CHAPTER I

GENERAL INTRODUCTION

A non-perturbative study of collective phenomena in classical quark plasma is carried out in the present work. In this chapter we begin with a brief introduction to quark-gluon plasma(QGP),and then a discussion about the aims and scope of this work will be presented. Finally, a summary of each subsequent chapter will be given.

1.1 Introduction : According to current understanding, all strongly interacting particles such as nucleons and mesons (hadrons) have composite structure.[1] The constituent particles of a hadron are called quarks. Quarks are spin-1/2 particles and carry all the intrinsic quantum numbers possessed by a hadron such as electric charge, baryon number, flavor (isospin,strangeness etc). There are at least five flavors of quarks called up(u), down(d), strange(s), charm(c) and bottom(b). Quarks carry fractional electric charges which have values, in the units of proton's charge, +2/3 for u,c and -1/3 for d,s,b. All the quarks have baryon number 1/3 and anti-quarks have baryon number -1/3. In addition to all these quantum numbers, quarks possess a new quantum number called color which plays a very important role in their interaction. Each quark (anti-quark) can be found in one of three color states labelled as r,b,g ($\bar{r},\bar{b},\bar{g}$). The color quantum number resembles in its properties electric charge in the sense that total color is exactly conserved and it can act as a source for the force fields. Hence color quantum number is often referred as color 'charge'. The major difference between color and electric charge of a quark is that the former is a triplet where as the latter is a scalar.

Quarks interact among themselves via exchange of spin-1 particles called gluons. Gluons also carry color charge and therefore interact among themselves. The Lagrangian of a system of interacting colored particles can be determined from the principle of SU(3) local gauge invariance. The theory is called quantum chromodynamics (QCD)[1] and its Lagrangian is

$$L_{QCD} = \sum_f \{\bar{\psi}_f (i\gamma^\mu \partial_\mu - m_f)\psi_f - g(\bar{\psi}_f \gamma^\mu A_\mu \psi_f) - 1/2 Tr\{F_{\mu\nu}F^{\mu\nu}\} \qquad (1.1)$$

where f denotes the flavor of quark, ψ_f is a three component column matrix in color space in addition it has the usual four Dirac components. m_f is the mass of a quark of flavor f and g is the dimensionless coupling constant. $A_\mu(\mu = 0,1,2,3)$ are the components of the gluon (gauge) fields. $F_{\mu\nu}$ is the gluon field tensor defined as

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + ig[A_\mu, A_\nu] \qquad (1.2)$$

The first term in the parenthesis of Eq.(1.1) represents the "kinetic" energy term of the free quark while the second term corresponds to interaction energy between the quarks and gluons. The last term is the pure gauge field Lagrangian containing the gluon self interaction. The QCD Lagrangian is strikingly similar to that of quantum electrodynamics (QED). The major difference between the two Lagrangians lies in the definition of $F_{\mu\nu}$. Eq.(1.2) clearly shows that unlike the field tensor of photons the gluons field tensor is non-linear in the gauge fields A_μ. This indicates that gluons interact among themselves.

It should be noted that A_μ and $F_{\mu\nu}$ are 3 x 3 matrices in SU(3) color space and they can be expanded in terms of the group generators as: $A_\mu = A^a_\mu T_a$ and $F_{\mu\nu} = F^a_{\mu\nu} T_a$ where, a summation over the index a (a= 1,2,..,8) is implied. T_a are the generators of SU(3) group satisfying commutation relations :

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

where, a summation over the index c is implied. f_{abc} are the completely antisymmetric structure constants of the SU(3) group.

The Lagrangian in Eq.(1.1) is invariant under local color gauge transformations i.e

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

$$A_\mu' = U^{-1}A_\mu U - i/g\, U^{-1}\partial_\mu U \tag{1.4b}$$

where, U is 3x3 unitary matrix and is a function of space and time. One can show that $F_{\mu\nu}$ remains form invariant under these transformations i.e.:

$$F_{\mu\nu}' = U^{-1}F_{\mu\nu}U \tag{1.5}$$

It should be noted that due to the self interaction of gluons QCD differs significantly from quantum electrodynamics (QED). The major differences are: *(i)* Asymptotic Freedom and *(ii)* Confinement.

