Quark-Gluon Plasma in the inflationary era

Abstract

This paper reviews the theory behind quark-gluon plasma (QGP) as a state of matter of de-confined quarks and gluons predicted to have existed at high temperature and pressure during the inflationary era of the Big Bang. The circumstances results in a spontaneous restoration of otherwise broken chiral symmetry and a phase transition from hot hadronic matter to quark-gluon plasma. An overview of the particle colliders RHIS at Brookhaven and LHC at CERN will be given including a short review of the underlying theory and the results leading to the publication of the evidence of the existence of QGP. The focus of the paper will primarily be on the theory behind the evidence more than the structure and results of the involved experiments.

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Introduction

In order to better understand our universe, how it is built, and how it functions it is important to understand what it was previously. Our current knowledge of the beginning of the universe is based on the Big Bang Theory describing a series of stages of varying temperature and density as a function of time. In the inflationary Epoch stage of the early universe (from 10^{-35} s to 10^{-33} s) the temperature of the universe was of a scale of >10^{20} K and very dense (> $4x10^{9}$ g/cm^{3}) [1]. Due to this it is theorised that hadrons "split up" into its partons such that quarks and gluons are non-confined which is confronts the current observations in particle physics of quarks as only found confined.

Before the theory of QGP physicists believed that the state of matter at high temperatures was defined by the nucleons merging together [2]. The concept leading to the later prediction of QGP was introduced in the 1960's by Rolf Hagedorn who described the behaviour of hadron gas at high temperatures as having a limit at which additional energy to the system only would produce new hadron species instead of increasing the energy of the components of the system. In 1975, the existence of a phase of non-confined quarks and gluons was predicted based on the discovery of the asymptotic freedom. The name quark-gluon plasma was given in 1978, the word plasma was chosen to the analogy to the state of matter plasma where electrons leave their atoms [3].

Theory

Throughout this paper the Parton Model will be referenced in the form of using the word partons. It describes the nucleus as made of points-like components called "partons". It was introduced by Feynman and Bjorken in the 1960' and it was later proven that the mentioned partons are quarks [4].

Quark, Gluons & Quantum Chromodynamics

The theory of QGP is based on quarks, gluons and quantum chromodynamics (QCD). Quarks are fermions with flavour, mass, charge and spin. The spin of the quarks can

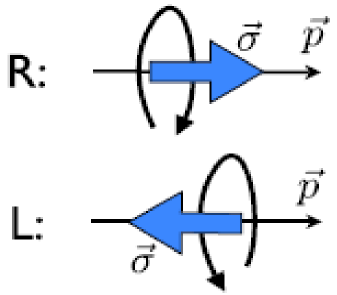

FIGURE 2; RIGHT- AND LEFT-HANDEDNESS OF FERMIONS. SOURCE: [5]

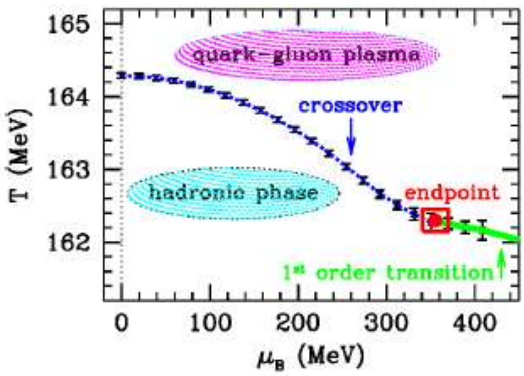

FIGURE 2; LQCD CALCULATION RESULTS FOR NON-ZERO CHEMICAL POTENTIAL. SOURCE [7]

either be in the same or in the opposite direction as the motion of the quark as seen on figure 1 [5]. This results in the concept of chiral symmetry; interaction between quarks should be depending on handedness. But no such have been observed hence the symmetry must break at low temperatures. The strong interaction between quarks is carried out by the boson called gluon which has colour charge which is the basis for the strong force. The theory of quantum chromodynamics (QCD) describes these interactions between gluons as they react to the presence or motion of colour charge [6].
The coupling constant of an interaction describes the strength exerted by the force and for the strong interaction is given by;

$$\alpha_s(Q^2) = \frac{1}{\beta_0 \ln(Q^2/\Lambda^2)}$$

where $Q^2 = -q^2$ for momentum q of particle, $\beta_0 = (11N_c - 2n_f)/12\pi$ for N_c is the number of colours, and n_f is the number of flavours, and Λ is a scale parameter found to be around 200 MeV. At small momentum the strong interaction is large and quarks are confined to hadrons ie. no quarks are found isolated. [7].

Quark-Gluon Plasma

The existence of QGP can be studied by analysing the physical aspects of QCD in order to determine the possibility of a phase transition of hadronic matter under circumstances similar to during the inflationary era [3].

At high temperatures the momentum of particles increases and using the formula for the strong coupling one sees that the force is weakened and theoretically this could cause de-confinement as the motion of the quarks might exceed the strong force. For de-confined quarks the gluons created in the interaction between quarks will also be de-confined, and together this causes a heavy increase in degrees of freedom from 3 to 52. This causes a drastic change in the energy of a system and hence the energy density as well as pressure [6]. Therefore, an experiment tracking either as a function of temperature should show a radical change at a critical temperature for which the phase transition between hadron matter and QGP should exist [8].

Using Lattice Gauge Theory, it is found that below a temperature around 260 MeV the free energy of an isolated quark is infinite but above 260 MeV it is finite resulting in a likeliness of de-confined quarks in high-temperature hadron gas [8].

