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Fluctuations and Inhomogenities of Energy Density and Isospin in Pb+Pb at the SPS *

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1. Motivation

The main goal of heavy ion physics in the last fifteen years has been the search for the quark-gluon-plasma (QGP) [1]. Until now, unambigous experimental evidence for the QGP is missing. However one intuitively doubts that every event produces the plasma state, at least at SPS energy: The necessary energy density, the reaction volume and the life time may be reached [2], but probably only as a fluctuation. I.e. just a small fraction of the reactions will create this novel phase of matter. The new generation of heavy ion colliders, the SPS, RHIC and LHC, provides a new diagnostic opportunity with its data on thousands of identified particles - the event by event analysis of plasma signals [3]. In the following, we try to tackle some of these questions within a microscopic theory[4].

2. Thermalization and Temperatures

Let us first explore the approach towards collectivity - and maybe thermalization - that can be achieved in central Pb on Pb collisions at 160 AGeV. It is convenient to introduce a quantity Φ which is definied as[5]:

$$\Phi := \sqrt{< Z > / < N >} - \sqrt{\overline{z^2}} \quad , \quad \text{with} \quad Z = \sum_{i=1}^{N} z_i \quad , \quad z_i = p_{\perp_i} - \overline{p_\perp} \tag{1}$$

and $\overline{p_\perp}$ as the particle averaged transverse momentum, $\overline{z}$ denotes the particle averaged z, $< N >$ average number of particles per event and $< Z >$ being the event averaged Z.

Fig.1 shows the mass dependence of the collectivity variable Φ vs. the system mass normalized to the proton proton value. The uniformity increases by one order of magnitude going from p+p to Pb+Pb in line with recent NA49 data[6].

Does this uniform particle emission indicate global equilibration of the hadronic source? Fig.2 shows the calculated temperature fluctuations of the source at freeze-out (cut: $|y| <$

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0.5). The fluctuations are due to the finite particle number and flow dynamics. In thermal equilibrium they are connected to the heat capacity of nuclear matter via [7]:

$$P(\Delta T) \propto \exp\left(-\frac{C_V(T)}{2}\left(\frac{\Delta T}{T}\right)^2\right) \quad , \tag{2}$$

with the heat capacity of hadronic matter $C_V(T)$, T being the temperature and ΔT giving the deviation from the mean value. It is obvious that the mean apparent temperatures (inv. slopes) include the effects of transverse expansion, resulting in larger temperatures for heavier particles, when going from π's to p's. By ignoring any non-equilibrium effects or different flow contributions (modifying the width of the distribution), one calculates heat capacities of $C_{V_{\pi^-}} = 298$ and $C_{V_p} = 57$ in line with the classical limit of: $C_V = 3/2N$, N being the number of particles.

Additional insight may also be gained by studying particle number fluctuations which are connected to another key quantitity, namely the compressibility of hadronic matter under extreme conditions[8].

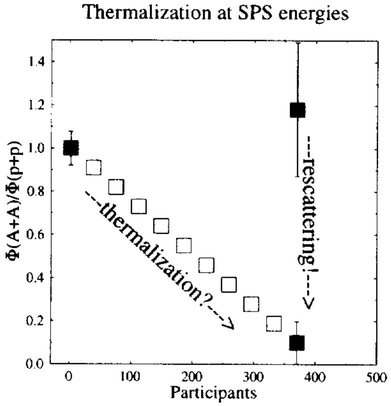

Figure 1. "Collectivity" variable Φ as a function of system mass. Open symbols are guide to the eye.

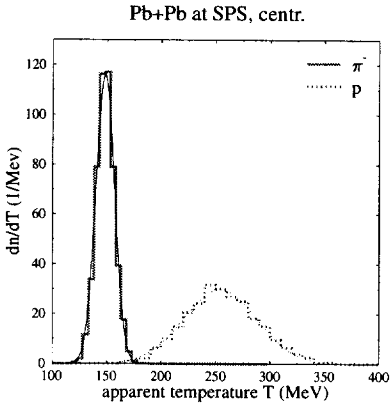

Figure 2. Fluctuations in the apparent "temperatures" of protons and pions in Pb+Pb at the SPS

3. Energy Density Fluctuations and Hot Spots

Turning to a detailed investigation of the fluctuations, we define a "thermalized" energy density ϵ by the condition (isotropic expansion): $\left(p_x^2 + p_y^2\right)/2p_z^2 \approx 1 \pm 0.2$. This effectively removes the free streaming nucleons from our consideration, reducing the mean energy density (at 1 fm/c) to 0.8 GeV/fm^3. Note that this microscopically calculated energy density is 3-25 times lower than the initial energy density needed in hydrodynamical scenarios[9]. Fluctuations of this "thermalized" quantitity in the central region ($|x| <$ 3fm,$|y| <$ 3fm,$|z| <$ 0.5fm, $t = 1$ fm/c after the first collision) are depicted in Fig.3. 10% of all events reach energy densities quite beyond assumed phase transition values of about 1 GeV/fm^3.