(i) Asymptotic Freedom : At small distances (« 1 fermi) or at high momentum transfers quarks exhibit free particle behavior. This characteristic of quark-gluon interaction is called asymptotic freedom, and it can be clearly seen from the expression of running coupling constant[2] $g^2(Q^2)$ (order 1-loop level):

$$g^2_{QCD}(Q^2) = \frac{g^2(\mu^2)}{1 + \frac{g^2(\mu^2)}{12\pi}(33 - 2N_f)\ln(Q^2/\mu^2)} \tag{1.5}$$

where N_f is number of flavors and μ is a scale parameter which can be determined experimentally.Thus for high momentum transfer $Q^2 \to \infty$ and $N_f \leq 16$, $g^2_{QCD} \to 0$. The running coupling constant in QED shows exactly opposite behavior i.e $g^2_{QED} \to \infty$ as $Q^2 \to \infty$. Thus, due to asymptotic freedom the perturbative methods may be used to study quark-gluon interactions at small distances or at high momentum transfers. Indeed, deep inelastic scattering of leptons from nucleons have revealed that the particles within a nucleon behave essentially as free particles. This observation is a major success of QCD as a fundamental theory of strong interaction.

(ii) Confinement : We have seen that for Q^2 above the momentum scale μ^2 the coupling constant becomes small. However, to learn what happens below this scale (or at large distances ≅1 fermi) is very difficult, because, at present, there are no analytical techniques available to solve the field equations in this regime. This is a consequence of the fact that the running coupling constant increases as the momentum transfer Q^2 decreases below μ^2. This behavior is consistent with the fact that free quark states, have not been observed so far. This experimental fact implies that the binding force between quarks, due to the exchange of gluons, increases without limit as the separation between them increases. Therefore, it is not possible to "ionize" a nucleon and break-up the bound state formed by the quarks and observe free quarks in the laboratory. Secondly, as no long range force exists between the hadrons, they must be color neutral. This means that color charge is confined absolutely within a hadronic volume. It should be mentioned that extensive numerical calculations confirm this expectation.

Thus, to summarize, asymptotic freedom and confinement are the two most important features of quark interaction which QCD exhibits. The picture of hadron as a composite particle can have profound consequences on the behavior of nuclear matter at high density or at high temperature. The boundaries of the nucleons overlap at high temperature or at high density and bring quarks from different hadrons in the immediate neighbourhood of each other. There is then no way to ascertain which quarks were partners inside a hadron. Further, the long range of forces in such a many body system are expected to be screened, and hence the confinement forces may not be very significant within the medium. The concept of a hadron loses all its meaning in this situation. In this new state of matter quarks and gluons are no longer confined within a hadron but they can move freely in the larger ("macroscopic") volume occupied by the nuclear matter. As a consequence of their (confinement) interaction quarks and gluons cannot be observed outside this volume in their free state. This state of matter is called quark-gluon plasma(QGP).[3]

Transition from a strongly interacting pion gas to QGP may be considered as the transition from a color insulating state to a color conducting state. Although in this respect it is analogous to the transition from atoms to ions, the nature of the phase transition in QCD is not yet completly clear. There are ,however, evidences, from the numerical simulation of QCD, that the phase transition is of I^{st}- order in pure gauge theory and for massless quark species of more than three flavors.[4] Recent numerical results indicate that for heavy quarks the phase transition might be continuous.[4] However, irrespective of the order of the phase transition the plasma phase is fundamentally different from the hadronic phase. This is because in QGP quarks and gluons constitue physical degrees of freedom and determine the dynamics of the plasma whereas in the hadronic phase quarks and gluons are not suitable for an economic description of the hadronic matter.

