National Research Nuclear University "MEPhI"

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Small thesis on the topic:

" QUARK GLUON PLASMA AND SUPERSYMMETRY "

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FOREWORD

According to the well-established Big Bang model, shortly after the cosmic inflation and electroweak epoch, the forces of the Standard Model reorganized themselves into their “low temperature” form [1]. We call this stage as the quark epoch. Bosons were rearranged from the Higgs and Electroweak interactions. Fermions got massive due to the nonzero vacuum expectation value of the Higgs Field. At such high energy densities, quarks were not yet ready to form hadrons, instead a plasma of quarks and gluons existed for a brief period of time until the temperatures further cooled down and resulted in the hadron epoch. The leptons would have been present at this time, but it was Quark-Gluon Plasma (QGP) that dominated the properties of matter in the universe. Physical analysis of this primal fermio-bosonic bond might give us promising evidences for the presence of certain supersymmetric models at extreme energy scales. Here, we will go through the practicalities of Quantum Chromo-Dynamics, understand the importance of relativistic heavy ion collisions, analyze the extreme energy states similar to that of the early universe and explore the probable extension in Standard Model from the possible presence of Supersymmetric partners in QGP.

FUNDAMENTALS OF QUANTUM CHROMO-DYNAMICS

Quantum Chromo-Dynamics (QCD) is a significant part of the Standard Model of particle physics. It is a theory of the strong interaction - based on color force, a fundamental force describing the interactions of the quarks and gluons, making up hadrons (such as the protons, neutrons or pions) [2]. QCD, a non-abelian gauge theory, is a section of Quantum Field Theory with a SU (3) symmetry group. There are two different types of SU (3) symmetries, one that acts on the different colors of quarks and the other rotates different flavors of quarks to each other (flavor SU (3)). QCD has approximate flavor symmetry, which is broken by the differing masses of the quarks [3].

Quarks are massive spin half fermions, have 3 color charges, carry electric charge (either $-1/3$ or $+2/3$). There are 6 flavors of quarks namely up, down, charm, strange, top, bottom. For every quark flavor there is a corresponding antiparticle, known as an anti-quark. They carry global quantum numbers including the baryon number ($+1/3$ for each quark and $-1/3$ for each anti-quark), hypercharge and one of the flavor quantum numbers. Quarks are the only elementary particles in the Standard Model of particle physics to experience all four fundamental interactions. They get their mass through Higgs Mechanism.

Gluons are spin-1 vector gauge bosons that have 8 independent color states and a color singlet state. They are electrically neutral and massless.

The few techniques that have been developed to work with QCD are perturbative QCD, non-perturbative (lattice) QCD and Hadron resonance gas Boltzmann equations. Confinement and asymptotic freedom are the two major consequences of QCD. Confinement means that the force between quarks does not decrease as they are separated. Thus, hadronic matter at normal energy densities is composed of confined, color neutral quarks and gluons. Asymptotic freedom is a theory that showed a decrease in the strong coupling constant with an increase in momentum transfer or distance scales between quarks. This suggests that in very high-energy reactions, quarks and gluons interact only very weakly.

ULTRA-RELATIVISTIC HEAVY ION COLLISIONS

Collisions between heavy atomic nuclei at relative velocities close to the speed of light are usually divided into two different domains, relativistic and ultra-relativistic collisions [4]. Depending on whether the kinetic energy per nucleon is either close to the rest mass of the nucleon, about 1 GeV (relativistic collisions), or much larger than the nucleon rest mass (ultra-relativistic collisions). Relativistic heavy ion collisions offer the possibility to study strongly interacting matter under extreme conditions [5]. By accelerating lead or gold nuclei to almost the speed of light and smashing them together, a hot and dense fireball will develop in the overlapping region. Temperatures and densities can be reached as they have existed in the early universe, only microseconds after the Big Bang. It is the properties of this fireball of nuclear matter that is the primary research goal of most experiments using high-energy heavy-ion collisions.

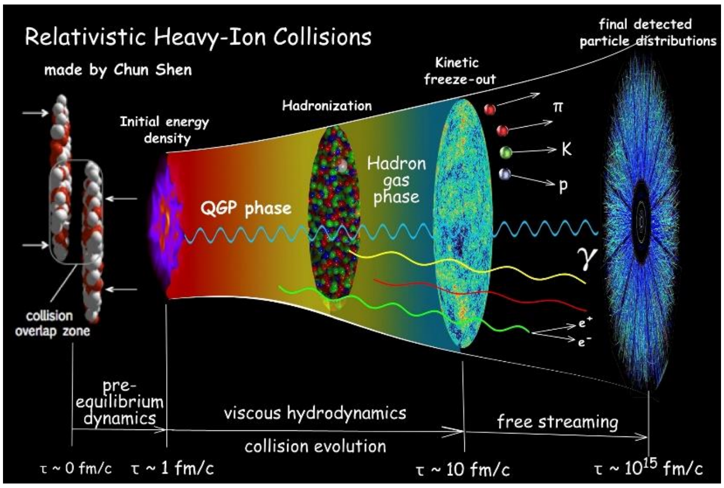

Fig.1

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL), USA is an intersecting storage ring particle accelerator, which operates on this very phenomenon (Fig.1) for the experimental objective of creating and studying the QGP. It can provide centre of mass collision energies of up to 250 GeV per nucleon [6-9]. Numerous signatures supporting the formation of the QGP have been reported from Large Hadron Collider (LHC), CERN as well. Jet quenching, non-viscous flow, direct photons, and Debye screening effects are few among them [10].

