Crossover between hadronic and partonic phases and liquid property of sQGP †

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Abstract

It is argued that, due to the existence of two vacua – perturbative and physical – in QCD, how to realize crossover between hadronic and partonic phases without contradiction with color confinement is a challenge. In order to solve this problem the assumption on molecule-like aggregation of hadron is proposed. A bond-percolation model is constructed basing on this assumption. The mechanism of crossover is then the appearance and growth up of hadron-clusters, resulting in a grape-shape QGP – gQGP. The pair-correlation function of gQGP is calculated, showing a short range correlation typical for liquid.

The theory of strong interaction – quantum chromodynamics QCD has a complicated phase structure [1]. It has been shown that the first order phase transition line ends at the critical point, above it is analytic crossover [2], cf. Fig. 1. But what really happens in crossover and in first order phase transition is still open question.

Let us take some examples.

Example-1 First order phase transition in QCD. Consider a nucleon gas. At high temperature and/or density some nucleons combine to a big bag, refereed to as QGP droplet. There is thus a co-existence of QGP and hadron gas with a boundary in between, which is typical for a first order phase transition, cf. Fig.2(a).

Example-2 Analytical crossover in QED. The atoms in an atomic gas can be ionized one by one and eventually turned to E.M. plasma. In the intermediate stage there is a mixture of electrons, positive-ions and neutral atoms without phase boundary and phase separation, cf. Fig.2(b).

Example-3 Analytical crossover in QCD. At zero temperature and high chemical potential there could happen an crossover between Bose-Einstein condensation BEC, due to the formation of di-quarks, and BCS superconducting, due to the existence of Cooper pairs. In the intermediate stage there is a mixture of di-quarks and Cooper pairs, cf. Fig.2(c), both of them being colored objects, mixed in perturbative vacuum, causing no problem.

However, if similar mechanism were applied to the crossover between hadron gas and QGP there would be in the intermediate stage a mixture of colored quarks and color-singlet hadrons, cf. Fig.2(d), which contradicts color confinement and is, therefore, unallowed.

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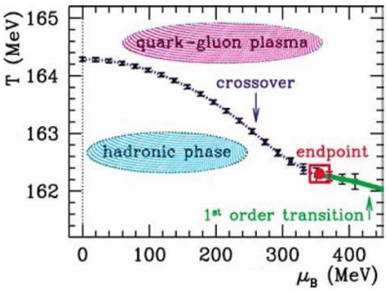

Fig. 1: (Color online) The phase diagram of QCD.

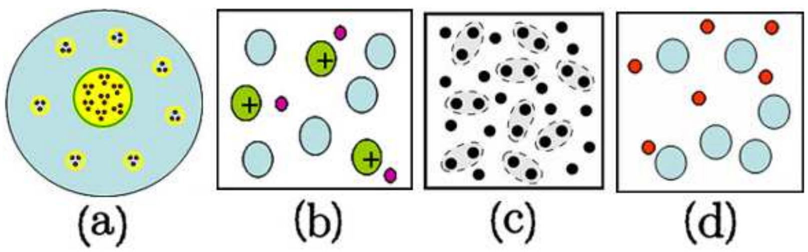

Fig. 2: (Color online) A comparison of the intermediate states in (a) first order phase transition between hadron gas and QGP in QCD and (b) crossover between neutral atomic gas and E.M. plasma in QED; (c) crossover between BEC and BCS superconductor in QCD; (d) a wrong mechanism for crossover between hadron gas and QGP in QCD.

How to solve this problem? Let us take still another example, i.e. the geometrical bond percolation model [3]. In this model hadrons connected by bonds form clusters, cf. Fig.3(a). When an infinite cluster, i.e. a cluster extending from one boundary to the other, cf. Fig.3(b), is formed, we say that the system turns to a new phase. Thus the crossover from one phase to the other is realized through the formation and growth up of clusters. No contradiction with color confinement anymore. But we have still to turn this geometrical model to a dynamical one, i.e. to provide the bond-formation with physical meaning.

In this respect we borrow the concept of delocalization from low energy nuclear physics [4] and propose the assumption on *molecule-like aggregation* [5] or MAM in short, i.e. in addition to the fusion of hadrons to QGP-droplet, cf. Fig.2(a), which is refereed to as *gas-like aggregation*, we assume that at high temperature the quarks in adjacent hadrons can tunnel through the potential barrier between the hadrons, cf. Fig.4, and bond the hadrons to cluster. Since color can flow through bonds, the hadrons in a cluster become colored objects, which will be referred to as *cells*, and only the cluster as a whole is color-singlet.

The average size of cluster increases as the increase of temperature. The appearance of infinite cluster marks the start of crossover, cf. Fig.3(b). The corresponding temperature is denoted by T_c. When all the hadrons are combined to a unique cluster, crossover ends, cf. Fig.3(c), and the corresponding temperature is T_c'.