In order to obtain the critical values of thermodynamic parameters one should evaluate the partition function using the QCD Lagrangian (Eq.(1.1)). However, it is not possible to evaluate the partition function, in general, analytically. It is possible only in the weak coupling limit ($g \ll 1$). Actually we need to know it in the strong coupling limit ($g \geq 1$), as our prime interest is in the phase transition going from the strongly interacting nuclear matter to the weakly interacting plasma. Hence, in order to estimate the critical parameters either simple QCD based phenomenological models are used instead of the actual QCD Lagrangian or they are evaluated numerically using the full QCD Lagrangian.

Indeed, the QCD based models exhibit the phase transition from the nuclear matter to QGP and provide an estimate for the critical temperature and the density for the QGP.

Consider pion gas at temperature $T \gg m_\pi$ where, m_π is the mass of the pions In this limit, we can neglect the mass of pions and obtain the energy density of the relativistic pion gas as

$$\varepsilon_\pi = g_\pi(\Pi^2/30)\ T^4 \qquad (1.6)$$

where, g_π=3, counting three charged states for the pions.

If we suppose that there is a phase transition from the pionic gas to the deconfined quark-gluon state (QGP) then we can write the energy density of the QGP as:

$$\varepsilon_Q = g_Q\ (\Pi^2/30)\ T^4 + B \qquad (1.7)$$

where g_Q=(2x8+7/8x2x2x2x3) represents the total number of degree of freedom for the QGP and B is the phenomenological constant which takes into account the confinement effects. Its value can be taken as $B^{1/4} \cong$ 190 MeV from hadron spectroscopy. In g_Q the first term takes into account contribution from the gluon sector, they come in 8-colors with two different spin polarizations. The second term in g_Q is from the quark sector where 7/8 is the Fermi-Dirac factor, three factors of two represent particle-antiparticle, spin and flavor degrees of freedom respectively,while the factor 3 stands for the color degree of freedom

For a massless gas (when chemical potentialμ=0) the pressure and the internal energy are related by:

$$P=T.S-\varepsilon \tag{1.8}$$

where, S is the entropy density of the gas which is given by

$$S = 4/3\ g_{\alpha}\ (\Pi^2/30)\ T^3 \tag{1.9}$$

where, $g_{\alpha}=g_{\pi}$ or g_Q. Then using Eqs.(1.7) and (1.8) pressure for the pion gas and the QGP are found to be:

$$P_{\pi} = 1/3\ \varepsilon_{\pi} \tag{1.10}$$

$$P_Q = 1/3(\varepsilon_Q - 4B) \tag{1.11}$$

Due to the bag pressure term B, the pion gas is the favored state ($P_{\pi}>P_Q$) at lower temperature. When the temperature is higher ($P_Q>P_{\pi}$) the QGP state is favored. At the critical temperature $T = T_c$ the pressure in the two phases are equal and hence one can determine T_c by equating Eqs.(1.10) and (1.11) at $T = T_c$:

$$T_c= [(g_Q - g_{\pi})(\Pi^2/90)\ B\ ] \tag{1.12}$$

One finds for the above mentioned value of B $T_c \cong$ 136 MeV. Comparing the energy densities one can see that there is a sudden jump at $T = T_c$ and hence a first order phase transition. In addition, a comparison of entropy density for both the phases (Eq.(1.9)) reveals that the entropy density of QGP phase is an order of magnitude higher than that of the pion gas. Thus in view of these considerations, it appears that at high temperature ($>T_C$) color deconfined state of nuclear matter (QGP) can be more favored.

In such a phenomenological approach, where the two phases are treated differently, if there is a phase transition it is always of Ist- order. However, finite temperature "lattice" QCD does not have such shortcomings of the phenomenological models. More direct information (using the QCD Lagrangian) about the phase transition can be obtained from numerical studies of lattice QCD. In lattice QCD it is very difficult with the present techniques to consider fermions in a realistic situation[4], i.e with two nearly massless quarks and one massive quark. The results, with two or four flavors, are found to be dependent on the mass and the number of flavors of quarks. No consensus has yet been reached about the lattice results with fermions. However, pure gauge theory as compared to full QCD is easier to study on lattice and has been studied extensively in the past to investigate the phase diagram of QCD.

