Chapter 1

Introduction

1.1 The Strong Interaction

All particles that have been experimentally observed, except for the leptons, contain either three quarks or one quark and one anti-quark. Quarks are believed to be the most fundamental constituents of matter which can not be isolated. They have one third or two third of the charge of an electron and the colour charge responsible for the strong interaction. The strongly interacting matter is described at the fundamental level as interactions between the quarks via exchange of gluons, the quanta of the colour field. This theoretical framework is commonly known as ‘Quantum Chromodynamics’ (QCD) [1].

QCD is a non-Abelian Gauge theory which exhibits the following features:

(1) At short distances or large momenta, the effective coupling constant $\alpha_s(q^2)$ decreases logarithmically which causes the quarks and gluons to be weakly coupled implying asymptotic freedom of quarks and gluons;

(2) At large distances or small momenta, the effective coupling constant becomes strong which causes the phenomena of quark confinement and spontaneous breaking of the chiral symmetry.

(3) At low energies, the QCD vacuum is characterised by nonvanishing expectation values of quark condensate and gluon condensate.

The quark condensate describes the density of quark-antiquark pairs found in the QCD vacuum, which is the source of the chiral symmetry breaking. The gluon condensate measures the density of the gluon pairs in the QCD by quantum effect.
1.2 *Quark - Gluon Plasma* Introduction

An important consequence of QCD under extreme conditions of density and temperature is the 'existence' of the *Quark - Gluon Plasma* (QGP) [2, 3]. QCD predicts that nuclear matter at densities 10 - 15 times the normal nucleon density (\( \rho_0 \approx 0.15 \text{ nucleons/fm}^3 \)) or at a very high temperature (\( \approx 200 \text{ MeV} \)) will not continue to be in the hadronic form, but would become a 'soup' of freely moving quarks and gluons. The quarks and the gluons in QGP are not confined within the hadronic volume but are free to move in a much larger (macroscopic) volume. The transition from the (confined) hadronic matter to (deconfined) quark matter exhibits certain discontinuities in the order parameters (such as quark condensates and gluon condensates) [4] and is, therefore, characterised by a phase transition which can be understood in terms of Fig. 1.1.

The phase diagram suggests that hadronic matter can be transformed into QGP under two extreme conditions,

(i) At very high temperature, (\( \approx 200 \text{ MeV} \)), and
(ii) At very high nucleon density (10 - 15 \( \rho_0 \)).

The first condition is applicable for the early universe. The standard cos-
mological model predicts that the temperature of the cosmic background radiation exceeded 200 MeV during the first 10 μs of the Big Bang [5]. The early universe was filled with hot QGP rather than the hadrons. The second scenario is satisfied in case of neutron stars where one might expect the existence of the 'cold' QGP [6].

The order of the phase transition, however, is a controversial issue. In this connection, we can imagine the following three scenarios, viz,

(a) a discontinuous, or first-order phase transition releasing a large amount of latent heat at the transition point,

(b) no sharply defined transition, but rather a smooth passage from one phase to another as a function of temperature, and

(c) a continuous but not entirely smooth transition, which is the characteristic of a second-order phase transition.

Thus, the problem of determination of the order of the phase transition is still unclear. Information on this phase diagram can be obtained by a number of techniques, such as lattice gauge calculations, chiral perturbation theory, or various models. Lattice simulations of QCD at finite temperature indicate that there is a first order phase transition in the pure SU(3) gauge theory.

The study of QGP is of interest to explore and test QCD on its natural scale ($\Lambda_{QCD}$) and addresses the fundamental questions of confinement and chiral symmetry breaking, which are connected to the existence and properties of the quark-gluon plasma.

### 1.2.1 QGP in the laboratory

In order to verify these ideas one needs to create highly excited compressed hadronic matter in the laboratory. The only way to recreate such an environment is with ultrarelativistic heavy ion collisions. We consider two different energy regions [7], namely,

(a) the stopping region (at laboratory beam energy above 10 GeV/nucleon), and

(b) the central rapidity region (at beam energy 100 GeV/nucleon).

