Transverse Baryon Flow as Possible Evidence for a Quark-Gluon-Plasma Phase

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In order to investigate the coupling between the collective flow of nucleons and pions in hot pion-dominated hadronic matter, we calculate the pion-nucleon drag coefficient in linearized transport theory. We find that the characteristic time for flow equalization is longer than the time scale of the expansion of a hadronic fireball created in high-energy collisions. The analysis of transverse-momentum data from $p+\bar{p}$ collisions at $\sqrt{s}=1.8$ TeV reveals the same flow velocity for mesons and antinucleons. We argue that this may be evidence for the formation of a quark-gluon plasma in these collisions.

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Rather general arguments indicate that the state of high energy density temporarily formed in ultrarelativistic central collisions of nuclei, and possibly even of single hadrons, exhibits approximate local thermal equilibrium and thus can be characterized by a temperature. This scenario is generally supported by the observation that transverse-momentum spectra of emitted particles fall exponentially at high p_T. It has often been speculated that a collective outward flow may develop during the expansion and final breakup of the high-density state [1]. The presence of a collective flow would be manifest in a nonthermal shape of the transverse-momentum spectrum. Because the flow velocity is superimposed with the random thermal motion, this effect grows with the mass of the emitted particles, and should be most clearly visible in baryon spectra. So far, experimental evidence for the existence of transverse flow at center-of-mass energies far above 1 GeV/u has been inconclusive [2,3], in contrast to collisions below this energy [4].

Gerber, Leutwyler, and Goity [5] recently showed that the expansion of a dense pion gas, as is formed in the central rapidity region after a highly relativistic nuclear collision, must lead to a rapid transverse flow. Gavin [6] pointed out that the expansion is even so rapid that the system may have difficulty maintaining local thermal equilibrium, possibly resulting in an enhancement of pions emitted with small transverse momenta [7]. Since baryons are better flow probes than pions, we address here the question of whether the few baryons present at central rapidity can be expected to participate in the collective flow and thermal evolution of the pion gas. This depends on the strength of kinetic coupling between the average flow velocities of pions, v_π, and of nucleons, v_N, which is given by the *drag coefficient* δ [8],

$$d\mathbf{v}_N/dt=\delta(\mathbf{v}_\pi-\mathbf{v}_N)\,, \tag{1}$$

on the one hand, and that between the pion and nucleon temperatures, T_π and T_N, on the other hand, which is governed by the coefficient θ of heat exchange,

$$dT_N/dt=\theta(T_\pi-T_N)\,. \tag{2}$$

The latter equation, of course, makes sense only if the deviation from local thermal equilibrium is not too severe. We will now calculate δ and θ from first principles.

We assume that the evolution of the phase-space distribution functions $f_i(x,p)$, $i=\pi,N$, of pions and nucleons in the dense hadronic phase is described by the relativistic Boltzmann equation:

$$p^\nu\partial_\nu f_i(x,p)=\sum_j \mathcal{C}_{ij}(x,p)\,. \tag{3}$$

Here $\mathcal{C}_{ij}$ are the collision terms, which can be calculated from the known cross section for collisions between particles of type i and type j. In order to make contact with collective variables, such as the local flow velocity u^μ, it is useful to consider the momentum-space-integrated form of Eq. (3), introducing the energy-momentum tensor $T_i^{\mu\nu}$. Dissipative terms can then be expressed as the failure of the energy-momentum tensor to be locally conserved for each fluid component separately:

$$\partial_\nu T_i^{\mu\nu}=\mathcal{S}_i^\mu\equiv\sum_j\int d\Gamma_p\, p^\mu \mathcal{C}_{ij}(x,p)\,, \tag{4}$$

where $d\Gamma_p=d^3p/(2\pi)^3p^0$ is the invariant volume element in momentum space and $\mathcal{S}_i^\mu$ is the covariant dissipation four-vector.

