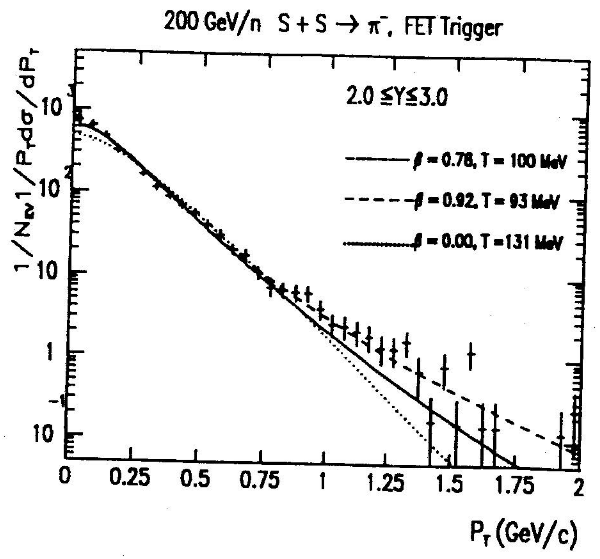

Fig. 4. Transverse momentum distribution of "π^-" at midrapidity from 200 GeV/n S+S collisions. Taken from Renfordt [12].

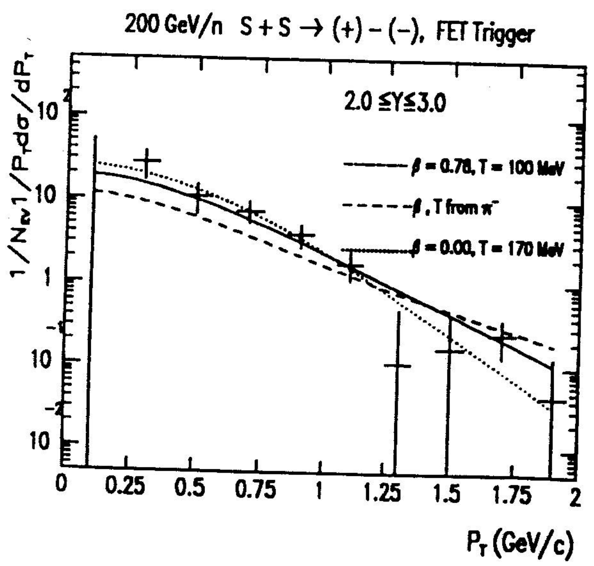

Fig. 5. Transverse momentum distribution of "protons" at midrapidity from 200 GeV/n S + S collisions obtained by subtraction method. Taken from Renfordt [12].

b) Neglecting the freeze-out criterion one can do a free fit to the data using β_s and T as parameters. The resulting π^- fit covers also the high p_t regime well but gives a pair $\beta_s = 0.93c$, $T = 93$ MeV which is definitely not compatible with our freeze-out concept. Applying this parameter pair to proton and Λ^0 spectra one sees that this curve barely hits the data points. In general it is too flat for these two heavy species, because they are strongly affected by the too high value for β_s.

c) Checking for the absence of collective flow one can fix $\beta_s = 0$ and do a free fit with T alone (purely thermal radiation). The curves are basically dropping faster than their competitors, even if one allows for different temperatures of pions and protons ($T_{\pi^-} = 137$ MeV and $T_{protons}$ = = 170 MeV = T_{Λ^0}). This procedure gives a slightly better fit to the proton data but has no obvious theoretical justification.

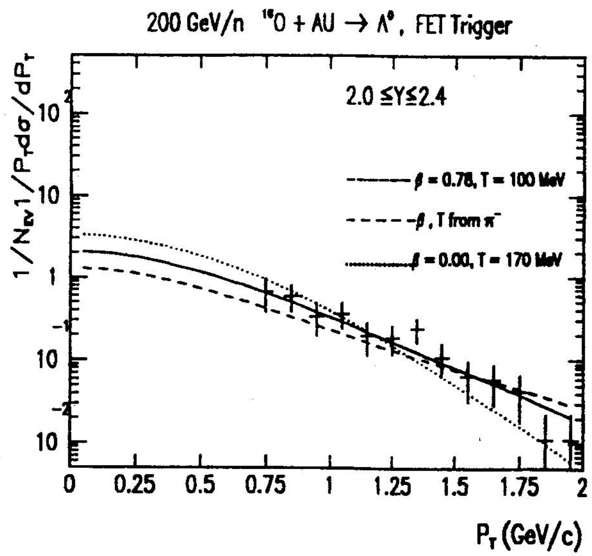

Fig. 6. Transverse momentum distribution of Λ^0 at midrapidity from 200 GeV/n O + Au collisions. Taken from Renfordt [12].

There are also preliminary data from BNL[3] which are in qualitative agreement with our picture of transverse flow. The E802 group evaluated slope parameters T^* for a parametrization $dn/dp_t = \exp(-m_t/T^*)$ for several particle species produced in 14.5A GeV Si + Au collisions, and they got values of about $T^*_\pi \approx 170$ MeV, $T^*_{proton} \approx 225$ MeV, $T^*_{deuteron} \approx 350$ MeV, where again the systematic increase of T^* with particle mass indicates transverse flow.

IV. CONCLUSIONS

Considering the above spectra and results we come to the conclusion that our collective flow model together with the thermal emission of particles explains the qualitative features of transverse momentum spectra quite well. I want to stress here especially that our model predicts different slopes for different particle masses in agreement with preliminary experimantal data (π, proton and Λ spectra from NA35). The same effect is seen in the data from the E802 group in Brookhaven.

Given some evidence for the validity of our model we can get a hold on the initial conditions of the fireball, especially energy density and baryon-number density. They both seem to be in a constant ratio of about 2 GeV per nucleon at 200 A GeV beam energy. The energy density could then be inferred from the number of participating nucleons and from the spatial dimensions of the reaction zone out of two-pion interferometry. But statements have to be made with great care since these quantities might also be affected by the longitudinal aspect of the expansion geometry. I finally list a few points of what we would like to do and what we are already working on [13]:

— We have to work out the exact form of the freeze-out hypersurface as resulting from the freeze-out condition.
— Furthermore we are currently investigating different geometries (e.g. cylindrical firebarrel) to analyse how much they influence our p_t-spectra.
— Also on the wish-list are more realistic density profiles: we have been using box-like profiles for temperature, density and all other thermodynamical quantities, but we see some need for profiles which are dropping smoothly on the outside.
— And we have to deal with the deviations from our spectra at high $p_t(> 2$ GeV), where we laid our suspicion on hard scattering effects.

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СПЕКТРЫ ПОПЕРЕЧНЫХ ИМПУЛЬСОВ АДРОНОВ ИЗ ЯДЕРНЫХ ВЗАИМОДЕЙСТВИЙ ПОЛУЧЕННЫХ В ЦЕРНе

С целью лучшего феноменологического описания соударений релятивистических тяжелых ионов анализируются в рамках термодинамической модели экспандирующего горячего шара спектры поперечных импульсов, полученные из экспериментов в ЦЭРНе. Сделано заключение что модель, в которой зона реакции представлена локально равновесным адронным газом, имеющим коллективное поперечное течение, можно применить при качественном описании спектра импульсов.