

For PHYS 569 Emergent State of Matter
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Discovery of Quark Gluon Plasma at RHIC

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Abstract

Recent experimental results from Relativistic Heavy Ion Collider (RHIC) have shown the evidence of a new state of matter at high energy density. Physicists believe that the new state of matter is "Quark Gluon Plasma"(QGP) that they have been seeking for long time. This paper will survey both theoretical and experimental studies on QGP.

1. Introduction to Quark Gluon Plasma (QGP)

To explore the substructures of protons and neutrons, which along with electrons are the substructure of atoms, a number of precision measurements have been made since 1960s. Among those experiments, deep-inelastic electron scattering experiments at Stanford Linear Accelerator Collider has first shown in 1968 the existence of charged, point-like substructure inside protons and neutrons. These substructures are believed to be the quarks that theorists had proposed in the celebrated quark model [1].

The Quark Gluon Plasma was first proposed by Collins and Perry and others [2] in the 1970s. Their arguments are based on the principle of asymptotic freedom in quantum chromodynamics (QCD). This principle says that the QCD coupling constant falls with increasing momentum transfer q^2 [3]. At low energy density, the interaction is so strong that the observation of deconfined quarks are impossible while at high energy density, the strong coupling constant is small enough so that a new state of matter of deconfined quarks and gluons may be created.

QGP has drawn many interests from physicists for several reasons: First, QGP is predicted by QCD, so the observation of QGP will be an essential test for QCD; Second, QGP is less difficult for QCD calculations. Structure of nuclear matter at low energy density (the QCD “vacuum”, a result of spontaneously chiral symmetry breaking at low energy density) is complicated because of strong interaction between the hadronic particles. But at higher energy density, the structure will be relatively simple with weakly interacting quarks and gluons with restoration of chiral symmetry [4]. Third, QGP study has significant impact on cosmology research. QGP must have been created in the early universe, it plays an important role in hadronization process which resulted the formation of protons and neutrons.

On the theoretical side, numerical study of QCD has been proved to be very useful for QGP study which is in the non-perturbative domain. The way lattice QCD works is through the calculation of QCD partition function. Take grand canonical ensemble as an example: the partition function is given by

$$Z = \text{Tr}(e^{-\beta H}) \quad (1)$$

by calculating the differentials of $\ln Z$ with respect to different variables, we can compute the thermodynamic values. To obtain other expectation values, one can insert the operator into the partition function as

$$\langle O \rangle = \frac{\text{Tr}(Oe^{-\beta H})}{Z} \quad (2)$$

For lattice QCD, the basic idea are the same, but the computation is much more complicated. To calculate QCD partition function using equation (1), one need to first switch to the path integral representation, and plug in the QCD Lagrangian, then sum over quark fields $\psi(x, \tau)$ and gluon field $A(x, \tau)$ [3]:

$$Z = \int DA \prod_f D\psi_f D\bar{\psi}_f \exp\left(-\int_0^{1/T} d\tau \int L d^3x\right) \quad (3)$$

Here τ is the imaginary time, f denotes different flavors of quarks. By dividing space into discrete grids, the functional integral in equation (1) can be numerically computed. However, powerful computing technology is required because lattice QCD involves numerical evaluation of large matrices in the integral in (1). Lattice QCD has been producing useful results for QGP study mainly due to improvements in computer hardware.

Lattice QCD has predicted the transition temperature T_c for a nuclear matter to become QGP [5]. As shown in Fig.1, there is a rapid increase of the energy density ($e(T)$) at temperature range 160~190MeV. Note that the energy density suddenly increases by ~ 10 times through a narrow window near T_c . The QGP transition energy density is therefore at the order of $1\text{GeV}/\text{fm}^3$. Strictly speaking, the abrupt change in energy density is not necessarily a first order transition because at small baryochemical potential (μ_B) it is just a crossover and is a first order transition only at high baryochemical potential [6].