Now let us assume that the pion-nucleon system can be described as a two-fluid system where pions and nucleons are coupled in bulk by dissipative terms. Each component, $i=\pi,N$, is characterized by its own local energy density ε_i, pressure P_i, and flow velocity u_i^μ. The left-hand side of Eq. (4) can then be expressed in terms of ε_i, P_i, and u_i^μ, but the dissipative terms $\mathcal{S}_i^\mu$ must be calculated microscopically. We need to specify the momentum distributions $f_i(p)$, which we take to be Lorentz-invariant Jüttner distributions:

$$f_i(x,p)\equiv d_i\exp(-\beta_i p^\mu u_{i\mu})\,, \tag{5}$$

where β is the inverse temperature and d_i are the degeneracies. Here we assume that the two fluids are in thermal equilibrium. Even if this is not satisfied, the true distribution may be well approximated by thermal distributions with appropriately chosen parameters [7]. In the following we will neglect effects arising from the spatial variation of the collective parameters, and will not allow for nonvanishing chemical potentials because we are interested in baryon-symmetric matter. The two fluids then differ only in their collective velocity or in the value of their temperature parameter.

Using the standard expression [9] for the relativistic collision term $\mathcal{C}_{\pi N}$, one obtains the following expression for the dissipation four-vector:

$$\mathcal{S}_N^\mu = \int d\Gamma_p \, d\Gamma_k \, d\Omega \, F_{\pi N} \frac{d\sigma_{\pi N}}{d\Omega} \times p^\mu [f_N(p') f_\pi(k') - f_N(p) f_\pi(k)] \,, \tag{6}$$

where $F_{\pi N}$ is the relativistic flux factor, and p,p' (k,k') are the nucleon (pion) momenta before and after the collision. We now expand the collision term to first order in the difference of the velocities, $\Delta u^\mu = u_N^\mu - u_\pi^\mu$, and the inverse temperature difference, $\Delta\beta = \beta_N - \beta_\pi$, of the two components. Denoting the average velocity and inverse temperature simply by U^μ and β, respectively, the first-order contribution becomes

$$\mathcal{S}_N^\mu = (A-B)(\Delta\beta) U^\mu - \beta B \Delta u^\mu \,, \tag{7}$$

where the coefficients A and B are given by

$$\begin{aligned} A-B &= \int d\Gamma_p \, d\Gamma_k \, d\Omega \frac{d\sigma_{\pi N}}{d\Omega} F_{\pi N} d_\pi d_N U_\mu p^\mu U_\nu (p^\nu - p'^\nu) \times e^{-\beta U_\mu (p^\mu + k^\mu)} \,, \\ A-4B &= \int d\Gamma_p \, d\Gamma_k \, d\Omega \frac{d\sigma_{\pi N}}{d\Omega} F_{\pi N} d_\pi d_N p_\mu (p^\mu - p'^\mu) \times e^{-\beta U_\mu (p^\mu + k^\mu)} \,. \end{aligned} \tag{8}$$

Multiplying Eq. (4) by some unit four-vector n_μ orthogonal to u_N^μ and utilizing the perfect-fluid expression for $T^{\mu\nu}$, the equation can be cast into the form

$$(\varepsilon_N + P_N) n_\mu \dot{u}_N^\mu = -\beta B n_\mu \Delta u^\mu \,, \tag{9}$$

where $\dot{u}_N^\mu$ describes the acceleration of the nucleon fluid, measured in its own rest frame, by the streaming pions. Comparing with Eq. (1) we thus find the desired relation

$$\delta = B/(\varepsilon_N + P_N) T \,. \tag{10}$$

A similar consideration yields

$$\theta = (A-B)/C_v T^2 \,, \tag{11}$$

where C_v is the heat capacity of the nucleon component at constant volume and nucleon number. We have calculated δ numerically as a function of temperature T, using the experimental pion-nucleon cross section [10]. The result for the characteristic relaxation time $\tau_\delta = \delta^{-1}$ is shown in Fig. 1 by the solid line. We observe that τ_δ falls quickly with rising temperature. However, τ_δ is considerably larger than the thermal equilibration time between pions and nucleons, $\tau_{\rm th}^{(N)} = \theta^{-1}$, which is shown by the dashed line in Fig. 1.

