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Small thesis on the topic:

" QUARK GLUON PLASMA AND SUPERSYMMETRY "

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ABSTRACT

The first signature of strange quarks and dip in the number of J/Ψ mesons reaching the detectors at the Super Proton Synchrotron (SPS) in CERN few decades ago, hinted to the formation of a new state of matter. Further experiments at the Relatively Heavy Ion Collider (RHIC) in BNL have revealed comprehensive information about the properties of this new phase of matter which we now widely refer to as the Quark Gluon Plasma (QGP).

In the early 1970s, a hypothesis of Supersymmetry (SUSY) between fermions and bosons had also been put forward. The Coleman-Mandula theorem, which states that "space-time and internal symmetries cannot be combined in any but a trivial way", singles-out supersymmetry as the "unique" extension of Poincaré invariance in 3+1 or more dimensional Quantum Field Theory (QFT) [1].

In the present small thesis, we will go through a brief analysis of this hot Quantum Chromodynamic (QCD) matter and explore the possible extension in Standard Model of particle physics by extrapolating the presence of SUSY partners in the QGP state.

CONTENTS

QUANTUM CHROMO-DYNAMICS

Quantum Chromodynamics (QCD), a non-abelian gauge theory, is the SU (3) component of the Standard Model of Particle Physics which describes the strong interaction between quarks and gluons. There are two different types of SU (3) symmetries, one acts on the different colors of quarks (color SU(3)) and the other changes different flavors of quarks to each other (flavor SU (3)). The SU(3) color group is the exact gauge symmetry of the Standard Model, which accounts for the strong interactions of quarks and gluons. While, the SU(3) flavor group is an approximate symmetry of QCD resulting from the universality of quark-gluon couplings [2-3].

The Lagrangian of QCD is given by :

$$\mathcal{L} = \sum_q \bar{\psi}_{q,a}(i\gamma^\mu \partial_\mu \delta_{ab} - g_s \gamma^\mu t^C_{ab} \mathcal{A}^C_\mu - m_q \delta_{ab})\psi_{q,b} - \frac{1}{4} F^A_{\mu\nu} F^{A\mu\nu}$$

The γ^μ are the Dirac γ-matrices. The $\psi_{q,a}$ are quark-field spinors for a quark of flavor q and mass m_q , with a color-index a that runs from a = 1 to $N_c = 3$ (quarks come in three "colors") .The $A^C{}_\mu$ correspond to the gluon fields, with C running from 1 to $N^2{}_c-1 = 8$ (there are eight kinds of gluon). The $t^C{}_{ab}$ correspond to eight 3 × 3 matrices and are the generators of the SU(3) group. They specify that a gluon's interaction with a quark rotates the quark's color in SU(3) space. The quantity g_s is the QCD coupling constant. $F^A{}_{\mu\nu}$ is the field tensor [4].

The few techniques that have been developed to work with QCD are Perturbative QCD, Lattice QCD (non-perturbative) and Hadron resonance gas Boltzmann equations. Confinement and asymptotic freedom are the two major consequences of QCD. Confinement means that the force between quarks increases as they are separated. Thus we do not observe free quarks. Hadronic matter at normal energy densities is composed of confined quarks and gluons. Asymptotic freedom refers to the decrease in strong coupling constant with an increase in momentum transfer (increase in energy scale) between particles (quarks). This suggests that in very high-energy reactions, quarks and gluons interact only very weakly. Confinement and aymptotic freedom mutually reveal that high temperature QCD matter should be deconfined and weakly coupled.

ULTRA-RELATIVISTIC HEAVY ION COLLISIONS

Heavy ion collisions are divided into relativistic and ultra-relativistic. Ultra-relativistic heavy ion collisions are those collisions in which the kinetic energy per nucleon is much larger than the nucleon's rest mass. They offer the possibility to observe strongly interacting matter under extreme conditions. These high energy collisions of heavy (Pb or Au) nuclei create a hot and dense fireball in the interaction region. The properties of this fireball can be described with the help of thermodynamics and fluid dynamics.

