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Re-Creating the Big Bang

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Abstract : A few microseconds after the Big Bang, our Universe may have been dominated by the quark-gluon plasma (QGP), an hitherto undiscovered phase predicted by the current theory of strong interactions. Heavy ion collision experiments at very high energies at Brookhaven National Laboratory, New York and the upcoming Large Hadron Collider in CERN, Geneva have the potential for producing the right conditions for such a phase transition to occur. This introductory review of the subject endeavours to explain what quark-gluon plasma is, why it is important and how it can be created and studied in laboratory.

Keywords : Quark-gluon plazma, Big Bang, Cosmic microwave background radiation.

Introduction : What is Big Bang ?

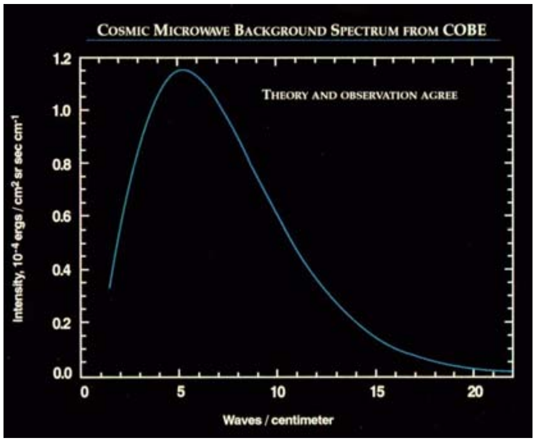
Edwin Hubble's observation of stellar objects lead to his propounding an expansion law for them: distant galaxies move away from us at a rate proportional to their distance (measured by their red-shift). This in turn led to a picture of our Universe as having been denser in the past than now. The Big Bang theory of Universe accounts for this law by the assertion that our Universe was born in hot big bang and subsequently cooled by expansion. The strongest evidence to date for this theory has come from the ever increasingly precise measurements of the cosmic microwave background radiation (CMBR), shown in the Figure on the next page. In spite of showing the error-bars a couple of hundred times more than actually are, one sees such a perfect agreement of the theoretical black body curve with the data that the latter are totally invisible. In fact, this is the most perfect observed black body radiation spectrum ever.

The temperature it measures is that epoch of the Universe at which electromagnetic radiation decoupled from the matter : 'T = 3000° K, redshifted due to the expansion of our Universe to 'T = 2.726° K. Using the fluctuations in this background temperature, astronomers from WMAP satellite experiment have constructed the earliest picture of our Universe at about 380,000 years of its age.

A natural consequence of the expansion is that the Universe was still hotter at earlier times. If we understand the physics of those early times, or very high temperatures, well then we should be able to take a peek in to still earlier times in the history of the Universe. Thus, e.g., our extensive knowledge of the many nuclear reactions has enabled us to estimate the composition of our Universe in terms of the basic elements. Its confirmation by observations has allowed us to have confidence in our scenario up to about first three minutes of the age of the Universe. As we approach the big bang itself, the next new landmark of physics is at about 10-20 μs, corresponding to formation of protons and neutrons.

Why Re-Create the Big-Bang?

The known interactions and elementary particles a century ago were



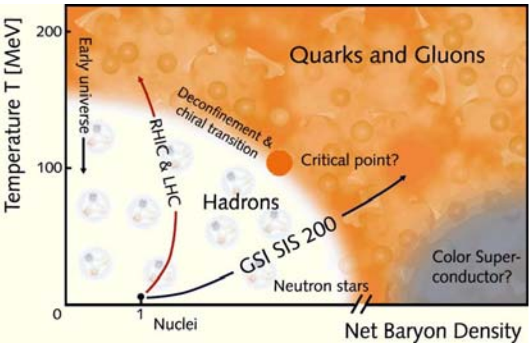
Electromagnetism, Gravity and electrons and atoms. Rutherford's classic scattering experiment, and its subsequent sophisticated versions in form of high energy particle accelerators and detectors, yielded various new layers of building blocks. Quarks and leptons are today regarded as the elementary particles from which our matter is made. Atoms consist of nuclei and electrons. Leptons are heavier electrons and their associated neutrinos. Protons and neutrons make up the nuclei discovered by Rutherford, while they themselves are made up of quarks: Proton (Neutron)consists of 2 u(d) type of quarks and 1 d(u) quark while a pion is made of a u-quark and d-antiquark.

Over the years, strong and weak nuclear forces got added to the list of forces above. A variety of vector bosons act as the carriers of forces. The strengths of these forces are progressively smaller with the electromagnetic interaction being two orders of magnitude smaller than the strong interactions which bind quarks together into protons and neutrons. Gluons are the vector particles which carry these interaction. Weak nuclear forces and gravity are smaller by 5 and 39 orders of magnitude respectively. These become relevant in the history of our Universe almost close to the instant of the big bang (a billionth of a billionth of a billionth of a billionth of second after the big bang).

