Overview

The Strongly Interacting Quark Gluon Plasma and Future Physics

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At RHIC, recent experiments over the last two years reveal a new state of nuclear matter, hitherto unknown to us. While the term "quark gluon plasma (QGP)" has been used in the past, the physical picture was often modeled after the weakly interacting electron plasma, which is very different from what has been discovered recently. At RHIC, this new state of nuclear matter is found to interact very strongly. Since it is composed of quarks and gluons, we may call this new state of nuclear matter sQGP, the strongly interacting quark gluon plasma.

The main focus of this workshop is about the present discovery of sQGP. It is an experimental discovery. The properties of sQGP are defined by the new findings of experiments at RHIC. While at the same time, there are many important and impressive theoretical advances, our theoretical progress remains imperfect. This may seem strange to some of our experimental colleagues since we do possess quantum chromodynamics (QCD) as the theory of strong interaction. How come, we still have difficulties in predicting and understanding the properties of sQGP?

1) Knowing the equation $\neq$ having its solutions.

Take the example of the nonrelativistic Schroedinger equation of a system of charged particles with Coulomb interactions. In principle, that single N-dimensional second order linear differential equation should contain in its solutions all informations about

1. atomic and molecular physics (except for small relativistic corrections)
2. condensed matter physics
3. chemistry

and

4. biology

It is clear, although we do have the equation for 74 years, we are still very far from deriving all its solutions.

Just take condensed matter physics, and within that field let us briefly review the experimental discoveries and theoretical understandings of superconductivity and superfluidity:

1911 Superconductivity (Kamerlingh Ounes)

1924 λ –transition of He (Kamerlingh Ounes and Boks)

1924 Bose-Einstein Condensation

1938 Two fluid Model of Liquid He (London)

1957 BCS Theory

1986 High T_c Superconductivity (Bednorz and Müller)

Superconductivity was discovered in 1911. However, BCS theory was formulated in 1957, 46 years later after the experimental discovery, and 32 years later after Schroedinger wrote down the basic equation of quantum mechanics. Yet, even today, we still have difficulties in our theoretical understanding of the high T_c superconductivity.

Superfluidity is another example: λ-transition of He was observed in the same year (1924) when the theory of Bose-Einstein condensation was formulated. Still, it took 14 years for F. London to propose the two fluid model of liquid He. Why should it take so long?

In 1924, the theory of Bose-Einstein condensation was developed for a system of ideal bosons with no interaction. On the other hand, the density of liquid helium is quite high, near the close-packing density of a system of hard spheres. Only much later, we understood that the critical element of Bose-Einstein condensation is the long range order of the phase of the Schroedinger wave function; it is insensitive to the density, since the density is the absolute value squared of the wave function. Thus, density-wise liquid He is very different from ideal bosons, but phase-wise these two systems share the same long-range Bose-Einstein condensation characterization. It took decades for the best of theorists, including Einstein and others, to be sure of this conclusion.

Yes, knowing the equation is not the same as having the solutions. However, having the equation is a prerequisite for a full understanding of its solutions. This is why a physics discovery is often made by experimentalists first, then followed by theoretical understanding. For the progress of our field, a close collaboration between experimentalists and theorists is of critical importance.

The experimental discovery of sQGP is only the beginning of an era of new physics. It will lead us to a more complete understanding of quantum chromodynamics, the basic theory of quarks and gluons. Because sQGP is a strongly interactive system, once produced its properties will dominate all subsequent physical phenomena that follow. Thus, sQGP physics may well be the threshold, through which we will reach LHC physics and beyond, including perhaps also dark energy and dark matter in our universe.

2) sQGP physics and dark energy

Recently, there exist very strong evidence[1] that cosmological constant Λ is not only nonzero, but very large. The energy density of Λ is negative, with a large magnitude

$$\rho_\Lambda \sim 3 - 7 \times 10^{-6}\ \mathrm{GeV/cm^3}, \tag{1}$$

which is the same order of magnitude as the critical energy density of our universe, given by

$$\rho_c \sim 1 \times 10^{-5}\ \mathrm{GeV/cm^3}. \tag{2}$$

What is the origin of this negative energy? Why should ρ_Λ and ρ_c be of the same order of magnitude?