The phase transition is also clearly seen, while studying the partition function of pure gauge theory Lagrangian on a lattice (replacing the space-time continuum by discrete points). The energy density which can be calculated from the partition function, (as a function of temperature) in one such calculation is depicted in Fig.1. This plot indicates a jump in energy density around a critical temperature $T_c \approx$ 200MeV and suggests a I-order phase transition. There is also a jump in entropy density. It is estimated that energy density values between 2-2.5 GeV/(fermi)^3 are necessary for this deconfinement transition. However, the estimate of the latent heat is not firmly established, the results vary from $\Delta\varepsilon$=0.9 to 1.9 GeV/(fermi)^3.

After finding the phase transition in numerical simulations of lattice QCD, it is natural to ask for the importance of studying QGP. The experimental and theoretical investigations of QGP are important due to the following reasons.

1. QCD predicts that under certain extreme conditions nuclear matter will exist in the QGP phase, and therefore a search for QGP can serve as a test of QCD in such extreme conditions.
2. According to the standard model of cosmology, temperature of the universe might have exceeded the critical temperature for the phase transition at time < 20μsec after the Big Bang. It has been suggested that the presence of QGP phase in the early universe can affect the primordial nucleo-synthesis[5]. There is also a possibility that, the density of nuclear matter in the core of heavy neutron stars may exceed the critical value required for the formation of QGP.
3 The most interesting possibility is that, the critical density > 2 GeV/(fermi)^3 may be reached in relativistic heavy-ion collision (RHIC) experiments so as to create QGP in the laboratory[6]. Already there are some experiments at CERN and at Brookhaven to search for QGP. Many signatures have been proposed to test the creation of QGP in these experiments. There are evidences but no conclusive evidence proving the existence of QGP[7].

A very important feature of any many particle system including the QGP is it's collective behaviour. As color is no longer confined to hadronic volume in QGP, it is possible to have macroscopic color fluctuations. However, due to the absolute color confinement globally the plasma still must be color neutral. This may constrain color particles to combine to be color neutral before they leave the volume occupied by the plasma. These fluctuations can cause collective behaviour in the medium and such behaviour can have impact on overall dynamics of the system e.g. collective behaviour can affect the eventual hadronization of QGP. It can also influence the thermalisation of QGP. Moreover, the spectra of particles coming out of QGP may show some of the effects of collective behaviour on them. In fact Matsui and Satz[8] have suggested that production of J/ψ mesons in relativistic heavy-ion collisions may get suppressed due to the presence of hot QGP environment. Any clear signature resulting from color collective behaviour can serve as an unique proof of this color deconfined transition.

AIMS AND SCOPE OF THIS STUDY

In order to study collective properties of QGP methods of quantum field theory (QFT) ought to be used. There are two somewhat different field theoretic approaches that are available to study the quark-gluon plasma.

1.Finite Temperature perturbative QFT: According to the asymptotic freedom property of QCD, when two quarks come close to each other the strength of interaction between them decreases. Thus, for high temperature or for high density one expects the coupling constant to be small and hence the interaction among the plasma particles can be regarded as a perturbation over the free particle gas behaviour. In such a situation, perturbation theory can be applied to calculate the color electric and magnetic properties of the medium. But it turns out that for collective properties, infra-red($k \to 0$) contributions from higher orders in perturbation theory also become important, and thus cast doubts about the validity of the perturbative treatments[9]. Also the perturbative treatment can break down near the critical temperature and this can have important consequences as it is generally expected that the plasma produced in the collision experiments would be close to T_c

