Chapter 1

Physics Of Quark Gluon Plasma

1.1 Introduction

We very briefly review some basic aspects[1] of QCD and QGP in this chapter. Particle physicists today believe Quantum Chromodynamics (QCD) to be the candidate theory of strong interaction. It is the theory of particles that constitute the observed hadronic world. The evidence that the hadrons are made up of point like constituents, called quarks, came from deep inelastic scattering experiments of leptons on hadrons. These quarks come with different flavours, up(u), down (d), strange (s), charm (c), bottom (b) and another one (though not observed yet but have strong reasons to exist) top (t).

The deep inelastic scattering data also suggested that these quarks are Dirac particles and carry non-integer electric charge. For u, c, t it is $\frac{2}{3}$ and for d, s, b it is $\frac{-1}{3}$ in units of proton charge. Quarks of different flavours differ from each other through their flavour quantum number and mass. Current algebra techniques have suggested the typical values for the current quark masses to be

$$m_u = 5 \text{ Mev} \qquad m_d = 10 \text{ Mev} \qquad m_s = 150 \text{ Mev}$$

$$m_c = 1500 \text{ Mev} \qquad m_b = 5000 \text{ Mev} \qquad m_t \geq 140 Gev$$

The existence of resonances like Δ^{++}, Δ^{-} and Ω^{-}, to be consistent with

Pauli principle, suggested, within the quark model, the existence of another quantum number called color. From the ratio of cross sections of $e^+ e^- \rightarrow hadrons$ to $e^+ e^- \rightarrow \mu^+ \mu^-$ it has been established that the number of colors $N_c = 3$.

We believe that color degree of freedom is like electric charge, is exactly conserved and is a source of long range interaction. The theory of color interactions, QCD is derived from the principle of local gauge invariance in color space.

The Lagrangian that describes QCD is given by

$$L_{QCD} = \Sigma_{f=1}^{N_f} i \overline{\psi_f} \gamma^\mu \left(\partial_\mu - igA_\mu^a T^a\right) \psi_f - m\overline{\psi_f}\psi_f - \frac{1}{4} F_{\mu\nu}^a F_a^{\mu\nu} \tag{1.1}$$

Here Lorentz index μ varies from 0 to 3, f is the flavour index with maximum value N_f and a varies from 1 to 8.

The color field tensor $F_{\mu\nu}$ is given by

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + ig\left[A_\mu, A_\nu\right] \tag{1.2}$$

It can be expressed as $F_{\mu\nu} = F_{\mu\nu}^a T^a$ with T^a as the generator of SU(3) color group. They obey the commutation relation

$$[T_a, T_b] = i\, f_{abc}\, T_c \tag{1.3}$$

where f_{abc} are the structure constants of the group.

Under a local gauge transformation U, the fields ψ and A_μ transform as

$$\psi_f' = U\psi_f \tag{1.4}$$

$$A_\mu{}' = U^{-1} A_\mu U - \frac{i}{g} U^{-1} \partial_\mu U \tag{1.5}$$

such that

$$F_{\mu\nu}' = U^{-1} F_{\mu\nu} U \tag{1.6}$$

From the structure of the Lagrangian, it is clear that though this theory looks like Quantum Electrodynamics(QED),but due to the presence of the non-abelian terms it differs significantly from QED. For instance, this difference can be seen from the expression of running coupling constant, at one loop level,

$$g^2_{QCD}(Q^2) = \frac{g^2(\mu^2)}{1 + \frac{g^2(\mu^2)}{12\pi}(33 - 2N_f)\, ln\left(\frac{Q^2}{\mu^2}\right)} \tag{1.7}$$

where μ^2 is a scale parameter to be deduced from experiments.

We can see that, for $N_f \leq 16$, as Q^2 the momentum transfer $\rightarrow \infty$, $g^2(Q^2)_{QCD} \rightarrow 0$. The running coupling constant in QED shows exactly opposite behaviour. i.e. $g^2_{QED} \rightarrow \infty$ as $Q^2 \rightarrow \infty$. This particular behaviour of the non-abelian coupling constant, termed asymptotic freedom, tells us that at high momentum transfer one has essentially free particles, and hence perturbation theory is applicable.