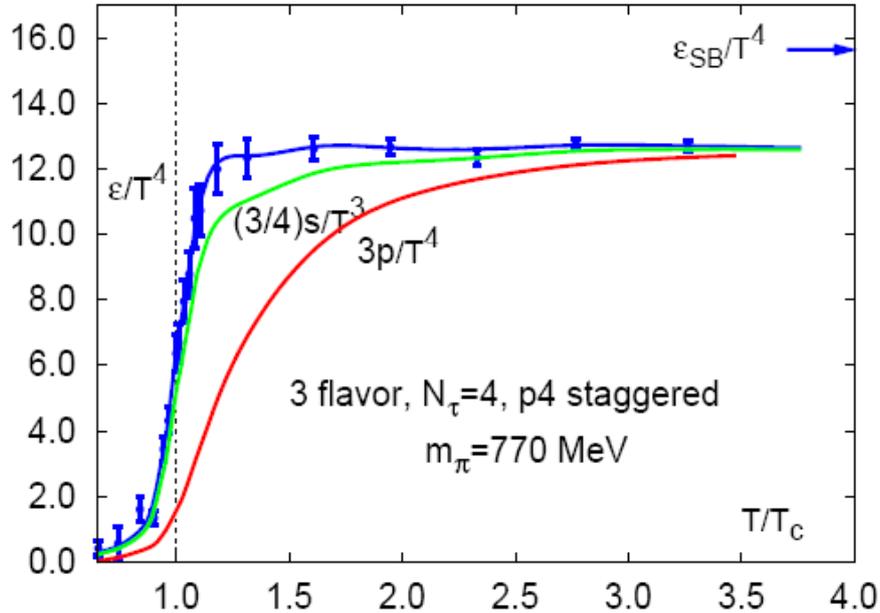


Fig. 1. Figure of $e(T)/T^4$, $P(T)/T^4$, $s(T)/T^3$ for 3 light flavors of quarks, calculated using lattice QCD. Taken from [8].

A summary of QCD phase diagram provided by lattice QCD is shown in Fig. 2. There can be a first order transition only if μ_B is above the critical endpoint. Critical endpoint on the phase boundary predicted by lattice QCD from Fodor is at $\mu_B \sim 400\text{MeV}$, $T \sim 160\text{MeV}$.

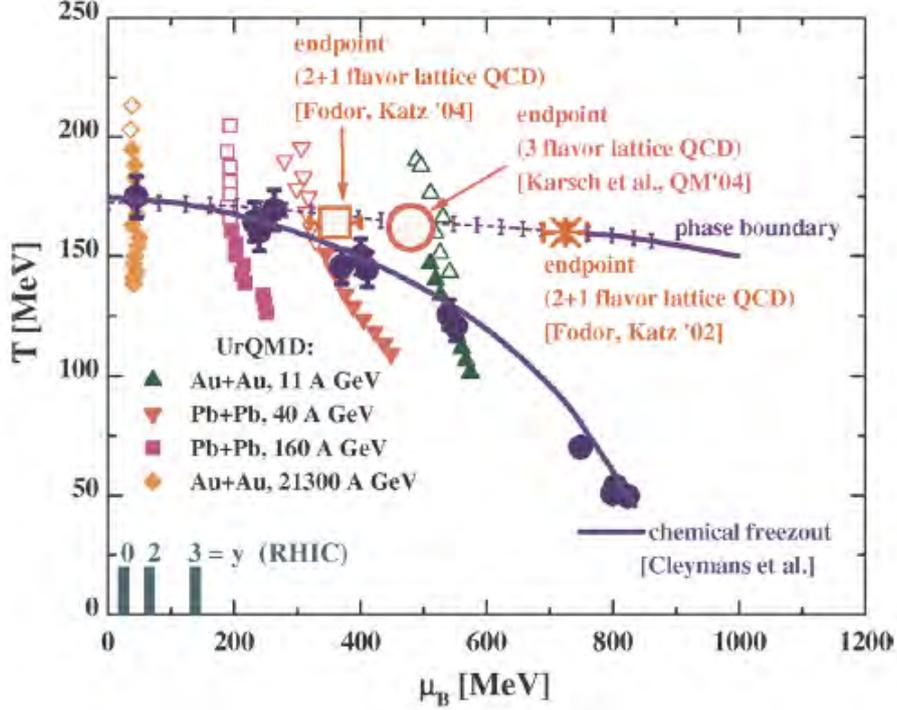


Fig. 2. QGP phase boundary and critical endpoint on the (μ_B, T) plane as predicted by lattice QCD (also contained some experimental data which we will discuss later.) Taken from [11].

The change in the energy density is the manifestation of a change in the number of degree of freedom of the system [3]. At high energy density, due to the principle of asymptotic freedom, a naïve model of an ideal gas of hadrons can be applied to the QGP to determine some of its static properties. The energy density of the ideal gas consisted of identical particle is given by:

$$\varepsilon = \int \frac{d^3 p}{(2\pi)^3} \frac{E}{e^{\beta E} \pm 1} \quad (4)$$

In (4) E is the energy of one particle; “ \pm ” indicates Bose or Fermi statistics respectively, however, at high temperature the “ ± 1 ” part can be neglected. So by evaluating the integral, we can obtain

$$\varepsilon \propto NT^4 \quad (5)$$

In which “ N ” is the degrees of freedom of number of particles. For high energy density state such as quark gluon plasma, it can be estimated as ~ 50 while for low energy density state such as a pion gas it is only 3 [7]. The difference in numbers of degrees of freedom is because at high energy density, degrees of freedom due to different colors (3 for quarks, 8 for gluons) will be released.