In Einstein's first edition of his masterpiece "The Meaning of Relativity," published in 1922, he wrote[2]:

> "Matter consists of electrically charged particles. On the basis of Maxwell's theory these cannot be conceived of as electromagnetic fields free from singularities. In order to be consistent with the facts, it is necessary to introduce energy terms, not contained in Maxwell's theory, so that the single electric particles may hold together in spite of the mutual repulsions between their elements, charged with electricity of one sign. For the sake of consistency with this fact, Poincaré has assumed a pressure to exist inside these particles which balances the electrostatic repulsion. It cannot, however, be asserted that this pressure vanishes outside the particles. We shall be consistent with this circumstance if, in our phenomenological presentation, we add a pressure term. This must not, however, be confused with a hydrodynamical pressure, as it serves only for the energetic presentation of the dynamical relations inside matter."

Immediately after this paragraph, Einstien inserted a negative scalar pressure term

$$-p$$

into his equation.

This negative pressure term is, of course, identical to the cosmological constant Λ. Only later, in the second and later editions of the same book, Einstein added an appendix, in which he said[3]

> " The objection to this solution is that one has to introduce a negative pressure, for which there exists no physical justification."

Now, there does exist strong experimental evidence for its existence. However, is there any theoretical justification or understanding of this large negative pressure term?

Actually, negative pressure is a familiar concept for a nuclear physicist. It has been used extensively in the MIT bag model[4]. A similar idea was also developed by Dirac[5] in his theory of muon. In the following, we give a general theoretical framework for the existence of negative pressure; it is the same original reasoning that led Wick and myself to propose the use of relativistic heavy ion collisions for possible creation of new states of nuclear matter [6].

Let us pre-suppose the existence of a scalar field ϕ, which can be either a fundamental field or a composite one, made of other fields, such as the σ-model and Higgs field. Since by using the products of any field, one can always construct a scalar component, the physical basis for the existence of such a scalar component ϕ is quite general. The vacuum is a scalar, hence, ϕ is coupled to the vacuum and therefore, to the inertia of any physical particle. In the physical vacuum state, the field ϕ has an expectation value designated by ϕ_{vac}. Consider the state of any single i th particle. Define its coupling g_i to ϕ by

$$m_i = g_i \phi_{vac} \tag{3}$$

where m_i is its physical mass. Next, consider the transformation

$$\phi \rightarrow \phi + c \tag{4}$$

where c is a constant; correspondingly the vacuum state is changed to an excited state, in which the expectation value of ϕ changes as follows:

$$\phi_{vac} \rightarrow \phi_{vac} + c. \tag{5}$$

Correspondingly the mass m_i of any i th particle (except ϕ itself) will also be altered, with

$$m_i \rightarrow m_i + g_i c \tag{6}$$

Choose the constant c to be given by

$$c = -\phi_{vac} \tag{7}$$

Accordingly, (5) and (6) become

$$\phi_{vac} \rightarrow 0 \tag{8}$$

and

$$m_i \rightarrow 0 \tag{9}$$

Since in any field theory, one can always construct a scalar component ϕ, this means for any single physical i th particle, there exists an excited single particle state in which its mass is zero. The generality of this argument is the origin of negative energy.

The transformation (4) transforms the vacuum state to an excited state, with a different expectation value from ϕ_{vac}. Its excited energy is proportional to the energy density function $U(\phi)$ and the volume Ω of the excitation. An example of $U(\phi)$ is given in Figure 1, with the abscissa ϕ denoting the value $\phi_{vac} + c$ in (5).

For a single particle state in an infinite volume, transformations (8) and (9) lead to excited states with an infinite excitation energy. But for a system of particles within a finite volume, such changes may occur spontaneously, as we shall see.

Figure 2 gives the energy balance of the MIT bag model of a single nucleon, consisting of three quarks. One assumes the expectation value of ϕ to be ϕ_{vac} outside the bag, but zero inside. Thus, the quark mass is zero inside the bag, yielding a quark matter energy E_Q proportional to 1/R, where R is the bag radius. Since the magnitude E_p of the energy due to the negative pressure $-p$ is proportional to R^3, from equipartition of energy, it follows that

$$E_Q = 3\,E_p \tag{10}$$

The total energy E of the system is determined by

$$E - E_p = E_Q. \tag{11}$$

From (10), it follows then

$$E = 4\,E_p. \tag{12}$$

There is an alternative version, the SLAC bag model[7], in which one assumes the function $U(\phi)$ to have two degenerate minima, with $U(0) = p = 0$. What replaces the negative pressure is a surface tension s, giving instead of (11), the following energy balance for the total energy E:

$$E - E_s = E_Q \tag{13}$$

where E_Q is the quark energy similar to the MIT bag, proportional to 1/R. But instead of E_p, one has