So far we have considered momentum scales Q^2 larger than μ^2. The important question is what happens to the running coupling constant at a scale $Q^2 < \mu^2$. It is worth mentioning that at this scale analytical studies are difficult and it is believed that g^2 increases with decrease in Q^2 and lattice results imply the same type of behaviour. Hence it is difficult for the quarks to separate themselves from each other beyond a distance of the order of one fermi. This particular phenomenon, called confinement, though not proved rigorously, confirms with our experience that no free quarks have been observed in experiments.

So these two properties, namely asymptotic freedom and confinement are the cornerstones of strong interactions and have profound consequences on the properties of hadronic matter subjected to high temperature or density or both.

1.2 QCD at High Density and Temparature

QCD predicts that in nuclear matter at densities ten to twenty times the nuclear density (≈ 0.15 GeV$/fm^3$) or at very high temperature (kT $\geq$ 200MeV), quarks and gluons will be liberated over a volume greater than a typical hadronic volume forming, a soup of quark gluon plasma.

QCD thermodynamics[2] is studied in the imaginary time formalism by compactifying the time direction, and putting a periodic boundary condition for the gauge fields in that direction. In this formalism one can define an order parameter,

$< L(x) >$, where

$$L(x) = N^{-1}\, tr\, P\, exp \left(i \int_0^{\frac{1}{T}} A_4(x,t)\, dt \right)$$

and P denotes path ordering.L(x) is called the polyakov loop. This quantity has been shown[3] to be related to the free energy of static quark in a gluonic bath at temperature T: $< L(x) >= e^{\frac{-F_a(x)}{T}}$. At low temperature one expects the free energy of the quark to be infinite and hence $< L(x) >= 0$ but at high temperature, if deconfinement of color occurs, then the free energy of the system will become finite and hence $< L(x) >\neq 0$. Numerical lattice studies of this quantity has suggested that the phase transition is of first order, and the critical temperature for such a transition to occur, is $T_c \geq 200 MeV$.

In view of these considerations, it appears that, the possible places in nature where such a phase may occur are (i) early universe[4], (ii) inside a neutron star, (iii) Relativistic Heavy Ion Collisions(RHIC).

In this thesis we will concentrate mostly on the RHIC. In RHIC, the plasma is expected to be produced when two heavy nuclei collide against each other at an energy of $\approx$ 200 GeV/nucleon. Once produced this plasma evolves in phase space to attain a state of thermal equilibrium following which it hadronises and particles stream out to the detectors. This whole process of formation to hadronisation of the plasma is supposed to take place within 5 to 10 fm/c.

The purpose of this thesis is to examine production and pre-equlibrium evolution of the plasma. Usually, as the plasma is produced it undergoes a simultaneous space time evolution, making it necessary to take these processes into account self-consistently. Since it is difficult to study these processes in entirety, we have studied some specific aspects of production and evolution of the plasma separately, with special emphasis on the non-abelian features of the underlying theory. We must mention that in the last few years extensive work has been done to study the production and equilibration of the plasma using parton cascade model[(5-7)], however we would not discuss it here.

The plan of this document is as follows. In chapter two we discuss the production mechanism of the plasma at zero temperature, in the color flux tube model[8] of Casher et.al. In contrast to the earlier studies we have done this analysis in the presence of a time varying external electric field and have tried to justify it, from the vacuum solutions of Yang-Mills equations. Results of our analysis show that, because of the presence of time varying chromo-electric field, the pair production rate instead of being exponentially suppressed (as in the constant field case of Schwinger[9]), follows a power law behaviour. Since the number of produced particles increases the probablity of producing a thermalised plasma also increases. Moreover the analysis[10] also shows that, a time varying field is capable of producing pairs even if the field strength is less than the critical field strength required to produce particles in the Schwinger model.

In chapter three we have examined the relevance of pair production at finite temperature in the presence of an external chromo electric field. Following which we have actually computed the pair production rate at finite temperature and have shown that because of screening the pair production rate becomes a space dependent quantity and it increases at high temperature[11].

In the following two chapters we have concentrated on the evolution of the plasma in phase space. In chapter five, we discuss the kinetic equation for gluons and suggest a simple model which shows that, color degrees of freedom can also give rise to new a mechanism for equilibration of the plasma. Chapter 6 contains a derivation of hydrodynamic equations for quarks and gluons starting from the kinetic equations. We also show that the non-abelian nonlinearities in the pre-equilibrium phase of the system lead to chaotic oscillations, that in turn tend to bring the system to thermal equilibrium. In the concluding chapter we have summarised our result and give a futuristic plan for further investigation along the same direction.

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