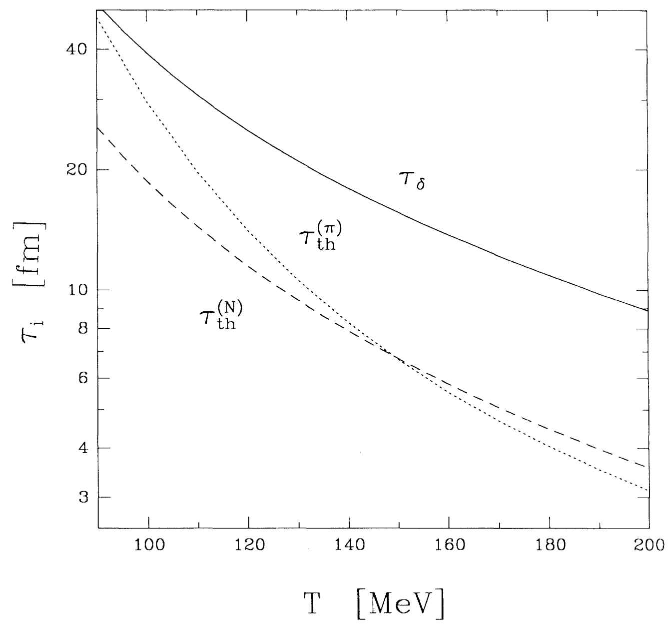

FIG. 1. The relaxation time for collective flow equilibration ($\tau_\delta = \delta^{-1}$, solid line), as well as the temperature equilibration time for nucleons ($\tau_{\rm th}^{(N)}$, dashed line) and pions ($\tau_{\rm th}^{(\pi)}$, dotted line) in pion-dominated hadronic matter as function of the temperature T.

For comparison we also show the thermal equilibration time for pions, $\tau_{\rm th}^{(\pi)}$, calculated on the basis of Eq. (11) with standard $\pi\pi$ cross sections [11,12]. $\tau_{\rm th}^{(\pi)}$ falls much faster with increasing T than $\tau_{\rm th}^{(N)}$ and τ_δ because the ρ resonance lies higher above the threshold in the $\pi\pi$ reaction than the $\Delta(1232)$ resonance in the πN reaction. The fact that $\tau_\delta > \tau_{\rm th}^{(N)}, \tau_{\rm th}^{(\pi)}$ implies that the baryonic collective flow decouples from the pion flow already at high temperature, whereas the nucleonic and pionic thermal motion can remain in equilibrium until $T \approx 140$ MeV if the reaction volume has a size of several fermis, and possibly down to even lower temperatures if the pions develop a large chemical potential [7]. Simulations of the transverse hydrodynamic expansion of the coupled π-N fluids, which we have performed [13], have shown that a common collective flow velocity can never be established at temperatures where hadronic matter can be described dominantly as pion gas. This argument can, of course, be turned around: If an experiment shows that pions and nucleons emitted in the baryon-poor region at central rapidity exhibit collective flow of equal magnitude, this flow must have been established at an earlier phase.

With this in mind, we consider the data on the dependence of the average transverse momentum of pions, kaons, and antiprotons on the total charged multiplicity in proton-antiproton collisions at $\sqrt{s} = 1.8$ TeV, which were obtained by the E-735 Collaboration at Fermilab [14]. We have analyzed these data for the presence of transverse collective flow in the boost-invariant hydrodynamical model of Bjorken [15]. This model is best formulated in cylindrical light-cone coordinates $t \pm z$. Here t is the time and z the longitudinal coordinate in the center-of-mass system. It is useful to introduce the coordinates (τ,α,r,ϕ), where $\tau=(t^2-z^2)^{1/2}$ is the proper time, $\alpha=\frac{1}{2}\ln[(t+z)/(t-z)]$ is the space-time rapidity, and r is the transverse radius.

Let us consider decoupled velocity fields v_L and v_T along longitudinal and transverse directions. The velocity four-vector is then given by

$$u^\mu=(\gamma_T,0,v_T\gamma_T,0)\,, \tag{12}$$

where $\gamma_T=(1-v_T^2)^{-1/2}$. Here we do not intend to explore the detailed time evolution of the transverse velocity field as it follows from the hydrodynamical equations (4); we are only interested in the flow at the time of freeze-out of the various hadrons. We therefore introduce a fixed linear transverse velocity profile [3] parametrized by the surface velocity $\dot{R}(\tau)$, where $R(\tau)$ is the transverse radius of the reaction region. Assuming that the temperature depends only on τ and freeze-out occurs at constant τ, one can then calculate the transverse momentum and rapidity distributions of the emitted hadrons [16]. Here we give the expressions for the space-time rapidity density of the particle number,

$$\frac{dN}{d\alpha}=\int \gamma_T\tau r\,dr\,d\phi\int d^3\bar{p}\,f(x,\bar{p})\,, \tag{13}$$

and of the average squared transverse momentum,

$$\frac{d\langle p_T^2\rangle}{d\alpha}=\int v_T^2\gamma_T^3\tau r\,dr\,d\phi\int d^3\bar{p}(\bar{E}^2-\bar{p}^2)f(x,\bar{p}) + \tfrac{2}{3}\int \gamma_T\tau r\,dr\,d\phi\int d^3\bar{p}\,\bar{p}^2 f(x,\bar{p})\,. \tag{14}$$