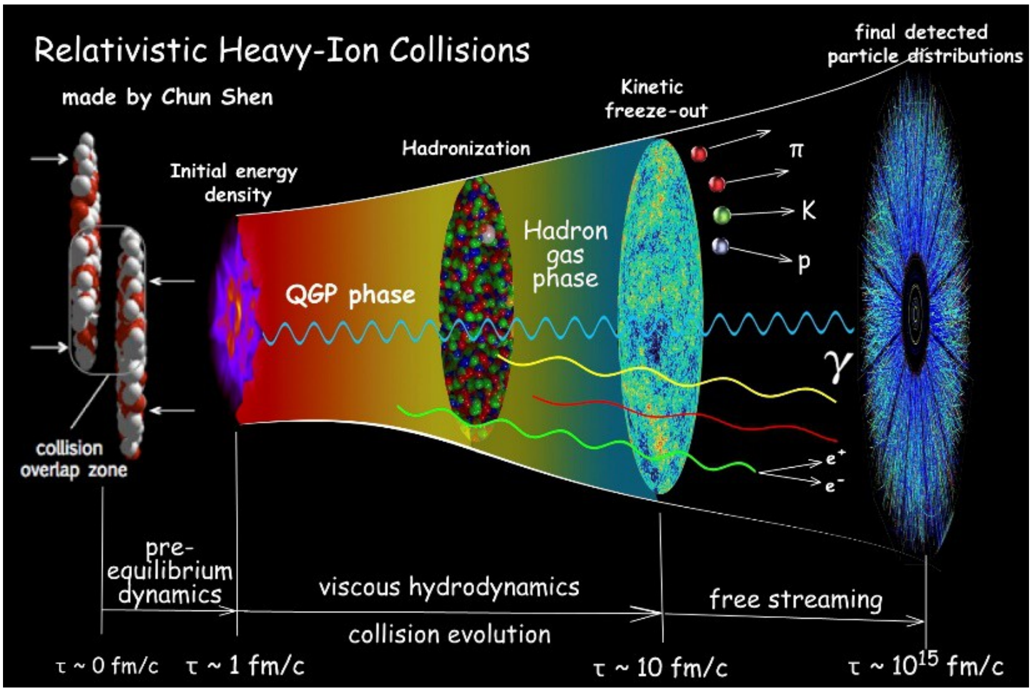

Fig.1

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL), USA is an intersecting storage ring collider, which studies the properties of QGP in high energy nuclei collisions (Fig.1). It can provide centre of mass collision energies of up to 250 GeV per nucleon [5-8]. Specific signatures like strangeness production, dip in the formation of heavy mesons at such extreme energies, jet quenching, non-viscous flow, direct photons and Debye screening effects, provide information on the formation of QGP in these heavy ion collisions. [9]. The ALICE collaboration of Large Hadron Collider (LHC) at CERN which carries out a comprehensive study of the hadrons, electrons, muons, and photons produced in the collisions of ^{208}Pb , have also approved to have observed these phenomena.

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 [10]. Theoritically QGP was first formulated by Lattice QCD calculations in 1980s and a decade later heavy ion experiments were initiated to search for this new phase of matter. As discussed above, QGP is a strong coupled plasma of quarks and gluons, which is formed when very high energy density and temperatures at and above the QCD deconfinement scale (Hagedorn temperature, $T_H \approx 150$ MeV or $1.7*10^{12}$ K) causes a phase transition amongst the hadrons. Due to this surplus energy, the gluons collide and produce an excess of strange quarks, but the formation of QGP hinders the further creation of other heavy quarks like charm or bottom. The top quark on the other hand decays before hadronization.

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 [11]. 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.

