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PIONS IN AND OUT OF EQUILIBRIUM

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ABSTRACT

Nonequilibrium phenomena in pion p_T spectra may signal the approach to equilibrium.

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Pions In and Out of Equilibrium

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Abstract

Nonequilibrium phenomena in pion p_T spectra may signal the approach to equilibrium.

1. INTRODUCTION

Can final state scattering wrestle the secondaries in nucleus-nucleus collisions into a fluid state near local thermal equilibrium? What do the pion p_T spectra measured in pp , pA and SPS light ion experiments already tell us about the approach to equilibrium? To begin to address these questions, we must face the nonequilibrium nature of hadronic evolution in the late stages of these collisions. I will outline efforts to apply transport theory to the nonequilibrium pion fluid at midrapidity focusing on two phenomena: partial thermalization [1] and pion conservation [2].

Ruuskanen and I [2] have discussed consequences of these nonequilibrium phenomena in the low p_T pion spectra at midrapidity from O+Au and S+S at $\sqrt{s} = 20$ GeV. Here, new results will be presented comparing high multiplicity to average (minimum bias) pp collisions at $\sqrt{s} = 63$ GeV, as measured by the SFM collaboration [3] at the ISR. These data show a low- p_T enhancement reminiscent of the SPS AB results in a truly baryon-depleted central region, so that contributions from $\Delta \rightarrow N\pi$ are reduced [4]. Moreover, these experiments are closer to RHIC energies!

2. PARTIAL THERMALIZATION

In high energy pp reactions as in nuclear collisions at the SPS, the dynamics of the central region is dominated by pions at proper times $> t_0 \sim 1 - 3$ fm, when hadronic degrees of freedom become well defined. Longitudinal expansion rarefies the system and inhibits thermalization during this 'late' period, because the pion scattering rate decreases strongly as the density drops. The pion density at midrapidity $n \propto t^{-1}$ falls as the proper time t increases. This dilution reduces the effective scattering rate $\nu \approx \langle \sigma v \rangle n$ roughly as t^{-1} , since the density dependence of the momentum transfer cross section $\langle \sigma v \rangle$ is weak [5,6]. Significantly, the expansion rate of the system $|\dot{n}|/n$ also falls as t^{-1} .

In [1] I suggested that the rapid longitudinal expansion prevents the pion fluid from reaching local equilibrium but, rather, drives the system towards a novel partially thermalized state. In essence, the macroscopic evolution is never strictly 'quasi-static' on microscopic scales. To exhibit the character of partially thermalized flow, I determined the energy density $\mathcal{E}$ on the central slice as a function of time t using the Boltzmann equation with the density dependent relaxation rate $\nu \propto n$. I find

$$\mathcal{E}(t) \approx C(t_0/t)^{1+\gamma}, \quad (1)$$

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Figure 1: (a) Degree of thermalization γ as a function of the coupling parameter α . Expected γ for ISR high multiplicity and minimum bias pp (filled and empty squares), and SPS S+S (empty circles) and O+Au (filled circles). (b) ISR pp data [3] compared to calculated ratio of dN/dp_T .

where the coefficient C depends on the initial conditions. The exponent γ in fig. 1a varies continuously between the noninteracting and ideal hydrodynamic extremes, 0 and $1/3$, depending only on the coupling parameter:

$$\alpha \equiv \nu n / |\dot{n}| = \langle \sigma v \rangle (\pi R^2)^{-1} dN/dy, \quad (2)$$

where R is the projectile radius and dN/dy is the pion rapidity density [1]. I extract $\langle \sigma v \rangle \approx 7 - 10$ mb from variational [5] and Chapman-Enskog [6] calculations based on $\pi\pi$ scattering data. Although (1) strictly applies for $t \gg t_0$, convergence is rapid for physically plausible initial conditions.

The exponent γ characterizes the degree of thermalization of the expanding fluid, as seen by comparing $\gamma(\alpha)$ to the hydrodynamic limit in fig. 1a. Hydrodynamics including viscosity describes the flow at the 20% level for $\alpha > 4$, while ideal, viscosity free hydrodynamics is only valid as $\alpha \rightarrow \infty$. This measure of thermalization is equivalent to the more familiar flow anisotropy [7], since $\gamma = P_{\parallel} / (2P_{\perp} + P_{\parallel})$ where $P_{\parallel}$ and $P_{\perp}$ are the longitudinal and transverse pressures at midrapidity in configuration space [1]. The partially thermalized state corresponds to a fixed, steady anisotropy $P_{\parallel} > P_{\perp}$.

To estimate the degree of thermalization expected in nuclear collisions for the central region at the SPS, observe that NA35 reports $dN^-/dy \approx 27$ and 41 for charged particles from S+S and O+Au. The $\gamma(\alpha)$ expected for O+Au and S+S are indicated in fig. 1a by the filled and empty circles, respectively. The fluid in O+Au is marginally in the viscous flow regime with $\alpha \approx 4$, while S+S is in an intermediate regime with $\alpha \approx 1.8$.

3. PION CONSERVATION

The pion number is approximately conserved in the late stages of AB or pp collisions, because inelastic pion interactions are too slow to vary the number of pions in the short lived hadronic fluid [8,5,9]. In a static gas, reactions such as $\pi\pi \rightleftharpoons K\bar{K}$ and $\pi\pi \rightleftharpoons \rho\rho$ maintain chemical equilibrium, so that the pion chemical potential μ_{π} vanishes.