Phase Diagram of Strong Matter

Quantum Chromo Dynamics (QCD) is the (gauge) theory of (strong) interactions of quarks and gluons. The strength of this force as well as its complexity leads to a much richer structure: Quarks are permanently confined to hadrons like proton and neutrons; a dynamical symmetry breaking ensures that the quarks become massive due to interactions although free quarks are rather light; and many more.

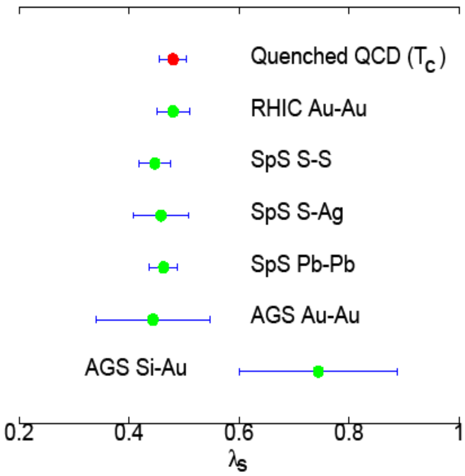
While in the early days of strong interactions, one attempted to understand these features based on models, one now has a powerful technique, called lattice field theory, to derive them from the basic theory. Indeed, only 50 years after the discovery of proton and neutron was it possible using lattice field theory techniques to understand their mass and the structure from the basic underlying theory QCD. The same lattice technique, as well as certain models, predicts new phases of matter at high temperatures and densities shown in the Figure below. Quark-Gluon Plasma is one such new phase. It is further expected to be produced in Relativistic Heavy Ion Collisions as we shall



see in the next section. Its experimental confirmation will test the predictions of the theory of strong interaction QCD in a new domain. Moreover, such temperatures being relevant to our Universe at a few microseconds after the big bang, these collisions will permit us to study the physics of such early times. The figure below shows a depiction of the various new phases one expects to see in the temperature-density phase diagram of QCD. At high enough densities, which exist in very dense stars, the novel phase of colour superconductivity may manifest itself. Whether that can have any observable consequences is a subject of active research.

Some Results :

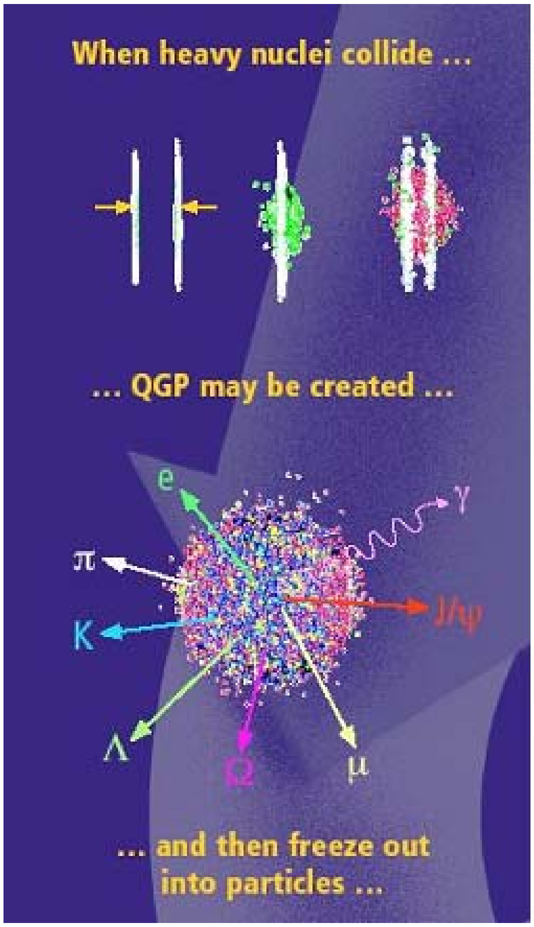
The lattice techniques have led to a prediction of the transition temperature Tc~ = 180 MeV (about 2 trillion degrees Kelvin). They have also resulted in the equation of state and many other properties, notably the Wroblewski Parameter, shown here on the right from our work (Gavai and Gupta, Phys Rev D65, 2002 and Phys.Rev. D73, 2006). It is a measure of the production of strange quark-antiquark pairs and has been proposed as a signal for the new phase, Quark-Gluon Plasma. As one sees in the figure, experiments agree with the lattice QCD estimate for the new state. Several other correlations for Heavy Ion Physics have been predicted theoretically in the same way. For instance, lattice QCD also suggests that strangeness is carried by quark-like objects, and supports the idea that flavour in general shows quasi-quark behaviour.