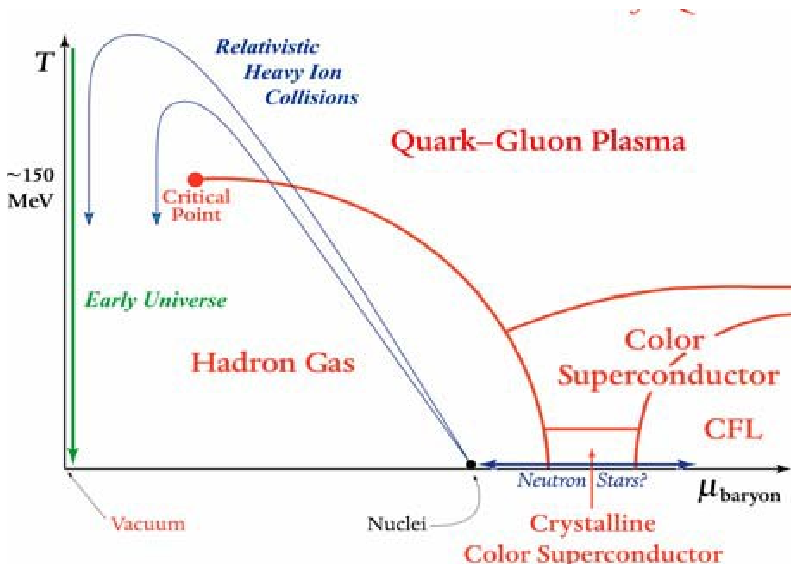

Fig.2

A phase diagram is shown in ***Fig. 2*** for the phases of hadronic matter. On the x-axis the baryon chemical potential (μ in MeV) is plotted which basically scales with the density of baryonic matter. In other words, μ is the measure of the imbalance between quarks and antiquarks in the system. Higher μ refers to a higher density of quarks, while higher temperature refers to a higher possibility of antiquarks.

Present baryonic matter exists at the low-temperature phase boundary between vacuum and nuclear matter, at μ = 310 MeV and T close to zero. On increasing the quark density and keeping the temperature low, a phase of more and more compressed nuclear matter is reached. This path leads to a neutron star (recent evidences suggests that neutron stars with mass ~ 2 solar masses were likely composed of quark matter [12]). Eventually, at ultra high densities, the color-flavor-locked (CFL) phase of color-superconducting quark matter is reached. In CFL phase, the quarks form Cooper pairs (similar to the electron pair state which is reponsible for superconductivity in metals). Chiral symmetry is broken at this phase. Color super-conductivity (CSC) is analogous to the superconductivity observed in metals, with a difference that CSC phase is a weakly interacting fermi liquid of quarks in sufficiently dense quark matter. Cooper pairs of quarks carry net color and electric charge, so some gluons become massive in a phase with a condensate of quark Cooper pairs, creating a color superconductor .

Lattice gauge theory (LQCD) quantitatively explains the properties of quark matter phase structure by brute force computer calculations.

Hence, QGP analysis may help us explore physics phenomena that encompass all three families of particles known today and a detailed description of matter at extreme baryonic potentials. Studies of QGP can provide a deeper theoretical understanding of the origin of the energy scales governing the vacuum structure of QCD confinement. Application of these ideas to the evolution of early Universe can address the composition of matter at the early stages of our Universe.

SUPERSYMMETRY

Supersymmetry is one of the most preferred extensions of the Standard Model because it solves the major hierarchy problem of unified theories and it was the most pratical explaination of the non zero mass of Higgs Boson. SUSY transformations provide transitions between bosons and fermions. It states that every fermion has a supersymmetric boson partner, and vice-a-versa. For instance, quarks (spin 1/2) have squark partners (spin 0), while gluons (spin 0) have gluinos (spin 1/2). Recent studies show that the SUSY partners, whose spins differ by ½, are very massive because in nature supersymmetry has to be broken either explicitly or spontaneously.

Supersymmetry, based on Lie superalgebra, is considered a loophole of Coleman-Mandula theorem because it contains supercharges (additional Poincare generators) which are spinors, rather than scalars. But, SUSY 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 [13].

A quantum mechanical approach can demonstrate that Hamiltonian of a mixed bosonic and fermionic oscillator of the same frequency is invariant under an interchange of bosons and fermions [14].

Till date none of the supersymmetric partners have been found in the experiments. 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.

Apart from quantum mechanics and high energy physics, Supersymmetry finds its applications to different areas of physics, such as condensed matter physics, nuclear physics, optics, stochastic dynamics, astrophysics, quantum gravity, and cosmology. Supersymmetry can also link Standard Model and Einsteins's Field equations resulting to the Grand Unification Model.