$$E_s = 4\pi R^2 s \tag{14}$$

The same equipartition of energy principle gives, instead of (10) and (12),

$$E_Q = 2\, E_s, \tag{15}$$

and

$$E = 3\, E_s. \tag{16}$$

We now take our universe to be a large spherical bag[8] of volume Ω and radius R, related by

$$\Omega = 4\pi R^3/3. \tag{17}$$

The total energy E of the universe is given by an approximate formula, identical to that in the MIT bag, but with (11) replaced by

$$E - E_\Lambda = E_M, \tag{18}$$

in which E_Λ is the negative energy due to the cosmological constant Λ, and E_M the matter energy in our universe, with

$$E_\Lambda = \Omega\rho_\Lambda \propto R^3 \tag{19}$$

and

$$E_M = \text{constant}/R, \tag{20}$$

Just as E_p and E_Q in the MIT bag model. We assume that in the early period of the universe, the matter energy is dominated by its long wave length components and that leads to (20). Setting the derivative of E with respect to R to be zero, we have from equipartition of energy

$$E_\Lambda/E_M = 1/3, \tag{21}$$

as in (10).

If we assume the universe to be like a SLAC bag, then E_Λ is replaced by a surface energy term E_s, with

$$E_s/E_M = 1/2, \tag{22}$$

as in (15). In either case, the amount of dark energy (i.e., negative energy) in the universe is of the same order of magnitude as the total amount of matter energy as indicated by (1) and (2). Considering our over simplification of neglecting the non-Euclidean geometrical effect, the shorter wave length contribution to the matter energy and the dynamical effect of the expansion of our universe, the above order of magnitude agreement is very encouraging.

So, a nucleon is a small bag. A nucleus is a slightly bigger bag, and our universe is a much much bigger bag. The pressure of a MIT bag is exerted by the physical space outside the bag. Similarly, the negative pressure described by the cosmological constant may also be due to the physical space outside our universe. Through RHIC and the study of sQGP, we can change the bag pressure p and the quark energy E_Q; likewise by examining carefully the change of matter energy E_M within our universe, we may gain insight to the dynamical properties of the cosmological constant Λ and its possible space-time variation. With that, we may also derive some information about the physical space outside the radius of our universe.

3) sQGP Physics at LHC and Beyond.

The strongly interactive quark gluon plasma can be produced by Au – Au collisions at RHIC. Therefore it will be produced at LHC. Since sQGP is produced by deutron-Au collisions at RHIC (in the forward direction), it will also be produced through pp collisions at LHC. Because its strong interactions, sQGP once produced will dominate other physics phenomena that follow. This begins a new era of physics.

At a small distance, r, the QCD coupling g(r) also becomes small. But QCD is nonlinear, there could be unstable soliton-like solutions in which the gluon amplitude is proportional to 1/g(r). Its excitation energy should be about 1/r. For r about 1/100 of a fermi or smaller, the excitation energy would be about 100 GeV or larger. It is quite possible that these soliton-like solutions may be described by a phenomenological super-symmetrical field. However, the super-symmetry is at best only approximate. Consequently, these soliton-like solutions are unstable. Such super-symmetrical resonances, if exist, could be an exciting mix between two fields: the traditional particle physics and the newly emerging sQGP physics.

The complexity of sQGP physics clearly signals the need of intensity, and the importance to have RHIC II. Likewise, e-RHIC can provide the unique opportunity of using e as a probe for the analysis of sQGP, using the much weaker QED to analyze the very strong QCD.

The discovery of the strongly interacting quark gluon plasma is a historical event. For this occasion, I wish to dedicate the verse shown in Figure 3.