As seen in other aspects of physics such as ferromagnetism, symmetry can be broking and restored in phase transitions. Therefore, it can be expected that hadron gas goes through a phase transition at a high temperature resulting in a restoration of the chiral symmetry [4]. The expected critical temperature is found using Lattice QCD calculations and one finds that this temperature of phase transition varies with the value of the chemical (baryonic) potential as seen in figure 2 [9]. Due to the breaking of chiral symmetry at low temperature, the critical temperature for $\mu_B = 0$ is expected to be $T = 173 \ \pm 15 \ MeV$ and the critical energy density of the matter $\epsilon = 0.7 \ \pm 0.3 \frac{GeV}{fm^3}$ [3].

Expectations for Experimental Results

Hence in the search for evidence of QGP one should look for large changes in energy density and pressure around a temperature above 165 MeV. Due to the methods used in the experiments hydrodynamics can be used to describe the theorised QGP; in particle collisions the hadronic fireball can be modelled by a relativistic fluid undergoing collective, hydrodynamic flow. This is because of high pressure in the plasma causes an outward flow and expansion. The expansion cools the plasma leading to an estimated lifetime of $4 \ \frac{fm}{c} \approx 12 \times 10^{-24} s$ of QGP. Though, the model fails when temperature falls below 120-130 MeV and the distance between particles exceed the mean free path. But it varies due to the difference in mean free path for hadrons species [8].

Experiments

The experiments used to investigate QGP are the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) and the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN). RHIS was built in 2000 and consists for two Au beams at 9 GeV per nucleon travelling in opposite directions in two different rings [3]. In 2010, LHC was constructed consisting of a 27 km ring of superconducting magnets wherein two particle beams at 177 GeV per nucleon travels in opposite directions in separate beam pipes. The centre of mass energy for RHIC is at 130 GeV whereas for LHC it is 2760 GeV (as by 2013) [10].

Theory behind the Experiments

In particle colliders, particles are accelerated to a high energy and then led to collide in a detection chamber. Before the collision, the system consisting of nuclei is not in equilibrium as the particles are accelerating. During the collision, assuming the available center of mass energy will be transformed into the internal degrees of freedom of the system, the strong interaction between the nucleon partons once they have passed each other will create a microscopic drop of hot hadronic matter. The drop will rapidly expand in the surrounding vacuum causing, as described earlier, a decrease in temperature resulting in a series of short lived thermodynamic states. Using J. D. Bjorken's description of the particle collisions, the nuclei is assumed to be a flat circular surface with crossing time $\tau_{cross} = 2R/\gamma$ for a radius R of nuclei and the Lorentz factor γ. For QGP to be created, we have that τ_{cross} < the time scale of the strong interaction. As the QGP expands and cools the hadronalization of the quarks take place causing a chemical freeze-out where the particles do not interact anymore and therefore can travel, decay and reach the detectors [3]. A depicturing of the process can be seen in Appendix 1.

In order to analyse the data from the detectors different probes and methods can be used. With kinematic probes, one can observe energy density ε, pressure p, and entropy density s of the hadronic matter as a function of temperature together with the baryon chemical potential μ_B. By this one can look for drastic changes and by the formulas ε/T^4 and s/T^3 over a small temperature range find the effective number of degrees of freedom. Using identical-particle interferometry (for example π π, K K, or N N correlations) one can measure transverse and longitudinal size, lifetime and flow patterns of the hadronic fireball created in heavy nuclei collisions [8].

At low energies due to colour confinement, single quarks and gluons cannot leave the collision without forming colour-neutral hadrons. This causes complications when trying to detect potential QGP since one can only measure momentum and correlations in relation to the produced particles of the collision and from that then investigate the interactions and particle decay resulting in the detected particles. Direct measurements of QGP can be made using electromagnetic signals emitted from the quarks at high temperatures in the QGP [3]. Though this method has drawback due to the large background signals form the hadronic processes which mixes with the thermal photons from the QGP [8].

Results

The energy densities measured in the experiments were of the scale at which QGP could be created and the freeze-out temperature agrees with the expectations from theory for both the chemical potentials of the experiments [3]. Using the method "Bose-Einstein interferometry" consisting of two-particle correlations between identical hadrons it was found that the pressure increased rapidly suggesting intense scattering in the early collision stages [2]. By observing the elliptic flow of the hadronic matter it was shown that the hydrodynamical models described the behaviour of QGP at low transverse momentum. Moreover, it was concluded that the formed matter behaved like an ideal, non-viscous fluid which motion can be described by its fluid velocity, pressure P, energy e and baryon densities n_B given by the function $P(e, n_B)$ [9]. Dilepton pairs (electron and positrons) were measured having a mass of 250-700 MeV and a transverse momentum 1-5 GeV/c which suggests an energy density just below the required for QGP [2]. These measurements also suggest a production of photons from a source with temperature above the theorised for QGP phase transition [3]. No results suggests the existence of more than one phase transition [9] which lead to CERN making the statement that evidence of QGP had been found analysing results from RHIC and the Super Proton Synchrotron (SPS) at CERN in 2000 [2].

Conclusion

The experimental results from RHIC and LHC suggest the existence of a phase transition for a hadron gas at high temperature or pressure into another state of matter. The theory of quark-gluon plasma corresponds to the observations and it can therefore be assumed the this is the observed new state of matter. This heavily suggests that during the inflationary Epoch stage of the early universe quark-gluon plasma existed and were the dominating state of matter. The theory of quark-gluon plasma can be applied to other fields involving hot hadronic matter than particle physics in the study of the cores of neutrons stars. Generally, another piece in the puzzle that is our universe has been placed and created the opportunity to placement of more pieces and hence new discoveries.

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Appendix 1

Particle collision and QGP creation.

Source: [2]