In the stopping region, the colliding nuclei completely stop each other to form a very high density of matter and hence we get a baryon-rich QGP. However, in the central rapidity region, two nuclei completely pass through each other at very high energy leading to the formation of hot and baryon free quark matter. In this case, the energy of the excited vacuum is liberated in
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Figure 1.2: Space-time geometry of relativistic heavy ion collision, the form of multiparticle pion production.

1.2.2 Collision geometry

Nuclei are extended objects, and therefore their geometry plays a significant role in heavy-ion collisions.

Fig. 1.2 shows a sketch of a collision of two heavy nuclei at ultra relativistic energies in the centre of mass frame. Two nuclei approach each other with nearly the speed of light, are Lorentz contracted along their directions of motion (z-axis), and finally collide at say z=0 and time t=0. Immediately after the collision, a large amount of energy is deposited in a small region of space in a short duration of time. In this region, the energy density is therefore very large. This energy density, an order of magnitude greater than the energy density of normal nuclear matter may favour the formation of new forms of matter such as the quark-gluon plasma. The plasma initially may not be in thermal equilibrium. Secondary interactions among the produced particles may bring
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it to local equilibrium and after that the system evolves according to the laws of relativistic hydrodynamics.

1.2.3 Space - time evolution

We discuss a simple picture of the space-time evolution of the matter produced in the central rapidity region of the nucleus-nucleus collisions provided by relativistic hydrodynamics. It allows us to describe all stages of the expansion from a QGP to a hadronization transition and decoupling into final-state hadrons. The hydrodynamical flow starts as soon as the system has reached local equilibrium and lasts only as long as the particles in the fluid are interacting. In order to describe the space-time evolution of a central collision at ultra relativistic energies, we consider Bjorken's hydrodynamical model [8]. According to this model, all the thermodynamic quantities i.e, energy density etc. are functions of the initial thermalization time $\tau_I$ only and do not depend on the space-time rapidity. The light cone diagram for the matter flow under Bjorken hydrodynamics is shown in Fig. 1.3. However, after the formation of QGP, due to large internal pressure, the system expands and cools rapidly until the critical temperature $T_c$ is reached. In this phase, the quark-gluon plasma and the hadrons coexist in pressure equilibrium. The length of time spent at the transition temperature is dependent upon the relative number of degrees of freedom available to the system in the two phases. This isothermal expansion continues till all of the QGP is converted into the hadronic phase. Upon completion of the phase conversion, the hadronic matter continues to expand until the mean free path of the hadrons becomes larger than the dimensions of the system and they lose thermal contact. This is called freeze-out. At this temperature ($T_F$), they cease to interact with each other and they stream freely away to be detected in the experiments.

To be able to establish that such a new, transient state of matter has been formed, it will be necessary to identify and study QGP signatures and the space-time evolution of the collision process. A big obstacle in this effort is the complicated space-time evolution of the hot fire ball. The fact that the region of formation is not macroscopic and the phase is short-lived makes the task even more complicated. As a result, it is not possible to probe the properties of the system directly, but only indirectly via the characteristics of the final hadron state.
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Freeze-out Time

Figure 1.3: Space-time evolution of a central collision of two heavy nuclei in Bjorken model.

1.2.4 Signatures of the Quark-Gluon Plasma

In spite of these difficulties, a large number of signals [9] have been suggested that would characterize the formation of the QGP. These are

(i) photon emission from QGP
(ii) dilepton emission from QGP
(iii) strangeness enhancement
(iv) suppression of $J/\psi$ production
(v) jet quenching

Photon and Dilepton emission

Among the various suggested signals, thermal photons and dileptons [10, 11] are regarded as very clean probes of the plasma, because, once produced they interact only via the electromagnetic force and thus escape from the early high density stage without being disturbed by the later hadronization. As a result, they carry informations on the thermodynamic state of the medium at the moment of their production to the detectors. The situation is quite different for final hadronic particles since they interact strongly after their formation.
with the rest of the system and thus their properties, such as abundances and momentum distributions, are changed.

This unique status is counterbalanced by an unsolved challenge: can we recognise them? This is a great experimental problem. Because, photons and dileptons are emitted not only in the QGP phase but also from many other sources both before and after the hot stage of the collision and hence they are often overwhelmed by relatively large backgrounds, especially electromagnetic hadron decays. So, in searching for QGP signal, one must look at the appropriate experimental observable window where the contribution from QGP dominates over all other sources.