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FIGURE CAPTIONS

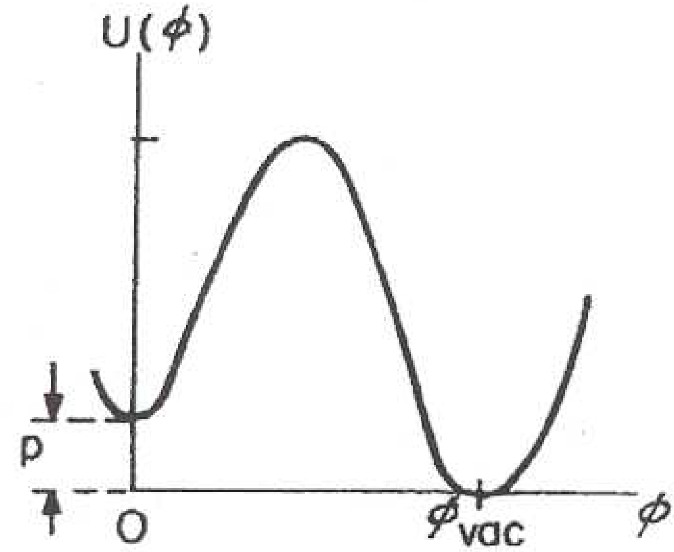
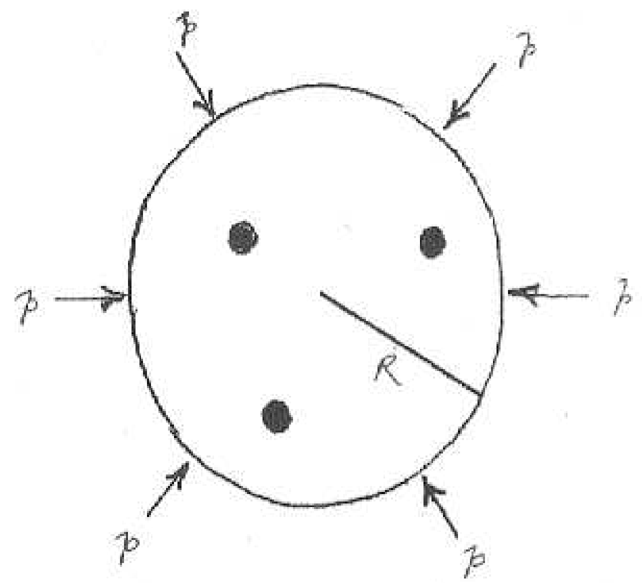


Figure 1.



$$E - \frac{4\pi}{3} R^3 p = N_Q \frac{2.04}{R}$$

$$4\pi R^2 p = N_Q \frac{2.04}{R^2}$$

$$\rho_E \equiv \frac{E}{4\pi R^3/3} = 4p$$

$$\rho_Q \equiv N_Q \frac{2.04}{4\pi R^3/3} = 3p$$

Figure 2.

Eight Gluons for the Universe
To set her gauge.
Six Quarks for Humankind
Search for the truth.
One Plasma with superstrength
One Plasma to bind them.
Through Dark Energy
One Plasma to quench them.
And from the Big Bang
One Plasma to shape them all.

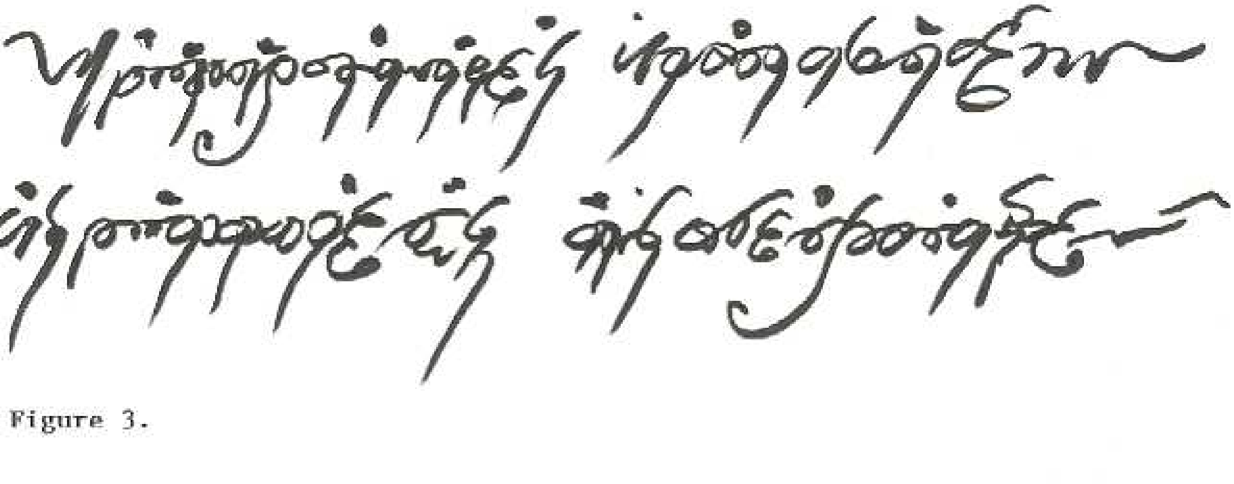


Figure 3.