In order to calculate the value of T_c and T_c' we need a dynamical model. An example is given in Ref. [5]. In this model there is a temperature dependent parameter. Using this parameter

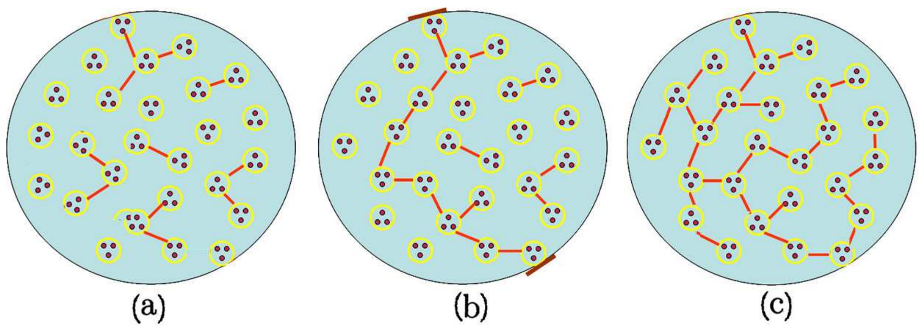

Fig. 3: (Color online) A schematic plot for the bond-percolation model. (a) Hadrons connected by bonds form clusters. (b) A cluster extending from one boundary to another is an infinite cluster. The appearance of infinite cluster is the start of crossover. (c) All the hadrons combined to a unique cluster is recognized as the end of crossover.

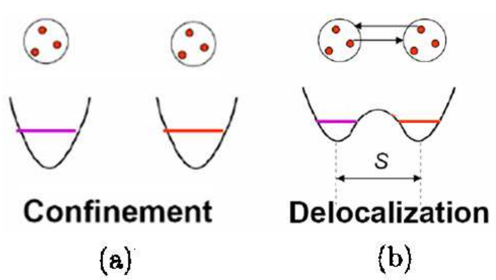

Fig. 4: (Color online) A schematic plot for confinement (a) and delocalization (b).

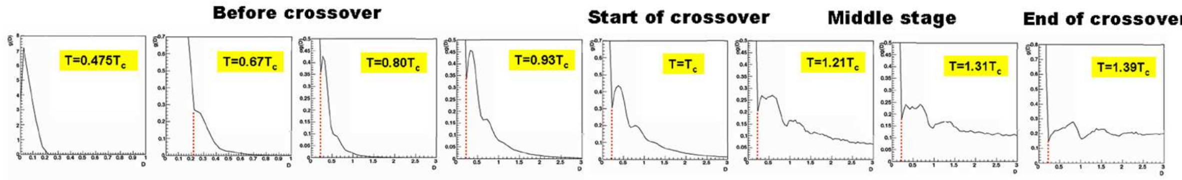

Fig. 5: (Color online) The evolution of $g(D)$. The head of the first highest peak in all the figures besides the leftmost one has been cut away.

the *maximum length of bond* $S(T)$ can be calculated. The quarks in two adjacent hadrons can tunnel through the potential barrier between hadrons, cf. Fig.4, forming bond when and only when the distance between these hadrons are nearer than $S(T)$. A bond-percolation model is constructed basing on the maximum bond-length $S(T)$ [5] and the crossover between hadron gas and QGP as well as the transition between sQGP and wQGP are successfully obtained.

In the molecule-like aggregation model MAM the QGP formed in crossover has a grape shape, cf. Fig.3(c), which will be refereed to as *grape-shape QGP*, or gQGP in short. The gQGP is a special form of strong-coupling QGP — sQGP. It is worthwhile noticing that the hot-dense matter produced in RHIC experiment is more like a perfect fluid rather than an ideal gas as previously expected. A question arises: does the gQGP posses liquid property?

To answer this question we make use of the *pair distribution function* defined as the probability of finding two atoms in the liquid at a distance r from each other [6],

$$g(r) = \frac{dN(r)}{2\pi\rho r dr}, \tag{1}$$

where $dN(r)$ is the number of atoms inside a ring with radius $(r, r + dr)$ apart from the selected center atom, ρ is the number density of the bulk homogeneous liquid. Applying to gQGP the distance between quarks in different cells should be measured along the bonds, which is refereed to as *chemical distance* and is denoted by D. So we define

$$g(D) = \sum_r \frac{dN(D,r)\cdot w}{2\pi\rho r dr}, \tag{2}$$

where w is a factor to correct for the boundary effect [7].

The resulting $g(D)$ at various temperatures are shown in Fig.5. The left 4 figures are before crossover, while the right 4 ones are during crossover. It can be seen that there is a high peak in all the figures, which is due to the intra-cell correlations among quarks. Long before crossover there is no correlation peak beside the first high one. Going nearer to crossover some shoulders appear, which develop to peaks, indicating short-range order typical for liquid at the start of crossover. This shows that the gQGP formed in crossover really possess liquid property. In the process of crossover, correlation peaks appears more and more and go farther and farther, indicating the reduction of viscosity in the process.

In summary, it is argued that how to realize crossover between hadron gas and QGP without contradiction with color confinement is a challenge. In order to solve this problem the assumption on molecule-like aggregation of hadron is proposed. A bond-percolation model is constructed basing on this assumption. The mechanism of crossover is then the appearance and growth up of hadron-clusters, resulting in a grape-shape QGP — gQGP. The pair-correlation function of gQGP is calculated, showing a short range correlation typical for liquid.

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