2.Finite Temperature Lattice QCD: This is a numerical treatment of finite temperature QCD which allows one to treat the QGP non-perturbatively i.e. taking the full interaction into account. As already mentioned, the critical temperature for deconfinement as well as some thermodynamic properties have been calculated in this approach. The major difficulty with such an approach is that, the present techniques can only consider equilibrium properties of QGP. They can not give information about non-equilibrium or time dependent phenomena in QGP. Also, the lattice QCD results indicate that even at $T \cong 2T_c$ there are still substantial deviations from the ideal gas behavior.[10]

To remove the doubts from lower orders in perturbation theory it is desirable to do calculations using the non-perturbative approach. One might expect that lattice QCD, atleast for a thermal equilibrium state, can throw some light on this. But the recent calculations on the finite temperature lattice QCD indicate that certain quantities (like pressure) are very sensitive the lattice size and therefore they are very sensitive to the infra-red cut off. Thus the lattice calculations, at this juncture, cannot prove the validity of lower orders in perturbation theory.[11]

In addition, there are quite general arguments to say that massless ideal gas equation for state $PV = 1/3\ \varepsilon$ does not imply that quarks and gluons interact weakly[12]. Such behavior might arise due to the relevant quasi-particles. Thus the massless ideal gas behavior, in the lattice calculations (Fig.1) does not justify the use of perturbative QCD at high temperature.

Hence on the one hand there are reasons to believe that essentially non-perturbative effects may determine the QGP properties even at high temperature while on the other hand there is no suitable quantum field theoretic treatment available to deal with the dynamics of the quark-gluon plasma non-perturbatively. Due to this we have adopted a classical non-perturbative approach to examine the collective time dependent properties of the plasma. Ideally speaking, QGP should be described by QCD only. But whether a classical approach is valid or not depends upon the kind of observables and kinematic regimes we want to describe. It seems that to describe collective behaviour (like oscillations and screening) classical approach is good. This is because, finite temperature perturbative QCD (at one loop level) gives the same values for plasma frequency and screening length as those obtained by the lowest order in perturbation using the classical equations.[13] However, the quantum effects may play important role, when the discrete particle aspects of the plasma need to be considered. In our opinion, classical non-perturbative study may give reliable information about QGP in the situation when both - classical and quantum perturbation theories in the lowest order yield the same result. Hence, we expect the classical studies to provide qualitatively novel features of the QGP. Further, we should mention that classical approaches have already used to study various collective phenomena in the QGP [e.g. Ref.14]. But in these approaches the plasma is considered to be essentially abelian and only linear perturbations are studied. Our studies reveal that non-perturbative effects bring about qualitatively new features to the standard abelian (Coulomb) plasma behavior.

In the present work we have used classical color hydrodynamic(CHD) equations to study the collective QGP dynamics. Hydrodynamics approach is preferred over the kinetic one because the hydrodynamic equations are simpler to study and they can describe almost all the collective modes that can be studied by the kinetic approach. Further for simplicity, SU(2) gauge group is used instead of SU(3).

Finally, we would like to add that, the classical methods have also been applied in other quantum many particle systems such as molecules and nuclei to study collective behaviour. For example, liquid drop model describes binding energy and fission phenomena. There are instances, as suggested by experiments, where the classical considerations fail e.g. for the observed binding energy systematics and mass distribution of fission fragments shell corrections (quantum effects) are vital. But experience in quantum many particle system to study collective phenomena shows us that qualitative features obtained by classical considerations are mostly correct. We expect this to be the case with our classical study of QGP.

The thesis is organized into six chapters. A summary of each one, excluding the introductory chapter, is given below.

CHAPTER II : In this chapter we present a derivation of CHD from the classical kinetic equation by taking appropriate moments. The CHD equations were first obtained through heuristic arguments by Kajantie and Montonen(ref.15) in cold collisionless plasma limit.

It should be pointed out that there are, in the literature, two kinds of kinetic equations[16]:

1. In the first kind, the single particle (distribution function) phase space for quarks is augmented to take color degree of freedom into account. As a consequence this kinetic equation has a drift term in color space due to color exchange of quarks with the gluon fields. The kinetic equation also contains a drift term in momentum space (like a Vlasov equation) due to the action of color force.

