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TITLE: # HYDRODYNAMICAL ANALYSIS OF SYMMETRIC NUCLEUS-NUCLEUS COLLISIONS AT SPS ENERGIES

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HYDRODYNAMICAL ANALYSIS OF SYMMETRIC NUCLEUS-NUCLEUS COLLISIONS AT SPS ENERGIES

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We present a theoretical study of ultrarelativistic heavy-ion data obtained at the CERN/SPS by the NA49 Collaboration using 3+1-dimensional relativistic hydrodynamics. We find excellent agreement with the rapidity spectra of negative hadrons and protons and with the correlation measurements for $Pb + Pb$ at 160 $AGeV$ (preliminary results). Within our model this implies that for $Pb + Pb$ a quark-gluon-plasma of initial volume 174 fm^3 with a lifetime 3.4 fm/c was formed.

1 Introduction

It is very appropriate to discuss relativistic heavy ions in a meeting honouring Walter Greiner. It is a field which he helped found, in which he has provided many of the seminal ideas, in particular the use of fluid dynamics and the equation of state of nuclear matter[1], and which he has continued to strongly influence[2,3,4].

A prediction of the theory of quantum chromodynamics is that at sufficiently high energy and/or baryon density, the quarks inside hadrons are deconfined and a quark-gluon plasma is created, albeit for only a very brief time. In the past several years there have been vigorous experimental programs in high energy heavy ion physics pursued at CERN and at the Brookhaven AGS. Ever higher energies and/or masses have been used to increase the lifetime of the hot matter by increasing the initial energy density, the size of the system, or both. The probability of preparing a strongly interacting system that shows thermodynamical behavior and therefore is treatable by well known thermodynamical or fluid dynamical methods increases with the size of the system.

2 Modeling the reaction using relativistic heavy ions

Fluid dynamics provides an intuitively simple description of heavy ion collisions: two nuclei smash into each other, are rapidly thermalised and compressed; the resulting fireball then expands and breaks up into bits of hadronic matter that ultimately reach the detectors. Because some of the underlying principle assumptions of fluid dynamics, *e.g.*, that of a zero mean free path and instant thermalisation, it has been long assumed that this model would not be valid at relativistic bombarding energies. The experimental observation at the AGS and CERN of complete or nearly complete stopping of matter has altered this perception. Many researchers over the past few years have successfully simulated heavy ion collisions using fluid dynamics and it continues to provide accurate estimates of experimental observables from relativistic heavy ion collisions.

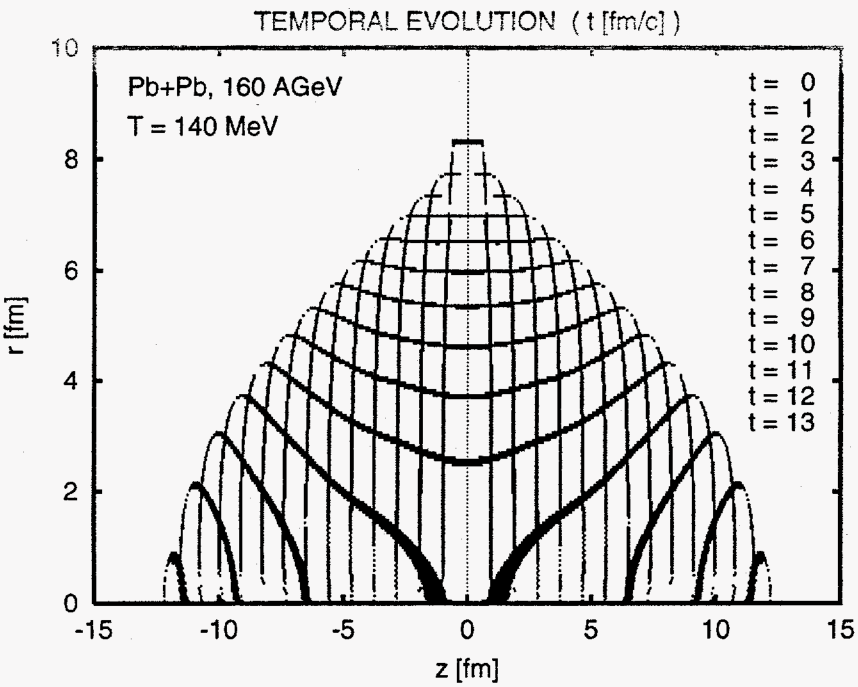
A theory of relativistic fluid dynamics is not guaranteed to exist: it requires that a system of N particles (with $N \approx$1000 or more) with $6N$ degrees of freedom be accurately represented by a system of 6 equations. Arguments to justify fluid dynamics in conventional physics have been made, *e.g.*, Bogoliubov[5], but their applicability in the relativistic regime is unclear. The apparent validity of fluid dynamics in describing hadronic reactions may be that five of the six Euler equations are kinematic constraints: conservation of mass and energy-momentum. The observables currently examined may simply be dominated by such constraints, although Bose-Einstein correlations may be a much more severe test. There are severe difficulties in relativistic fluid dynamics when one attempts to include dissipation[9,10]. There are ambiguities in the choice of the rest-frame[11,12,13]. All first-order theoreies are known to have difficulties such as being singular or to admit acausal solutions[14]. For a justification of hydrodynamics, the reader is referred to a recent text[8] or reviews of the subject[2,6,7].