Strangeness enhancement

One of the earliest proposals for detecting the formation of the plasma is the enhancement in the production of strange particles \([12]\) resulting from chemical equilibrium of a system of quarks and gluons. The idea is that, in QGP at sufficiently high temperature, the probability of producing strange mesons and antibaryons, would be enhanced relative to a hadron gas. This is because in the baryon rich region, the production of light antiquarks \((\bar{u}, \bar{d})\) would be suppressed due to chemical potential \(\mu\). Thus, there will be a suppression of \(u\bar{u}\) and \(d\bar{d}\) pairs but not of \(s\bar{s}\) pairs. Hence, it is suggested that if the QGP is formed, then on hadronization one would observe enhanced \(K/\pi\) ratio.

\(J/\psi\) suppression

Among the various signals, the \(J/\psi\) plays a special role, that of a witness of the early stages of a nucleus-nucleus collision. In nucleus-nucleus collisions, \(J/\psi\) particles are produced in the initial stage of the collision process, for example, by the hard-scattering processes. If a quark-gluon plasma is formed in the region of \(J/\psi\) production, then the effect of the plasma will be to make the \(J/\psi\) particle unbound, and the final yield of \(J/\psi\) particles will be suppressed as compared to the case when there is no quark-gluon plasma, the reason being a Debye screening of the \(c\bar{c}\) binding potential by the freely moving colour charges in the case of deconfinement. Thus, a relative suppression of the \(J/\psi\) yield in nuclear collisions could reveal quark-gluon formation. It has ever been argued that such a \(J/\psi\) suppression \([13]\) could be an unambiguous signal of deconfinement, at least if the energy density is very high.
Jet quenching

Jets produced by high-energy quarks and gluons in ultrarelativistic heavy-ion collisions can also provide a potential probe for the existence of a QGP. High energy partons coming from the initial hard collisions lose energy while propagating through the dense matter. The energy loss is greater in the nucleus-nucleus collisions, as compared to pp and pA collisions. This phenomenon is known as jet quenching [14]. Jet quenching is also of interest because it gives us information on the final-state interaction processes which result in a partial chemical and thermal equilibrium of the dense matter produced in heavy-ion collisions. Jet quenching results from the energy loss (-dE/dx) of a high $p_t$ parton as it traverses the dense matter. In the case of hadronic matter, the partons are decelerated due to the string tension, whereas in a QGP, the quarks suffer energy loss by elastic scattering with the thermal quarks and gluons and by radiation or bremsstrahlung of gluons. However, the radiative energy loss is proportional to the square of the Debye mass which, according to the lattice calculations, decreases rapidly close to the phase transition. Therefore, in the mixed phase, in which the system is expected to spend most of its time, variations of jet quenching may provide a signature for the phase transition.

1.3 Thermalisation

An important question of heavy-ion reaction dynamics is whether the system is sufficiently large and long-lived so that a chemically and thermally equilibrated system is formed in the collision because signatures upon which one relies for detecting the deconfined matter are directly influenced by the initial collisions.

In the following, we present the basic concepts of thermal and chemical equilibrium [15].

1.3.1 Thermal equilibrium

A system is said to be in thermal equilibrium when the momentum distributions of the particles do not change with time, even though momentum exchanges continue through the interaction between particles. The gain in the momentum distribution from one reaction is balanced by the loss in the momentum distribution from the inverse reaction or other reactions. The momentum distributions of the particles at thermal equilibrium are then governed
1.3.2 Chemical equilibrium

In the QGP, there will be quarks, anti-quarks, and gluons. They will continuously interact with each other via the QCD subprocesses:

\[ gg \rightarrow qq, qq \rightarrow gg, qq \rightarrow \bar{q}q \]

where \( \bar{q} \) represents a different flavour quark. After several interactions, the reaction rates and the abundances of the gluons and the different flavour quarks and anti-quarks reach a steady state even though the particles continue to interact and transform from one kind to another. The gain in the density of one kind of particle from one reaction is counterbalanced by the loss in the density from the inverse reaction or other reactions. This is called chemical equilibrium, which is characterised by chemical potentials. If the system is not in chemical equilibrium there is no relation between different chemical potentials. The number of potentials necessary to describe the state of the system gives an idea of the degree of equilibration. The principal probe of chemical equilibrium is the particle composition. By chemical equilibrium we mean that the different constituent species are present according to their relative thermodynamic weights.