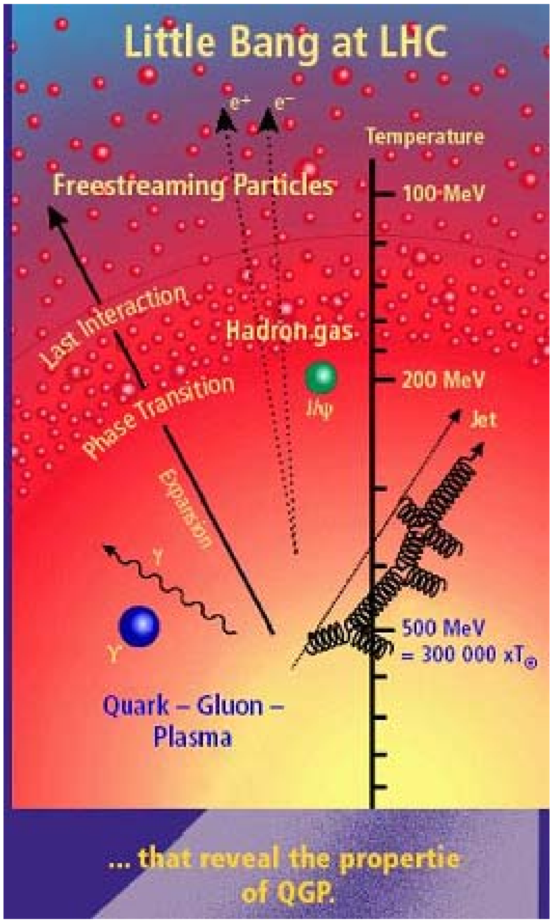


Theoretical physicists, including us (R V Gavai and S. Gupta, Phys. Rev. D71 2005) have also attempted to look for the critical point. We find it to be located at smaller densities than expected. As shown in the figure on the next page, our estimate is that the relativistic heavy ion collider (RHIC), if run at lower colliding energy of about 20-30 GeV, can potentially discover it.

Heavy Ion Collisions

Let us now address the questions of where one can find these new phases and whether they can they be produced in a laboratory. As remarked in the beginning, our Universe was full of QGP at about 10-20 μs after the Big Bang. However, our best chance of studying the Quark-Gluon Plasma is in re-creating that instant of Big Bang. It turns out that the necessary conditions for QGP production in a laboratory are, high energy density, large system size and production of many particles. Heavy Ion Collisions at velocities 99.5-99.995% that of light, possible at the colliders in CERN, Geneva and BNL, New York, do meet these conditions. How this happens is schematically illustrated in the left picture on the next page. The fireball of QGP condenses into hadrons in extremely short duration of almost an instant. Looking though the products of the collision to establish that QGP was formed


When heavy nuclei collide ...
... QGP may be created ...
e
γ
π
K
J/ψ
Λ
Ω
μ
... and then freeze out into particles ...


Little Bang at LHC
e+
e−
Temperature
Freestreaming Particles
100 MeV
Last Interaction
Hadron gas
200 MeV
Phase Transition
J/ψ
Jet
Expansion
γ
γ
500 MeV = 300 000 xT☉
Quark – Gluon – Plasma
... that reveal the propertie of QGP.

needs clever detective work. As the picture on the right shows the similarity of the cooling of the fireball with the early universe can be exploited to devise tools for this task of looking for the new phase QGP. One such tool is jet quenching. It is well known that rare high energetic scatterings of quarks and gluons in the colliding hadrons produce jets of particles. Such jets have been widely studied in proton-proton and electron-positron collisions. If Quark-Gluon Plasma, any medium in general, interacts with such a jet, it causes a loss of energy due to multiple scatterings. Since these jets emerge back-to-back due to momentum conservation, only one of them will be missing (or extinguished) by QGP. Such jet quenching has been seen rather extensively. Moreover, an on-off test has been also performed by comparing the collisions of heavy-heavy nuclei, where QGP is expected to be formed, with light-heavy or light-light, where it is not.

Additional evidence for QGP has also been found by looking for the flow in transverse direction which suggests QGP to flow as perfect liquid with essentially no viscosity. Debye screening, characteristic of a plasma, can stop quarks from binding in to hadrons. Anomalous suppression of heavy particles called, J/Ø, has shown that such Debye screening may have been present in the aftermath of the heavy ion collisions.

Summary

Lattice QCD predicts new states of strongly interacting matter and is able to shed light on the properties of the Quark-Gluon plasma (QGP) phase. Our results on strangeness production are consistent with the expectation of formation of QGP in experiments. We found that correlations of quantum numbers suggest QGP to have quarklike excitations.

Heavy Ion Collisions in CERN Geneva, and BNL, New York, have produced tell-tale signatures of QGP. Many surprises have already been produced by the data and more excitement is likely to come in the upcoming Large Hadron Collider in CERN, Geneva.