There are several assumptions in the hydrodynamical approach: (i) the initial conditions, (ii) the equation of state (EOS), (iii) the magnitude of the viscosity and heat conduction, and (iv) models of the final stage of the reaction when hydrodynamics has ceased to be valid and one must worry about the emission processes, freeze-out, and evaporation.

We have undertaken a comprehensive study of data taken at CERN by the NA35 and the NA49 collaborations[15,16]. Results of Pb+Pb at 160 AGeV were obtained[17,18] using 3+1 dimensional relativistic fluid dynamics. There are several assumptions in the hydrodynamical approach: the initial conditions, the equation of state, and models of the final stage of the reaction when hydrodynamics has ceased to be valid, i.e., freeze-out. All the dynamics is contained in the equation, $P = P(\mu, T, n, ...)$, the equation of state. Initial conditions specified in terms of energy density and initial velocity profiles was chosen so as to reproduce the measured rapidity distribution of particles. An equation-of-state was assumed that contains a phase transition from the hadronic phase to a quark-gluon phase at a critical temperature T_C=200 MeV. Because of the need for a relativistic framework, a covariant freeze-out scenario developed by Cooper and Frye[19] was used.

A reaction of two baryonic fluids leads to a deceleration of the projectile and target baryonic currents and thus to the spread of their width in momentum space. In our model we impose an initial rapidity field $y(z)$ on the fluid.

The kinetic energy of the two incoming baryonic fluids is converted into internal excitation (thermal energy) of a third fluid which is created in the central region. The relative fraction of the thermal energy inside the initial fireball volume fixes also the initial state of the formed fireball.



3 Discussion of Results

The numerical simulation reproduced simultaneously mesonic and baryonic rapidity and transverse momentum spectra[17,18]. The lifetime of the hot dense matter was calculated to be about 15 fm/c - the quark-gluon plasma persisted for 3.4 fm/c - and the collision time and baryon density increase is about 20-30% larger if a phase transition is present compared to the case in which there is no phase transition. The density achieved in the center of the hot fireball is calculated to be as much as 20 times that of normal nuclear matter. Under such extreme conditions as occurs in central collisions, a quark-gluon plasma is formed which in our calculations is 174 fm^3 which is an appreciable fraction of the total matter.

In the first figure we exhibit the space-time geometries of the hadron sources, /it i.e., the time contour plots of the freeze-out hypersurface in the z-r plane. Each line represents the freeze-out hypersurface at a fixed time t. The numerical solution represented in the plot show an evolution of an initially disk-shaped fireball which emits hadrons from the very beginning. Due to the effect of transverse, inwardly moving rarefaction waves, the transverse freeze-out positions move towards the center of the fireball. In the late stage of the hydrodynamical expansion the hadron-emitting fireballs separate into two parts while cooling down until they cease to emit.

Bose-Einstein correlation functions for pions have also been calculated. The preliminary NA49 data on interferometry are surprisingly well described. In the case of pion interferometry a large fraction – 40% to 50% – of the pions originate from resonances which strongly influences the calculated radii. Bose-Einstein correlations are a very complicated observable defined through quantum statistics. The more resonances taken into account, the narrower the correlation function becomes because the resonance halo increases the effective source size. As seen in the first figure, the hadron source (the real fireball) is represented through a very complex freeze-out hypersurface. The longitudinal and transverse extensions of the fireball change dynamically as a function of time, rather than show up as static effective radii.

We have shown that data from heavy-ion experiments for single and double inclusive cross sections of mesons and baryons can be reproduced with a three-dimensional relativistic hydrodynamic description assuming an equation of state with a phase transition to a QGP. Our data analysis indicates aan enhanced transverse flow in the case of $Pb+Pb$ collisions at CERN/SPS energies. The results of this work constitute further evidence that heavy-ion collisions in the SPS region show fluid dynamical behaviour and can be described by assuming an equation of state with a phase transition from a quark-gluon plasma to hadronic matter.

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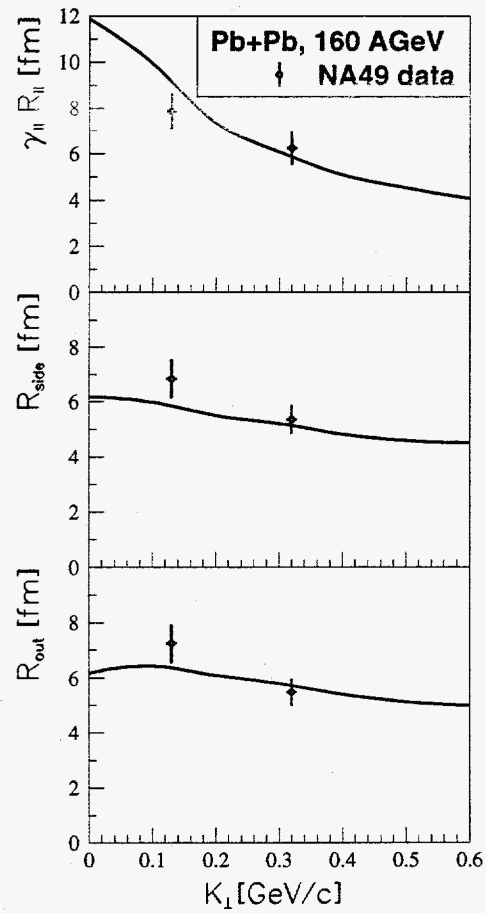
Pb+Pb, 160 AGeV
NA49 data
$\gamma_{\parallel} R_{\parallel}$ [fm]
R_{side} [fm]
R_{out} [fm]
$K_{\perp}$[GeV/c]