1.4 Experimental Perspectives

In recent years, considerable progress have been achieved in the quest for the QGP. At present, the heavy ion experiments dedicated to probing the QCD phase diagram and the possible existence of quark gluon plasma are done at the Brookhaven AGS at 11 AGeV and at the CERN Super Proton Synchrotron (SPS) at \( \approx 200 \) AGeV beam energy. The new data from Pb + Pb collisions at CERN SPS conveys several interesting implications which clearly show that we are certainly close to the requirements of the phase transition. It is, however, still uncertain whether QGP has been formed in these collisions or not. In the near future, new colliders will be taken into use where the available center of mass energy \( (\sqrt{s}) \) will be 200 AGeV in Relativistic Heavy Ion Collider (RHIC) at Brookhaven and 5.5 ATeV in the Large Hadron Collider (LHC) at CERN. As the collision energy increases, this would lead to the initial temperature well beyond the critical temperature. From this viewpoint, it is expected that
if QGP can be formed in a heavy ion collision, it should be formed at the latest in those experiments. In this section, we shall discuss the highlights of the recent experimental results.

1.4.1 Initial condition and global features

Recent results from ongoing fixed target programme indicate that the initial conditions realized in ultrarelativistic nucleus - nucleus collisions could indeed be favourable for QGP formation. In head-on central collisions, hundreds of particles are produced per unit rapidity, the system expands to a size of the order of 1000 $fm^3$ (as measured by particle interferometry [16]), and initial energy densities are estimated to exceed 2 GeV/$fm^3$. However, the expansion is also extremely fast, with an estimated total lifetime of the order of only a few fm/$c$ from the first instance of the collision until the final freeze-out of hadrons.

While these results show that the requirements of QGP formation are closely met in these reactions, they are by no means sufficient. In particular, the energy density estimates are inversely proportional to the assumed formation time, i.e. the time needed to reach thermal equilibrium, and might well be smaller by a factor of two. Also, the lifetime of the system seems marginal, and even if a QGP is formed, it might simply not live long enough for its signals to clearly stand out from the background created in later, hadronic phases of the evolution. The existence of QGP phase can only be settled experimentally by searching for direct and specific signals.

1.4.2 Recent results

All experimental efforts in this direction are motivated on the following three routes:

1. Equilibrated hadronic matter,
2. Chiral symmetry restoration, and
3. Deconfinement.

**Equilibrated hadronic matter**

The study of non - equilibrated hadronic matter might be of considerable interest. But in order to reduce the complexities in the analysis, one has to look for those degrees of freedom which evolve in equilibrium. As a result, we
have to lose the informations concerning the events preceding the equilibrium, as the memory of the earlier stages of the evolution is largely lost.

In reality, we have to deal with a hierarchy of processes and scales, some of which have large cross-sections and correspondingly small relaxation times and therefore might evolve close to equilibrium, and others which decouple early from a thermal evolution and are sensitive to the hot initial phase of the reaction. Prime candidates for the former are hadronic observables, like $p_T$ spectra and particle ratios, and for the latter hard probes and electromagnetic signals.

In a purely thermal system of hadrons, the momentum distributions, when expressed as a function of the transverse mass ($m_T$) will be independent of the particle mass with a slope inversely proportional to the temperature ($T$). In an expanding system, an additional collective flow component can develop which blue-shifts the momentum spectra with a common transverse velocity ($\beta_T$) leading to a mass dependent component. Likewise, the abundance of particle species in equilibrated hadronic matter is given by two independent parameters, i.e, the temperature $T$ and a baryochemical potential $\mu_B$ (which reflects baryon asymmetry in the initial state). A hadronic system in both thermal and chemical equilibrium is therefore fully determined by only three independent parameters $T$, $\beta_T$, and $\mu_B$.