2. The second kind of kinetic equation does not have an augmented phase space but the single particle distribution function has a matrix structure in color space. The kinetic equation also has a matrix structure in the color space.

CHD equations are obtained, in cold collisionless limit, from both the kinetic equations by taking appropriate moments. In the first case we found that when the distribution function is separable in color and momentum variables then, the moment equations are identical to the CHD equations of ref 15. In the second case we do not require such an assumption.

The CHD equations have some similarity with hydrodynamic equations of the electrodynamic plasma in the sense that both of them have four flux conservation and energy-momentum equations. But the most important difference between them is that CHD equations contain color charge evolution equations, showing that color charge can be exchanged with the gluon fields.

It should be mentioned that the hydrodynamical equations derived in this chapter correspond to quark-plasma only. One would expects the gluons to thermalise as they interact among themselves. Hence there would be a set of equations to describe the hydrodynamical evolution of the thermal gluons. But this has not been worked out to date. One of the difficulties may be in determining the nature of the collision term in the corresponding kinetic equation.

The hydrodynamical equations derived in this chapter will be used together with the Yang-Mills equations (providing the dynamics of the gluon fields) to study various physical situations in the subsequent chapters.

CHAPTER III: We first use the CHD equations described in chapter II to study longitudinal oscillations of QGP. The study of longitudinal oscillations is important because it is one of the simplest manifestation of collective behaviour of the system. Moreover, even though they are stable they can contribute to energy density and pressure of the plasma. They can also influence the spectra of emitted particles.

For simplicity, we consider the plasma to comprise of two species (particle and antiparticle). The color density fluctuations in such a system can cause longitudinal oscillations. The basic equations describing the oscillations are a set of coupled non-linear partial differential equations. In the linear limit (when the strength of the non-abelian term is very small) they will reduce to abelian plasma oscillation equations and give rise to the usual plasma oscillation frequency. For simplicity we setup the oscillation problem in 1-space and 1- time dimension. The partial differential equations are reduced to ordinary differential equations by using a stationary wave ansatz ($\xi=x+\beta t$). The equations contain a parameter ε which characterizes the strength of non-abelian term(arising due to the inherent non-linearity of color fields). For certain values of ε it was found that the oscillations have two distinct modes: (i)the usual plasma mode for which the oscillations are at plasma frequency and the amplitude is nearly constant, (ii)a non-linear mode arising due to non-abelian terms with frequency higher than the abelian mode. Also, the amplitude is greatly modified in this mode. It is not clear when the transition from the abelian mode to the non-abelian mode and vice versa will take place but the transition is sudden. For large values of ε the oscillations show chaotic behaviour. It is difficult to see how this novel feature could have been obtained by the use of perturbation theory. A detailed derivation of the equations will be given together with discussion of numerical results. This work is published in Phys.Rev.D,39,646(1989).

As we have already mentioned, the oscillations show chaotic behaviour for some values of ε. It is likely that in such a parameter regime, if one does a full x-t problem, the oscillations may get damped and contribute to the thermalisation of QGP.

CHAPTER IV: This chapter examines the screening of a moving test sheet source in QGP at finite temperature. Screening can be used for finding a signature of the QGP. In fact, Matsui and Satz[17] have suggested that the screening of the color potential in QGP can suppress the binding of quark-antiquark ($q\bar{q}$) pairs.This is because the $q\bar{q}$ pair cannot form a bound state in the plasma if it's binding radius is greater than the Debye length in the plasma. It turns out that the production of J/ψ ($c\bar{c}$) meson will be suppressed in the plasma and it can serve as a signature of QGP in RHIC experiments. Indeed, the J/ψ suppression is observed in NA38 experiment at CERN which was performed after the suggestion was made. However, there are other mechanisms which can also explain the suppression of J/ψ. The different mechanisms actually lead to different results in magnitude and pattern for the suppressions. Hence a detailed investigation of QGP screening in a very realistic situation is necessary.