In order to compare with the experimental data, we define

$$\langle p_T\rangle \approx 0.8165\left[\frac{d\langle p_N^2\rangle}{d\alpha}\left(\frac{dN}{d\alpha}\right)^{-1}\right]^{1/2}, \tag{15}$$

which is exact for an exponential slope of the p_T spectrum. Since α is equal to the rapidity y in the boost-invariant model, the quantities (13)-(15) can be directly identified with the measured rapidity distributions.

In Fig. 2 we show the collective surface flow velocities at freeze-out, $\dot{R}(\tau_f)$, deduced from the data of Alexopoulos *et al.* [14]. As one observes, the velocities obtained for pions, kaons, and antiprotons are equal within the error bars given by the uncertainty in the freeze-out temperature, especially for large-multiplicity events. This behavior is even more apparent in recent unpublished data [17] obtained with a longer beam time, which extend up to $dN_{\rm ch}/d\eta=25$ and show the same phenomena for Λ hyperons.

In the light of our previous discussion we do not believe that this apparent uniform flow, which is the same for all observed hadrons, can be explained by hydrodynamic expansion in the hadronic gas phase. On the other hand, a collective flow which is established in a quark-gluon plasma phase before hadronization would naturally account for this phenomenon. We think that our results constitute a powerful indication for the existence and formation of such a deconfined phase.

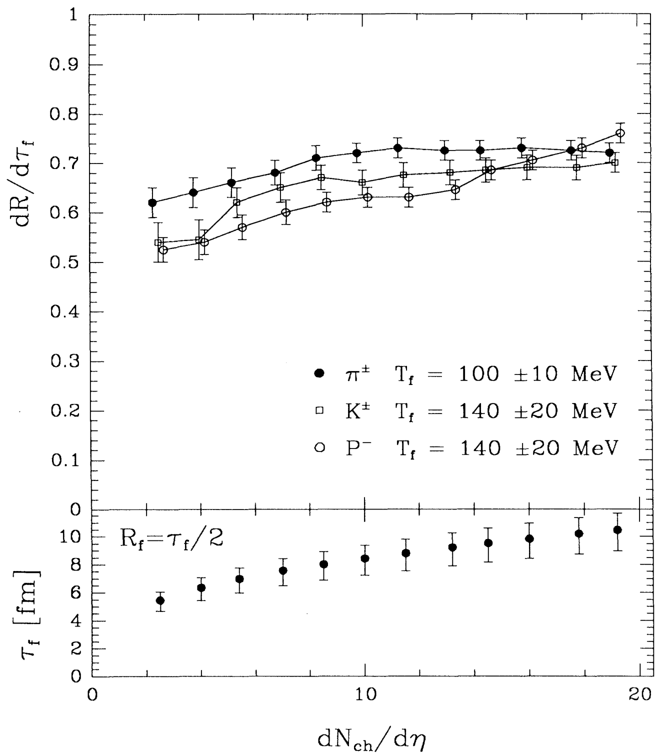

FIG. 2. Top: Surface collective flow velocities for pions, kaons, and antiprotons deduced from the data of Ref. [14] by means of Eq. (15). The error bars reflect the stated uncertainty in the freeze-out temperature T_f, and not the experimental errors. Bottom: Transverse radius R at pion freeze-out time τ_f, as deduced from the measured multiplicity $dN_{\rm ch}/d\eta$ arbitrarily assuming $R(\tau_f)=\tau_f/2$.

It would be interesting to investigate this further in the context of a three-dimensional hydrodynamical calculation, which allows for different flow velocities of the various hadronic species. Alternatively, the effect could be investigated in a transport model similar to the one employed by Bertsch *et al.* [18]. Finally, it must be explored whether the common transverse flow of all hadrons could be generated by multiple uncorrelated large-p_T parton scattering (minijets) without the need for the assumption of a collective flow [19].

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