So far, a vast amount of evidence has been accumulated by experiments NA44, NA49, NA52, WA97, and WA98 that the hadron yields and hadron spectra in $Pb + Pb$ collisions at the SPS can be well described by chemical and thermal equilibrium concepts. Furthermore, the collective nature of the expansion of the initially hot and dense fireball has been demonstrated by the observation of spectral slope constants which scale linearly with particle mass and, recently by the discovery (by NA45, NA49, and WA98) of directed and elliptic flow patterns in $Pb + Pb$ interactions. Interestingly, the chemical freeze out, i.e, the determination of the hadron yields, appears to take place at a temperature close to where lattice QCD calculations place the phase boundary. The fact that this chemical temperature consistently exceeds the kinetic temperature by about 40 MeV is not surprising, because reaction cross-sections among hadrons, which drive hadrochemistry, are falling much faster with decreasing temperature than elastic cross-sections, which maintain thermal equilibrium.
1.4 Experimental Perspectives

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Chiral symmetry restoration

Weakly interacting electromagnetic probes (photons or leptons) are a direct means of gaining information on the early dense and hot stages of the collision, as they leave the interaction volume without being altered by final state effects. While, so far, only upper limits exist for direct (thermal) photon production, recent data on lepton pairs show an unexpectedly large yield at low masses, below the $\rho$ meson.

The analysis of the data taken by the NA45 experiment in 1996 confirms the excess yield of $e^+e^-$ pairs with invariant masses above twice the pion mass and below the rho mass observed earlier (by NA45 and Helios-3) in the $S + Au$ and $Pb + Au$ systems. The recent NA45 data also demonstrate that the excess is concentrated at low pair $p_T$ and scales with the square of the charged particle multiplicity. The observed shape of the excess yield in the lepton pair mass spectrum is not consistent with expectations for $\pi^+\pi^-$ annihilation in free space. These data provide the first glimpse into the dynamics of mesons in a baryon-rich environment exceeding a temperature of 120 MeV.

However, more precise data are needed to distinguish between different theoretical models and to determine the relation of the observed excess to chiral symmetry restoration. A significantly improved mass resolution of the NA45 spectrometer coupled with an increased data rate capability is expected to provide new high precision data from the upcoming heavy ion beam times.

Deconfinement

Signals originating from hard-scattering processes at the very beginning of the reaction are an ideal tool to probe the state of the surrounding QCD matter. The earlier evidence for an anomalous mechanism of $J/\psi$ suppression [13] in $Pb + Pb$ collisions has been confirmed by a new analysis of the data taken by the NA50 collaboration in 1996. The new analysis, which utilizes a comparison of the $J/\psi$ cross section as a function of transverse energy $E_T$ with the minimum bias cross section (rather than the Drell - Yan cross section), has much smaller statistical and systematic errors. The data reveal clearly that the $E_T$- dependence of $J/\psi$ suppression differs strongly from that observed in lighter systems. If the analysis can be extended to smaller and larger values of $E_T$ in the present heavy ion run, the confirmation of a threshold behaviour in a single collision system may be feasible. Such a behaviour would indicate...
that the QCD deconfinement transition occurs within the $E_T$-range covered by NA50.

Earlier results from NA35/NA49 of an enhanced production of strangeness in nuclear collisions (carried mostly by kaons and hyperons) have been confirmed and extended by the precise measurement of all individual hyperon yields in $Pb + Pb$ collisions by the WA97 collaboration. The data cover most of the ranges in $E_T$ where the anomalous $J/\psi$ suppression is observed. These measurements show an enhancement of the hyperon yield, relative to that measured in $p + Pb$ interactions, which grows with increasing strangeness content culminating in an enhancement by more than a factor 15 of the $\Omega + \bar{\Omega}$ yield. The enhancement is independent of $E_T$ in the covered range, as would be expected if strange quarks are equilibrated in a deconfined and chirally symmetric quark-gluon plasma. The observed increase with strange quark content of the relative enhancement of produced hadrons contradicts expectations from hadronic rescattering models, where secondary production of multi-strange (anti) baryons is hindered by high mass thresholds and low cross-sections.

1.5 Thesis Organisation

This thesis is organised in the following way. Chapter 2 comprises the theoretical frameworks to understand the electromagnetic probes of quark gluon plasma like soft photons and low mass dileptons. The equilibration processes of the plasma is described in chapter 3. Different mechanisms of energy loss of heavy quarks (charm and bottom) are depicted in chapter 4. Finally, we summarize the works covered in this thesis in chapter 5.