A more precise prediction of number of degrees of freedom comes from lattice QCD calculation. First, the effective number of thermodynamically active degrees of freedom is defined:

$$v(T) = \frac{s(T)}{s_{SB}(T)} \quad (6)$$

$s(T)$ is calculated entropy density, and $s_{SB}(T) = \frac{2\pi}{45}T^3$ [3]. The results for $s(T)$ from lattice QCD are shown in Fig. 1.

Since QCD provided us with the equation of state for QGP (energy density $e(T)$ and pressure $P(T)$), we can predict the speed of sound inside the QGP as shown in Fig. 2. Speed of sound is defined as:

$$c_s = \sqrt{\frac{\partial P}{\partial \varepsilon}} \quad (7)$$

For QGP, since near T_c there is a sudden change in energy density, speed of sound will be relatively small compare to speed of sound at higher energy density. Lattice QCD calculation results are shown in Fig. 3.

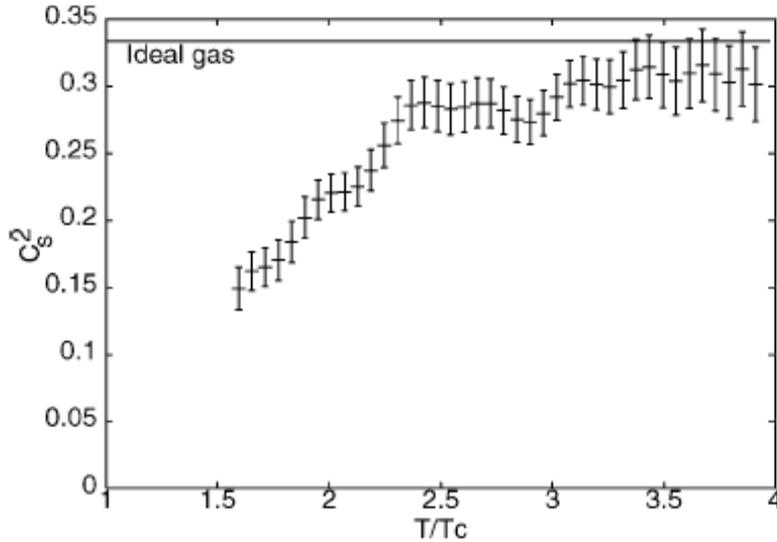


Fig. 3. Lattice QCD prediction Speed of sound as a function of T. Taken from [5]

2. Experimental observation of QGP at RHIC

To explore the quark gluon matter formed at high energy density, Relativistic Heavy Ion Collider (RHIC) was built at Brookhaven National Laboratory. RHIC accelerates two beams of gold nuclei, each of them has momentum of 100GeV per nucleon. The achieved energy density is estimated to be about $15\text{GeV}/\text{fm}^3$, which is much greater than $1\text{GeV}/\text{fm}^3$ as required for QGP formation from theoretical studies [9][10].

As planned, experiments at RHIC is proceeding through three stages: First, verify that in thermodynamic sense a new form of matter has been created at high energy density; Second, verify that the matter is not just a dense hadronic gas; Third, observation of its major physical properties[3]. By 2005, the first two steps has been completed and the third one is still in progress.

There are various signatures for QGP in the relativistic heavy ion collision experiment. Among them, the strongest arguments come from flow observables (elliptic flow) and hard observables (jet quenching), I will briefly cover the elliptic flow here.

The matter discovered at RHIC has demonstrated a collective behavior which is referred as a collective flow [3]. Since in heavy ion collision, we will first squeeze high energy into quark gluon matter, then there will be an outward pressure due to the strong interaction between quarks and gluons. This outward pressure is observed through non-central heavy ion collision experiments at RHIC.

For the non-central heavy-ion collision the overlapping area of two nuclei is not circular, i.e. anisotropic. This anisotropy is an increasing function of interaction between particles [3]. For a non-viscous ideal fluid, Euler equation gives the relation between velocity field and pressure:

$$\frac{d}{dt}(\epsilon\vec{v}) = -\nabla P \quad (5)$$

This equation tells us that the collective flow must be driven by a pressure gradient. The anisotropic pressure gradient can therefore drive an anisotropic flow.