QUARK GLUON PLASMA

The high temperature phase of QCD, the Quark-Gluon Plasma (QGP) is characterized by color deconfinement and partial restoration of chiral symmetry [11]. As discussed above, QGP is a strong coupled plasma of quarks and gluons, which is formed when very high energy density causes a phase transition amongst the hadrons. Two distinct features were discovered at RHIC and then confirmed at the LHC: the high opacity of the matter (jet quenching) and its non-viscous, fluidic nature.

Jet quenching is one of the major indicators of QGP. Similar to bremsstrahlung radiation, the jets of final state baryons and mesons that are emitted from the plasma will lose some of their energy due to strong interactions with the plasma which will result in a lower energy of the resulting particles [12]. This is observed experimentally from the suppression in the yields of high transverse momentum particles by binary scaling which essentially match the number of nucleon-nucleon collisions to proton-proton collisions [14].

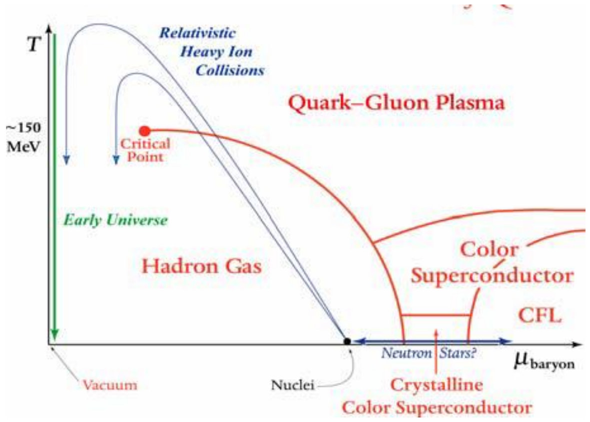

Fig.2

A phase diagram is shown in ***Fig. 2*** for the phases of hadronic matter. On the x-axis the baryon chemical potential is plotted which basically scales with the density of baryonic matter.

Studies of QGP can throw light in the composition of hadrons (namely protons and neutrons) and can provide a deeper theoretical understanding of the origin of the energy scales governing the vacuum structure confining quarks. Additionally, QGP analysis may help us to explore physics phenomena that encompass all three families of particles known today, allowing perhaps the study of the origin of flavour [14].

SUPERSYMMETRY

Supersymmetry is one of the most preferred extensions of the Standard Model. The conventional symmetry transformations rotate bosonic states to other bosonic states and fermionic states to other fermionic states. But, supersymmetric transformations are such forms of symmetry transformations which implies that bosons and fermions could be merely different manifestations of the same state, and in some sense would correspond to an ultimate form of unification [15]. The corresponding theories invariant under such transformations are called supersymmetric theories.

A simple quantum mechanical example and trivial linear algebra can demonstrate that Hamiltonian of a mixed bosonic and fermionic oscillator of the same frequency is invariant under an interchange of bosons and fermions.

The noteworthy property of supersymmetric theory (not actually a theory but a principle a theory could have) is that every fermion has a supersymmetric boson partner, and vice-a-versa. Like quarks have squarks, electrons have selectrons, while photons have photinos and gluons have gluinos etc. Moreover, these supersymmetry multiplets are equal-mass particles whose spins differ by ½ [16]. Supersymmetry also implies the existence of scalar quarks (partners of ordinary quarks with spin 0). These are bosons and can form a Bose condensate, which produces a baryon asymmetry after decay of the scalar quarks into quarks and gluinos [17].

Unfortunately, till date none of these supersymmetric partners have been found. According to recent hypotheses, it is believed that the supersymmetric partners could be very massive because supersymmetry in nature has to be broken either explicitly or spontaneously. It is expected, however, that if supersymmetry is a true symmetry of nature, these supersymmetric particles will be detected directly in the ultra-high energy experiments at the Tevatron or at the LHC.

The reason for its popularity is that supersymmetry solves the major hierarchy problem of unified theories. The large discrepancy between the aspects of the weak force and gravity can be resolved or in specifically, the unification between Standard Model and Einsteins's Field equations can be made possible using supersymmetry.

POSSIBILITY OF SUPERSYMMETRIC MODELS IN QGP STATE

Based on the stable hadronic composition of two quarks (mesons) and three quarks (baryons), the cumulative mass of the quarks and gluons (massless) comprises not more than 1% of the total mass of the corresponding hadron. 99% of the hadronic mass is due to the strong interaction between quarks and gluons. Increasing the temperature of the hadronic system, and thereby the random thermal motion of its constituents, could eventually lead to a complete disintegration of the hadron into free quarks and gluons. This plasma state is quite similar to that of the core of stars.

Using lattice QCD, it has been found out that quark condensate, quark kinetic energy, gluon kinetic energy and anomalous gluonic contribution constitutes approximately 9%, 32%, 37% and 23% of the baryonic mass respectively [18].

The lattice QCD calculation result (less than the Stefan-Boltzmann equation prediction by ~ 20%) and an extremely small viscosity can be predicted by gravitation phenomena in N=4 supersymmetric theories.

The limitations of lattice QCD, owing to the out of equilibrium system, need of transport coefficients and relativistic viscous hydrodynamics, questions its reliability.

An incorporation of supersymmetry in lattice QCD might address the baryonic mass problem. There is a likelihood that the quark condensate and anomalous gluonic contribution (as predicted by lattice QCD) came into existence because of the interaction among the quarks, gluons and their respective super symmetric partners in the extreme energy density state. Confirmation of this phenomenon requires promising experimental evidence.

However, we may not notice the individual supersymmetric partners but we might get a glimpse of the overlapping system in the relativistic heavy ion collisions at RHIC (BNL) or at LHC (CERN). The attempts to test such ideas are quite challenging. Hopefully, in the near future we might get an affirmation from the experimental analysis of this QGP state, which can decipher majority of the mysteries in the field of high energy physics and astrophysics.

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