We would like to mention that the CHD equations derived in Chapter II are valid in cold collisionless limit only. For the study of screening properties they are augmented by introducing a pressure gradient term in the CHD force equation to take effects of finite temperature into account. Equation of state for relativistic free quark-gas at temperature greater than the critical temperature and also the equation of state near the critical temperature, as obtained from the lattice calculations, are used to close the CHD equations.

The screening of a moving test source in QGP has already been studied earlier.[19] It was found that when the source has a relativistic velocity, its static potential is modified owing to its coupling with the magnetic sector. However, in this study the plasma was considered to be abelian. Our study reveals that even when the test source is moving with a non-relativistic velocity, the static field potential is significantly modified. This modification arises primarily because of the non-abelian nature of the plasma interaction. To be specific, our results indicate that with an increasing source velocity the screening becomes weaker as compared to the static source case. Moreover, the screening behaviour shows an oscillatory structure over and above the mean screening. An expression for a gauge invariant "effective" Debye length is found which depends upon gluon field terms.

Derivation of the basic equations of the screening, the results of calculations and their implications on J/ψ suppression will be discussed.

CHAPTER V: This chapter deals with the filamentation instability in QGP comprising of two counter streaming species. The motivation of such a study comes from RHIC experimental situation. When two heavy nuclei collide at very high energy, it is expected that they become transparent to each other. This can be visualized as two fluxes of color fields streaming against each other and partially decelerating each other. We study the stability of such a system against the perturbations. The geometry is very similar to that of filamentation instability in the electrodynamic plasma.

The filamentation instability in the QGP was first studied by Yu.Pokrovsky et al[19]. We have derived the dispersion relation for the instability, using the linearized color hydrodynamical equations. The growth time of the instability is found to be smaller than the the total interaction time of the two colliding nuclei. Further the non-linear state reached after the instability develops is analyzed in the stationary frame ansatz. Our analysis shows that a considerable fraction of initial energy of the plasma fluxes goes into energy of waves and into energy random motion. Thus, the directed velocity of the beams becomes smaller and this effect enhances the stopping power of the nuclei. The derivation of dispersion relation and the non-linear equations(in the stationary frame) will be presented. The numerical solutions of the non-linear equations and an analysis of time series for estimating the stopping power will be discussed.

CHAPTER VI: This chapter contains summary and conclusions.

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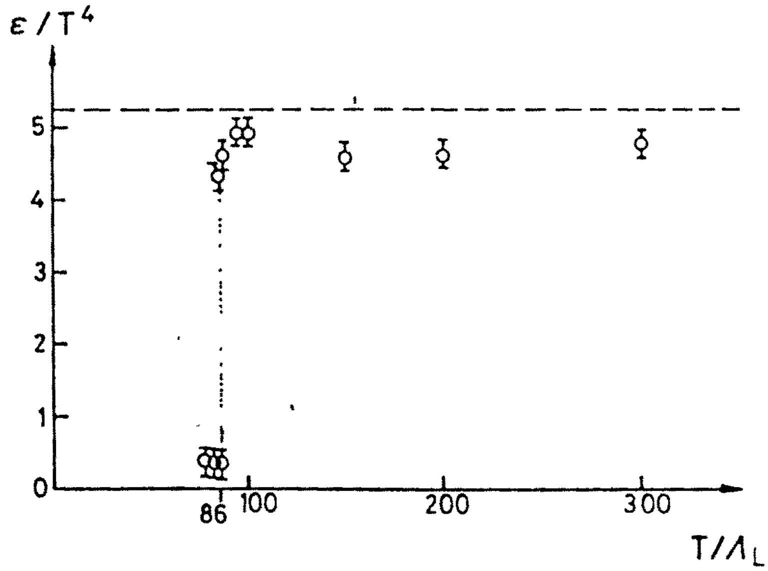

Fig.1

The energy density of SU(3) Yang-Mills matter as a function of temperature. The dashed line shows the corresponding ideal gas value.

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