Magnetic Component of Quark-Gluon Plasma

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Abstract. We describe recent developments of the "magnetic scenario" of sQGP. We show that at $T = (0.8 - 1.3)T_c$ there is a dense plasma of monopoles, capable of supporting metastable flux tubes. Their existence allows to quantitatively explained the non-trivial $T$-dependence of the static $\bar{Q}Q$ potential energy calculated on the lattice. By molecular dynamics simulation we derived transport properties (shear viscosity and diffusion constant) and showed that the best liquid is given by most symmetric plasma, with 50%-50% of electric and magnetic charges. The results are close to those of the "perfect liquid" observed at RHIC.

1. The "magnetic scenario" for sQGP

Dirac famously showed in 1931 that quantum mechanics requires inverse relation between magnetic coupling constant for monopoles and electric coupling. 't Hooft and Polyakov found monopole solution in 1974, for non-Abelian gauge theories with adjoint scalars. The "dual superconductor" idea of confinement by 't Hooft and Mandelstam led to significant interest in QCD monopoles, especially on the lattice. Guided by Motone-Olive electric-magnetic duality, Seiberg and Witten have solved exactly the $\mathcal{N} = 2$ SUSY gauge theory in 1994, identifying properties and dynamical role of monopoles. Inspired by these, we have recently suggested in [1] that quark-gluon plasma in $T = (1 - 1.5)T_c$ region is a liquid dominated by magnetic monopoles. In this talk we present some results: others are contained in the final talk by Shuryak [2]. Different arguments for "magnetic liquid" were provided in [3].

In the past few years, quark-gluon plasma in $T = (1 - 2)T_c$ region has been found to be strongly coupled, thus sQGP. Among others, two major evidences include: (i) successful hydro descriptions of RHIC measurements on radial and elliptic flows suggest a "perfect liquid" behavior (see e.g. [2]) with low viscosity and small diffusion, which requires strong coupling among constituents; (ii) lattice results for the static $\bar{Q}Q$ potential[4] in this region showed very nontrivial $T$-dependence of the interaction absolutely beyond the perturbative expectation. Below we show how in the newly suggested magnetic scenario the monopoles explain the static potential and make the "perfect liquid"
2. Monopoles Explain the Static $\bar{Q}Q$ Potential at $T \approx T_c$

The static $\bar{Q}Q$ free energy $F(T, r)$ both below and above $T_c$ has been calculated via lattice gauge simulations[4]. Furthermore the potential energy $V(T, r)$ and entropy $TS(T, r)$ are also calculated via $V = F - TdF/dT = F + TS$. Linear dependence on $r$, mostly in $0.5 - 1 fm$ region, is seen in free energy up to $T_c$. Remarkably in potential energy $V(T, r)$, such linear dependence persists all the way to $1.3T_c$, with $V(T, r \to \infty)$ (and $TS$) reaching values as large as 4GeV at $T_c$! The $T$-dependence of the effective string tensions $\sigma_F(T)$ and $\sigma_V(T)$, defined as the slopes of linear parts in $F(T, r)$ and $V(T, r)$ respectively, are shown in Fig[II](a). While $\sigma_F$ vanishes at $T \to T_c$, $\sigma_V$ peaks there, exceeding the vacuum string tension $\sigma_{vac} \approx (426 MeV)^2$ by about factor 5! Two questions have to be answered: (i) why $\sigma_V$ survives to $1.3T_c$ despite deconfinement; (ii) what could be the origin of such large tension in the potential energy and entropy around $T_c$ while $\sigma_F$ ceases out. The electric objects are not relevant as they are confined below $T_c$ and very heavy (thus rare) just above $T_c$[5], so the answers must lie in the magnetic component.

The first question is answered in [6]: electric flux tube can be formed between the static $\bar{Q}Q$ not only in a magnetic dual superconductor (as is the case below $T_c$), but
also in a magnetic plasma provided the monopoles are dense enough yet not too hot. To see this, we analytically calculated the quantum mechanic scattering of single monopole with transverse momentum \( k \) in the electric field \( \vec{E} \) of an infinitely long flux tube with size \( R \) and also the magnetic currents \( \vec{J}_M \) from such scattering. Fig\,(b) shows the current contribution from different angular momentum channel labelled by quantum number \( \nu \). The dual Maxwell equation relating \( \vec{E} \) and \( \vec{J}_M \) requires the current to be negative and strong enough to self-consistently hold the flux while Fig\,(b) shows only scattering in \( \nu = 0, 1 \) channels are favorable and all higher partial waves are “bad” for flux tube. The plasma monopoles have typical \( \nu \sim k_T R \) thus to make flux tube we need the monopoles to be dense and have \( k_T \) as small as possible. We derived a quantitative condition for mechanical stability of the flux tube:

\[
\frac{g^2}{4\pi} \left( \frac{n}{T^3} \right) \geq 2.0 \left( \frac{k_T}{T} \right)^2 \frac{M}{T} \tag{1}
\]

The vanishing of \( \sigma_V \) at \( 1.3T_c \) can be attributed to the saturation of the above critical condition due to dropping monopole density and rising \( T \).