Figure 2: Transverse momentum distributions for O+Au and S+S [2].

However, these processes do not affect the pion distribution appreciably during the $< 5-10$ fm duration of a nuclear collision, as rate estimates variously based on $\pi\pi$ scattering data and chiral perturbation theory indicate. Baym realized that the expansion of the collision volume can then generate a nonzero μ_π [8].

Kataja and Ruuskanen recently observed that the pion fluid can be initially *superdense*, i.e. its density at t_0 can exceed the chemical equilibrium value corresponding to the initial $\langle p_T \rangle$ [10]. Indeed, the pion fluid in O+Au would have a large initial chemical potential, roughly $3m_\pi/4$, if the fluid were in thermal equilibrium: To estimate the pion density [2], we take the $dN/dy \approx 3\pi R_A^2 n(t_0)t_0/2$ applicable at midrapidity where the factor $\approx 3/2$ accounts for resonance decays. NA35 O+Au data then imply $n(t_0) \approx 1 \text{ fm}^{-3}$ at $t_0 \sim 3 \text{ fm}$. This estimate exceeds the $\mu_\pi = 0$ value $n_{\text{eq}} \approx 0.15 \text{ fm}^{-3}$ at the effective temperature $\approx \langle p_T \rangle/2 \approx 160 \text{ MeV}$ that describes the p_T spectrum (we assume $\langle p_T \rangle \approx \langle p_T \rangle_{NN}$ for pions formed in NN subcollisions).

In a superdense pion fluid, Ruuskanen and I find that the number-conserving $\pi\pi$ interactions shift the convex shape of the initial spectrum at low p_T in agreement with the concave form of the NA35 O+Au data (the “low p_T enhancement” discussed in refs. cited in [2] and Sarabura’s talk in these proceedings). To obtain the pion spectra in fig. 2, we again solve the Boltzmann equation for conserved, Bose pions using the relaxation rate from [1]. We assume that pions are formed in independent NN subcollisions to fix the initial spectrum (see [2] for details). The calculated low p_T enhancement reflects the low momentum peaking of the thermal equilibrium Bose-Einstein distribution for $\mu_\pi > 0$ relative to the chemical equilibrium distribution [9,10,11]. Because the system is not fully thermalized, however, the final state cannot be represented by a single T and μ_π at the instant of freezeout.

Recently, Welke and Bertsch have performed Boltzmann equation calculations with an exact numerical treatment of the $\pi\pi$ collision term [12]. They obtain both p_T and y distributions for O+Au, and find qualitative agreement with our results at midrapidity.

I emphasize that *both* the superdense initial conditions and the partial thermalization of the flow are needed to correctly interpret the qualitative low momentum behavior. The hydrodynamic evolution of μ_π is sensitive to the entropy per particle s/n through the Gibbs-Duhem relation $\mu_\pi/T = (\mathcal{E} + P)/nT - s/n$. Adiabatic expansion

($s/n = \text{const.}$) drives μ_π to positive values even if one takes $\mu_\pi(t_0) = 0$ [8,9]. However, entropy is generated by deviations from local thermal equilibrium. The estimated entropy increase from shear viscosity corrections in hydrodynamics [5] can drive μ_π to *negative* values for $\mu_\pi(t_0) = 0$. Therefore the large initial densities [10] are necessary, provided that one accepts the estimates of viscous corrections [5,6] based on the free space $\pi\pi$ cross sections. Of course, the in-medium effects discussed by Shuryak in these proceedings may change the entire picture [13] — many questions remain!

4. TOWARDS EQUILIBRIUM

Following [2], I have calculated the p_T spectra for charged particles in high multiplicity and minimum bias pp collisions at $\sqrt{s} = 63$ GeV for comparison to SFM measurements [3]. The filled and empty squares in fig. 1a indicate the estimated degree of thermalization for high multiplicity and average pp collisions at $\sqrt{s} = 63$ GeV. Like S+S, the pion fluid in the high multiplicity pp reactions fall midway between the free streaming and hydrodynamic regimes. In applying (2) to $pp \rightarrow \pi X$, I take $\pi R^2 \approx \sigma_{pp}$ and $(dN/dy)_{\text{high}} \approx 2(dN/dy)_{\text{avg}} \approx 8.5$ extrapolated from the SFM charged particle multiplicities and dN/dy . The spectrum at the pp initial time $t_0 \approx 1$ fm is taken so that $\langle p_T \rangle \approx 0.38$ GeV at the higher energy [3]; otherwise the initial distribution is the same as for SPS energies [2]. The results in fig. 1b are in good agreement with the data.

Figure 1a implies an increase in the degree of thermalization from pp to S+S or O+Au following the increase in $\alpha \propto A^{-2/3} dN/dy$. This trend is consistent with the behavior of the calculated and measured spectra in figs. 1b and 2. In particular, the partially thermalized distribution for O+Au is practically indistinguishable from the fully thermalized Bose distribution. The O+Au system is not fully thermalized, however, so that the link between the equilibrium equation of state final state quantities, e.g. $\langle p_T \rangle$ and dN/dy , is extremely subtle. Nevertheless, the trend that heavier systems are more thermalized is encouraging.

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