A snapshot of the coordinate space distribution of the "thermal" energy density in one single event is even more appealing (cut: $|z| < 0.5$ fm): Fig.4 shows hot spots[10] with more than 20 times nuclear matter energy density. However the volumina of these hot spots are of the order of 10 fm^3, which opens the possibility to study finite size effects in quark matter droplets at SPS energies[11].

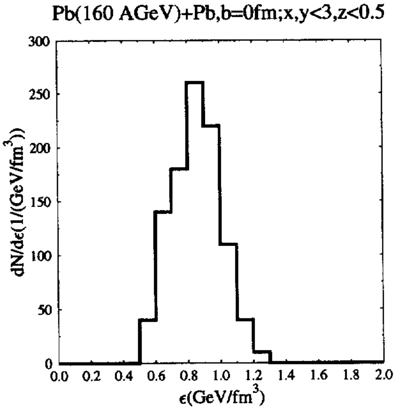

Figure 3. Fluctuations in the "thermalized" energy density from event to event.

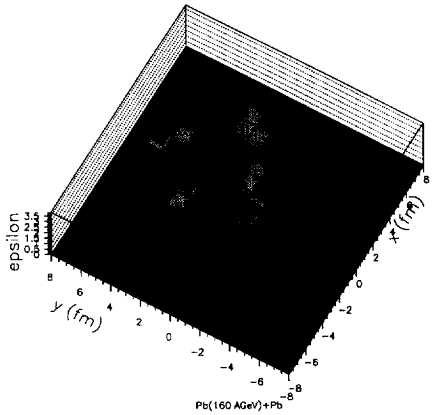

Figure 4. Coordinate space fluctuations in ϵ by hot and dense spots.

4. DCC Detection and Particle Number Fluctuations

At sufficiently high energy densities a phase transition to a chirally invariant phase is supposed to take place. It is speculated that after a rapid cooling of the hot and dense central region a droplet of disoriented chiral condensate may emerge[12]. This droplet decays into pions, which finally may be detected. In Fig.5 we show the isospin fluctuations of π^+ vs. π^- (in case of π^0's we get a similiar structure) at midrapidity $|y| < 0.5$ and low $p_\perp$ ($p_{\perp_\pi} < 100$ MeV). The distribution is nearly symmetric with respect to the isospin, with a mean value of 22 pions and a full width at half maximum of 10 units.

We have performed a microscopic analysis of the pions stemming from the decaying droplet, applying full elastic and inelastic scattering processes. The droplet is assumed to decay after 7 fm/c[†] into 30 pions (isospin probabilities are choosen according to [12]) with gaussian momentum distribution (width $\approx$ 70 MeV) in a sphere with radius 3 fm around $(x, y, z) = (0, 0, 0)$ fm[13]. Fig.6 shows the probabilities for the ratio $n_{\pi^0}/(n_{\pi^0}+n_{\pi^+}+n_{\pi^-})$ in single events at midrapidity ($|y| < 0.5$). The dotted line gives the initial pion isospin asymetry of the DCC. This DCC signal is completely washed out and the ratio is shifted towards the canonical value of 1/3 without any additional peaks. This can be understood, since the analysis reveals that 70% of all DCC pions interact strongly with the surrounding medium even at these late times, resulting in charge and momentum transfer. This is currently investigated in more detail to predict a critical DCC size and freeze-out time to support current experimental and theoretical investigations.

[†] This corresponds to a (non-)thermalized energy density below 0.5 $\mathrm{GeV/fm}^3$.

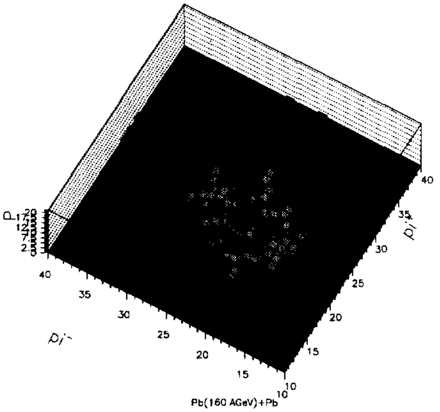

Figure 5. Particle number/isospin fluctuations in the pion channel.

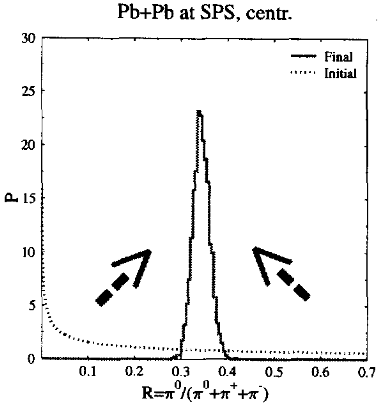

Figure 6. The DCC signal in the pion ratios is destroyed by rescattering

Summary

The approach to equilibrium has been analyzed within a microscopic framework. In particular we investigated energy density fluctuations and found extremely hot spots of "thermalized" energy density ($\epsilon > 3$ GeV/fm^3) of volume 10-20 fm^3 in individual events. Finally we have analyzed pionic isospin fluctuations as a possible DCC signal, and found that this observable is strongly washed out due to hadronic rescattering processes.

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