POSSIBILITY OF SUPERSYMMETRIC MODELS IN QGP STATE

Due to certain experimental limitations it is hard to map the phase diagram of quark matter. However, the crossover from hadronic matter to QGP can be ultimately explained using collisions of relativistic heavy ions .While on an astrophysical scale, models of the cooling, spin-down, and precession of compact stars offer information about the high-density low-temperature region of the phase diagram.

Supersymmetry helps to address few special QCD phenomena. For example, confinement can be proven analytically by supersymmetric gauge theories, similar to QCD but with slightly different matter content (Seiberg-Witten solution of N = 2 supersymmetric theories using super gravity models [15]). Furthermore, from 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 [16]. The lattice QCD calculation result and an exceedingly small viscosity can be predicted by gravitation phenomena in N=4 supersymmetric and Yang Mills Theory.

Charge of an electron and the quark content of baryons are dependent on specific symmetries. The creation of bosons from matter-antimatter annhilations and the production of fermion-antifermion pairs from high energetic bosons account to the symmetry between bosonic and fermionic fields. This further explains why we observe the neutral mesons for few femto seconds before it decays into photons. So, based on these conceptions we can reach to a certain deduction that the Universe at its earliest stages might have been supersymmetric and the massive supersymmetric partners (squarks and gluinos) were formed for about a yoctosecond before decaying into quarks and gluons in the QGP state which existed for roughly around a few microseconds before forming baryons. Stronger colliders exceeding the current energy scales in next few years can reveal this phenomenon and we will be able to understand our Universe and its constituents even better.

REFERENCES

1. Coleman, Sidney; Mandula, Jeffrey (1967). "All Possible Symmetries of the S Matrix". Physical Review. 159 (5): 1251. Bibcode:1967PhRv..159.1251C. doi:10.1103/PhysRev.159.1251.
2. Griffiths, D. Introduction to Elementary Particles. Wiley, New York, 1987.
3. Perkins, D. H. Introduction to High Energy Physics. Cambridge University Press, Cambridge, UK, 2000.
4. M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018) and 2019 update.
5. J. Adams, et al, [STAR Collaboration], Nucl. Phys. A 757 (2005) 102-183; nuclex/ 0501009.
6. K. Adcox et al, [PHENIX Collaboration], Nucl. Phys. A 757 (2005) 184-283; nuclex/0410003.
7. I. Arsene et al, [BRAHMS Collaboration], Nucl. Phys. A 757 (2005) 1-27; nuclex/ 0410020.
8. B. B. Back et al, [PHOBOS Collaboration], Nucl. Phys. A 757 (2005) 28-101; nuclex/ 0410022.
9. Niida, T., Miake, Y. Signatures of QGP at RHIC and the LHC. Association of Asia Pacific Physical Societies (AAPPS) Bulletin. Springer. 31,12 (2021). https://doi.org/10.1007/s43673-021-00014-3. Springer
10. Rafelski J. Discovery of Quark Gluon Plasma: Strangeness Diaries (2020). https://doi.org/10.1140/epjst/e2019-900263-x. Eur. Phys. J. Special Topics 229, 1–140 (2020).
11. B. Muller and J. Nagle, Annu. Rev. Nucl. And Part. Phys.1 (2006)
12. Annala, Eemeli; Gorda, Tyler; Kurkela, Aleksi; Nättilä, Joonas; Vuorinen, Aleksi (2020-06-01). "Evidence for quark-matter cores in massive neutron stars". Nature Physics. 16 (9): 907–910. arXiv:1903.09121. doi:10.1038/s41567-020-0914-9. ISSN1745-2481.
13. Khlopov M. Fundamentals of Cosmic Particle Physics. Cambridge International Science Publishing Ltd and Springer, 2012.
14. Das A., & Ferbel T. Introduction to Nuclear and Particle Physics. Singapore: World Scientific Publishing Co. Pte. Ltd, 2003.
15. N. Seiberg and E. Witten, Monopoles, duality and chiral symmetry breaking in N=2 supersymmetric QCD, Nucl. Phys. B 431, 484 (1994) [hep-th/9408099].
16. Y.-B. Yang, J. Liang, Y.-J. Bi, Y. Chen, T. Draper, K.-F. Liu, and Z. Liu, “Proton mass decomposition from the QCD energy momentum tensor,” Phys. Rev. Lett. 121, 212001 (2018).