Using hydrodynamic models, theorists have predicted the flow anisotropy. It can be written as:

$$\frac{dN}{d\phi} = \frac{v_0}{2\pi} + \frac{v_2}{\pi} \cos(2\phi) + \frac{v_4}{\pi} \cos(4\phi) + \dots \quad (8)$$

In (8), the v_0 , v_2 , v_4 are parameters characterizing the anisotropy. The second one, v_2 is the largest and is referred to as “elliptic flow” [3]. In the experiments, the azimuthal distribution ($dN/d\phi$) of the final state particles with respect to the reaction plane in each collision at different transverse momentum. Thereafter the data was fit with the function in (5) to obtain the characteristic parameter v_2 . In Fig. 4, the experimental results on v_2 are compared with theoretical results from the hydrodynamic model. The good agreement at momentum smaller than 1GeV/c for all species of particles between the data and hydrodynamic model implied that hydrodynamic model is relatively successful in interpreting the nature of quark gluon matter at high energy density [9]. This also confirmed that RHIC has reached the “softest point” near T_c where the speed of sound is at lowest level. The anisotropic flow pattern provided evidence that the resulting hadrons are created from the previously existent deconfined quarks and gluons, or QGP.

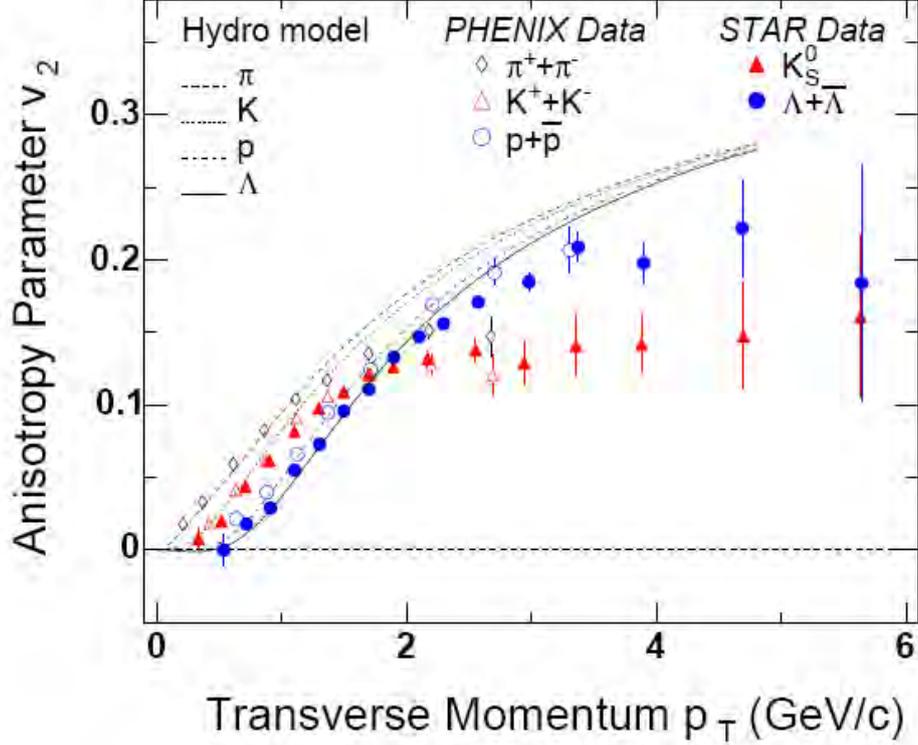


Fig. 4. Azimuthal anisotropy v_2 as a function of transverse momentum p_T , PHENIX and STAR data taken from gold-gold collision compared with hydrodynamic model prediction.

Picture taken from [11].

From the collective flow observation in QGP, we are able to study some of the dynamic properties of QGP such as shear viscosity η . In equation (5), theorists have assumed non-viscosity, in order to include the viscosity η one must add extra term on the right hand side of (5). Numerical solutions then showed that even a low viscosity will greatly influence the predicted v_2 which has a good agreement with experimental data when the model uses zero viscosity [12]. Viscosity in QGP is actually an indirect measurement of strength of interaction. In the normal plasma with weakly interacting particles, the interaction strength is defined as the ratio of potential energy to kinetic energy:

$$\Gamma = \frac{E_p}{E_k} \quad (9)$$

However, potential is not well-defined in QGP, the following ratio is related to coupling strength α :

$$\frac{\eta}{s} \sim \frac{1}{\alpha_s^2 \ln 1/\alpha_s} \quad (10)$$

in which s is the entropy density. Therefore, a small viscosity η indicates that the interaction must be very strong.

