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TIME EVOLUTION OF THE QUARK-GLUON PLASMA

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ABSTRACT

We review progress in our understanding the production and time evolution of the quark gluon plasma starting with boost invariant initial conditions in a field theory model based on the Schwinger mechanism of particle production via tunnelling.

1. Introduction

The present theory of Strong Interactions, namely Quantum Chromodynamics (QCD) has the property that the quarks, which are the building blocks of the protons and neutrons, are confined and cannot be liberated. Thus one can infer the properties of the quarks only indirectly using high energy probes which probe the short distant interactions of the quarks. In recent years, as a result of lattice gauge theory calculations, it was found that at high temperatures around 200 GeV and at energy densities around $2\text{GeV}/\text{Fermi}^3$ the behavior of QCD changes and there appears to be a first order phase transition from the phase where quarks are confined and particles exist as ordinary matter (the nucleons and pions) to a phase where there are quarks and gluons that are interacting weakly as in a weakly interacting gas — that is the quark-gluon plasma phase.

The question naturally arose how one could detect the presence of such a phase. One natural place where high temperatures and densities exist is in the early universe, but it was soon discovered that the existence of this phase in the early universe did not effect the standard nuclear synthesis processes which take place later in the time evolution of the big bang. Thus one could not see any striking experimental evidence for this phase existing. It was then realized that in relativistic heavy ion collisions possible at CERN and at RHIC at BNL having collision energies of $E_{\text{lab}} = 10 - 200\text{AGeV}$ (GeV per incident projectile nucleon) energy densities of up to $2 - 20\text{GeV}/\text{Fm}^3$ could be reached over space time volumes much larger than the characteristic confinement scale of QCD. Thus it was clear that this new phase of matter — the quark gluon plasma could be produced in relativistic heavy ion collisions. Although lattice calculations predicted the existence of the quark gluon plasma phase, the lattice calculations only could determine the static properties of equilibrium plasmas such as those expected in the early universe. The situation in a heavy ion collision could be very far from equilibrium and the signals of the quark gluon plasma, a state only expected to live

for 10^{-22} sec before turning into ordinary hadronic matter, might easily be washed out by interactions taking place in the ordinary matter phase. Thus one needs to look for processes taking place from a non-equilibrium plasma which are not affected by future interactions. One such process is the production of weakly interacting lepton pairs which escape the plasma without interacting strongly with the hadronic matter.

In order to determine the spectra of such processes and see if the production of weakly interacting particles coming from this phase is different than that coming from ordinary matter one needs to know the time evolution of the quark-gluon plasma and the distribution of quarks and antiquarks as a function of time since these are the source of the dileptons. This required a new formalism which allowed one to track the time evolution of a field theory starting from initial data. The need for such a formalism arose in a previous situation recently in connection with the time evolution of the early universe - namely the inflationary picture of the early universe.^{1,2} The formalism for doing this latter problem was developed³ and then applied to the problem of pair production by strong electric fields. These original simulations of pair production⁴ became the prototype for a more serious investigation of the time evolution of the quark-gluon plasma. What does relativistic heavy ion collision look like? The strong forces between hadrons are mediated by colored gluons, and as a result of exchanging gluons, the initially colorless hadrons become charged with opposite colors and get separated quickly since the hadrons move away from each other near the speed of light⁵. Thus one has a situation resembling two charged plates moving away from each other with a constant colored electric field between them. When the energy density in the field is large enough so that the work done by the field at a hadronic distance is equal to the rest energy of a quark anti-quark pair, then the "vacuum" becomes unstable to the production of this pair. The criteria for this to happen is:

$$gE(\hbar/mc) > 2mc^2 \quad (1)$$

where g is the color charge, E the color electric field and $\hbar/mc$ is the natural size - the Compton wave length of the quark. The first calculations of this process for constant external strong electric fields were done by Schwinger^{6,7}. The receding nuclei produce a strong color electric field which pops pairs of quarks and antiquarks as well as gluons out of the vacuum. A plasma of quarks and glue moving in and interacting with the original time varying color electric field gets produced. These quarks also emit pairs of leptons via electromagnetic processes which one detects in the detector. As the system expands the density decreases and then there is a phase change back into the ordinary hadronic phase as bubbles of the hadronic phase then become energetically favorable. The initial chromoelectric field can be determined from the QCD string tension under the assumption that during each collision taking place during the passage of two nuclei through each other chromoelectric field gets created as in a random walk. This problem has several time scales, the frequency determined by the quark mass, the plasma oscillation frequency which is from the effective mass of the gluon when in the presence of a finite density plasma, and finally the relaxation time for the energy to be transferred from the chromoelectric field to the quarks. Thus to get an accurate description of this process very tiny time steps must be used to not wash out all these important effects.

As a warm up problem we have studied QED in the kinematic situation favored by Bjorken⁸ in describing heavy ion collisions (all variables are a function of the proper time)

and determined the time evolution of the quarks in the background field evolving in proper time τ . In this simplified model we have been able to check many of the assumptions of more phenomenological pictures of the time evolution of the quark-gluon plasma. We have compared our exact calculations with semi-classical transport models which assume the mechanism of pair production described above as a source term for the time evolution of a single particle distribution function similar to that used in ordinary plasma physics^{9, 10, 11}, as well as tested several assumptions of hydrodynamic models^{12,13, 8} which assume that global macroscopic variables such as energy density and pressure can be used to study the time evolution of the plasma as one does in ordinary relativistic fluid flows.

What we found was that previous transport models had ignored a basic important fact the Pauli-exclusion principle which does not allow two quarks to be in the same state. When we included this fact we found that at least for the case where we could ignore the quantum fluctuations of the colored fields, that the modified transport theory agreed well with a coarse grained average (in both time and momentum space) of our field theory calculation. We also were able to verify some of the assumptions of hydrodynamic models, even though for our calculation we were far from the hydrodynamic equilibrium. By studying the microscopic analogues of energy density and pressure, we were able to verify that particle production rates could be determined from the hydrodynamic energy flows as assumed in hydrodynamic models.

We are now entering the next phase of our approach. In our previous calculation we ignored the quantum fluctuations of the colored electric fields as well as the scattering among the quarks and anti-quarks. We have developed a systematic method of calculating these effects. We also have developed the formalism for studying the production and time evolution of the purely gluonic plasma, where the glue is treated in a mean field approximation. Numerical simulations of these latter two problems are just beginning.

Details of these earlier calculations as well as time evolution results for the electric field, entropy and energy densities and particle distributions are published in the literature^{14, 15, 16, 17}.

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