The second question is studied in [7]. First of all we identify slow/fast process (i.e. the process of separating \( \bar{Q}Q \) to a finite separation \( L \)) with free/potential energy respectively. Supercurrent of condensed monopoles which has no dissipation can not distinguish slow/fast process, while thermal monopoles have finite relaxation time and do feel the difference. At \( T \approx T_c \) the originally dense condensate dies out as signaled by vanishing \( \sigma_F \), however these monopoles become normal d.o.f and form a thermal ensemble with density \( n_M \). Suppose charges are separated very fast to \( L \): a transverse loop drawn in between will see significant time derivative of the electric flux through it. Dual Faraday relation require the circulation of magnetic field \( \int \vec{B} \vec{dl} \) equal to this change of flux, leading to a strong solenoidal magnetic current, as illustrated in Fig\,(c). Subsequently the normal currents by thermal monopoles damp out due to collision with the bulk thermal matter, exchanging energy and generating entropy till the equilibrium. In this way large amount of heat \( TS \) is generated which is associated with this pair of charges, dissipating potential energy \( V \) back to free energy \( F = V - TS \) which one finds for slow separation case. Based on this picture we developed an analytic flux bag model and were able to relate the effective tension \( \sigma_V \) to the monopole density

\[
\sqrt{\sigma_V(T)} = 3.88 \times \alpha_{E}^{1/6} \times n_M(T)^{1/3} \tag{2}
\]

The \( T \) dependence of the monopole density in \( 0.8 - 1.3T_c \) is shown in Fig\,(d): the results agree well with the recent lattice results starting at \( 1.3T_c \)[8]. We see monopole density increases as \( T \to T_c \) indicating they become light and dominant in plasma and presumably reach condensation point at \( T_c \), below which the density drops quickly as thermal monopoles turn into condensate. The density at \( T > T_c \) suggests rapid increase of magnetic screening toward \( T_c \), which is also consistent with lattice results [9].
3. Monopoles Make the “Perfect Liquid”

It is important to check the consistency of the “magnetic scenario” for sQGP with the empirical discoveries at RHIC: i.e. whether it can explain low viscosity and small diffusion constant. Molecular Dynamics (MD) simulations as powerful tools for studying correlation functions and transport properties in strongly coupled plasma have been used by us to explore (to our knowledge, for the first time) a novel plasma made of a mixture of both electric and magnetic charges[1]. We used standard Kubo formulae to calculate the shear viscosity $\eta$ and diffusion constant $D$ in three settings: a pure electric plasma (M00), a mixture with 25% monopoles(M25), and a 50%-50% mixture(M50). In Fig 2 we show the results $\eta$ and $D$ as functions of the key classical Coulomb plasma parameter $\Gamma \equiv <\text{potential}>/ <\text{kinetic}> \sim \alpha n^{1/3}/T$ for all three settings. We found that at all $\Gamma$’s, the most symmetric 50%-50% mixture of charges and monopoles has the smallest viscosity. The diffusion has a power law dependence on $\Gamma$, for M50 we have $D = 0.273/\Gamma^{0.626}$. With suitable mapping from MD units to physical units of sQGP, the M50 plasma is found to have viscosity and diffusion constant values very close to those exacted from RHIC experiments: see transport summary Fig. in [2]. We conclude that the proposed plasma with both electric and magnetic charges has the desired “perfect liquid” behavior. More recently based on our MD as well as lattice results, a study of monopole-anti-monopole equal-time correlator in [10] further concluded that magnetic component of quark-gluon plasma is also a liquid.

One may ask about the microscopic origin of such transport properties in electric/magnetic plasma. We suggest an explanation based on a “magnetic bottle” effect. (Invented by G.Budker in 1950’s and routinely used in confined plasma fusion experiments.) More specifically, in mixed plasma with electric/magnetic charges, we
found that each charge can be trapped for long time bouncing between surrounding *charges of the other kind*. The Lorentz force leads to curling of the trajectory with decreasing radius, forcing charges and monopoles collide more often than in the gases made of only one type of particles, thus explaining the “perfect liquid” (to be discussed elsewhere[11]).

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