Along with other convincing experimental evidence and theoretical arguments, this reveals the striking fact that the matter observed at RHIC interacts with itself strongly and this is just the opposite as people predicted that QGP should be weakly interacting quarks and gluons. Therefore, it is better to call it “sQGP” to indicate the strong coupled quark gluon plasma.

Experimental observation at RHIC about sQGP left many questions for theorists.

First, sQGP is shown to be a strongly coupled system. It might be helpful to compare it with other coupled systems: ultra-cold atoms trapped in large scatter length regime and N=4 super-symmetric Yang-Mills theory so that theorists will have a better understanding of equation of state for QGP obtained by lattice QCD and hydrodynamic model [13].

Second, in spite of deconfinement above T_c , there might still be some bound states, as proposed by Shuryak in that lattice QCD results indicate that meson-like states consisted of charm and light quarks might be created [13]. A new phase diagram according to this idea is shown in Fig. 5.

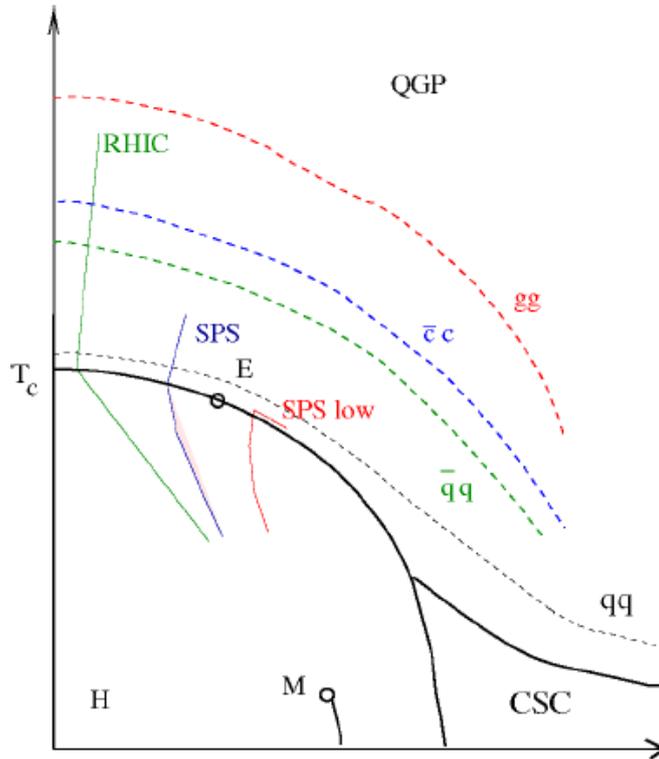


Fig. 5. Proposed new phase diagram on (μ_B, T) plane. Taken from [13].

Third, better understanding of the creation of QGP using hydrodynamic model requires full solution to the relativistic Euler equation. However, in the recent available numerical solutions, the viscosity is missing. The experiment has shown that viscosity is non-zero though very low. The full solution of hydrodynamics from a given equation of state will provide a upper limit of the viscosity [3].

Lastly, Lattice QCD has produced many useful results about the new state of matter at RHIC such as transition temperature, equation of motion, and crossover rather than first order phase transition at T_c . Nevertheless, lattice QCD is only a useful tool, and numerical results cannot replace the importance of physical pictures. So far there does not exist any self-consistent theory on the microscopic structure of QGP especially in the regime from T_c to $2T_c$.

3. Summary and Outlook

Experiments at RHIC for the first time showed us that the QCD vacuum can be excited as a result of the deconfined quarks at high energy density. Using flow observables and hard observables, experimentalists have discovered a strongly interacting matter (sQGP) rather than a weakly interacting matter as previously believed. This gave rise to many interesting topics such as dynamic properties of the matter, the microscopic structure of sQGP and so on. It would be a demanding task for both theorists and experimentalists to find out the nature of the new state of matter that has been created at RHIC.

Since the observables previously used in experiments at RHIC are very rare, the future luminosity upgrade of RHIC will enhance statistics in the measurements thereafter. In addition, Large Hadron Collider (LHC) at CERN will be operating its heavy ion programs soon at higher energy (5.5TeV per nucleon pair) [3]. Since the energy at LHC will be much higher than at RHIC, the coupling constant will be very small compared with unity. Thus, the originally proposed quark gluon plasma with weakly interacting particles might be created at LHC. But there is still no reason to rule out the possibility that a matter with weakly interacting particles which is the same as RHIC has created will be found. Whether the matter to be created at LHC is weakly interacting or strongly interacting will be an exciting discovery.

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