Magnetic Scenario for the QCD Fluid at RHIC

J. Liao, E. Shuryak
Department of Physics & Astronomy, SUNY Stony Brook, NY 11794, USA

We present new developments of the “magnetic scenario”[1][2] for the QCD Fluid observed at RHIC. The recent lattice data for finite T monopoles are used to pin down the parameters of the magnetic component of quark-gluon plasma: in particular we show how the magnetic density and plasma coupling $\Gamma_M$ change with $T$. We then discuss one central issue imposed by the heavy ion data: i.e. the extremely short dissipation length in the QCD fluid around $T_c$. We show that the Lorentz trapping effect, present only in a plasma with both electric and magnetic charges and maximal for an equal 50%-50% mixture, is the microscopic mechanism leading to the nearly perfect fluidity.

1. E-M DUALITY FOR SQGP

In very brief term, E-M duality says that a D+1 dim. local field theory E with D dim. topological excitations M allows a direct description convenient at weak coupling $e < 1$ while has to switch to a DUAL description at strong coupling $e > 1$ in terms of a local effective field theory which has M as the fundamental degrees of freedom (D.o.F) and its coupling $g \sim \frac{1}{e} < 1$ (for example à là Dirac condition $\alpha_E \cdot \alpha_M = 1$): for excellent introductions see e.g. [3]. One good example is the dual superconductivity for color confinement: QCD vacuum is better considered as a condensate of monopoles while the perturbative D.o.Fs (i.e. quarks and gluons) get confined into hadrons [3].

The main message we’ve learned from the RHIC program for the last 8 years is that the quark-gluon plasma(QGP) created at RHIC (with the highest temperature reached about $2T_c$) is characterized by fast thermalization and extremely short dissipation length which means the QGP in 1-2$T_c$ is a very strongly coupled fluid (dubbed as sQGP). The conclusion is also strengthened by many lattice calculations. For recent reviews on sQGP, see e.g. [4].

Now combining the above two points, one is led to rethink about what is the most relevant D.o.F for describing the sQGP system. Indeed there are evidences showing that constituents of the electric component (quark and gluon quasiparticles) are rather heavy ($M/T > > 1$) already at 1.5$T_c$ and become less and less important down to $T_c$ and their composite bound states can survive up to about 2$T_c$ but are heavy too [5][6][7]. On the other hand, by borrowing lessons from Seiberg-Witten theory[8], we expect in the deconfined phase there should be a magnetic component in which monopoles become light, abundant and weakly coupled when getting very close to the confining point: in Seiberg-Witten the point is labelled by specific Higgs while here in QCD the point is $T_c$. The lightness, abundance and weak coupling should be such as to ensure the monopoles reach the condensation criteria right on $T_c$ and enforce confinement. This further leads to two important points: firstly such a dominant magnetic component in 1-1.5$T_c$ is necessary and natural for the dual superconductivity in QCD vacuum; secondly the weakness of magnetic coupling requires via Dirac condition that the electric coupling must be strong, explaining theoretically why we have a strongly coupled QGP in 1-2$T_c$. Furthermore there is the “struggle” for dominance between the electric and magnetic sector, fuelled by the opposite running of electric and magnetic coupling constants: thus there should be an equilibrium point at about 1.5$T_c$ where E/M couplings cross each other (both being 1) and the electric/magnetic components are comparable, while below/above it the magnetic/electric component wins.

Such a systematic “magnetic scenario” for sQGP was first proposed in [1]. The existence of a magnetic component of Yang-Mills plasma and its liquid nature in 1-2$T_c$ was pointed out in [1] and [2] from independent arguments and is confirmed in [9][10] by analysis of monopole-antimonopole correlation functions, a traditional and convincing observable for distinguishing gas/liquid/solid. The opposite running of E/M couplings was first demonstrated in [10] based on data from [8]. Lattice evidences for the conjectured equilibrium point around 1.5$T_c$ can be found in [11] where observables (e.g. screening mass, spatial string tension, $A^2$ condensate) are shown to have their E/M dual parts cross around that region. More recently it has been shown [12] that the angular dependence of jet quenching indicates its strong enhancement near $T_c$ which can be naturally explained only by the “magnetic scenario”.

arXiv:0809.2419v3 [hep-ph] 22 May 2009.
2. PIN DOWN THE PARAMETERS OF THE MAGNETIC COMPONENT

To understand the properties of sQGP, it is crucial to know the parameters of its magnetic component, i.e. the monopole density, magnetic coupling, monopole mass, etc. To that end, lattice gauge theory is a unique and reliable approach. The excellent lattice results reported in [9] provided important information on monopoles’ density $n_M(T)$ and their spatial correlation in a wide region $1.3-4T_c$. Analysis in [10] extracted the magnetic coupling $\alpha_M(T)$ and the plasma coupling $\Gamma_M \equiv \alpha_M(4\pi n_M/3)^{1/3}/T$ of the magnetic component: $\Gamma$ is also a well-known observable that can distinguish a gas ($\Gamma < 1$), liquid ($\Gamma \sim 1-10$), glassy matter ($\Gamma \sim 10-100$) and solid ($\Gamma > 100$). Another development concerns the strong linear rise observed in the lattice calculated static $\bar{Q}Q$ potential energy: the linear part persists and splits from the free energy linear part (which ceases out when heated to $T_c$) in $0.8-1.3T_c$ and its slope, defined as an effective tension $\sigma_V$, peaks at $T_c$ with a value 5 times the vacuum string tension. This was interpreted in [13] as formation of electric flux tube in a magnetic plasma in that T-regime due to the presence of dense thermal monopoles. Based on a model calculation the plasma monopole density is related to $\sigma_V$ and from lattice data for $\sigma_V$ one can infer the monopole density in $0.8-1.3T_c$. Some results are summarized in Fig.1 and below:

- **Density** [Fig.1(a)] — $n_M/T^3$ decrease at higher $T$ while soars close to $T_c$, as expected. It is a very densely packed liquid 1-2$T_c$ and especially below 1.5$T_c$, much denser than the relativistic massless ideal boson gas limit $n/T^3 = 0.1218$ (this was the original argument in [2] for a liquid while we showed in [1] the transport properties is in liquid regime). As comparison the quarks/gluons get denser and denser to high $T$ end.

- **Correlation** — monopole-antimonopole correlations obtained from both lattice calculation[9] and our MD simulation[10] show similar shape and peak magnitude that are typical for a liquid, thus providing convincing proof of the liquid nature. In particular the lattice data showed the correlation grows stronger at higher $T$. Such liquid correlation was also found in recent lattice study[14] where no Abelian projection was involved.

- **Magnetic coupling** — the extracted magnetic Coulomb coupling as a function of $T$ indeed runs in the direction opposite to the electric one, again as expected, and at high $T$ end it is roughly inverse of the asymptotic freedom formula for the electric one (see [10] for details).

- **Plasma coupling** [Fig.1(b)] — down toward $T_c$, $\Gamma_M$ decreases but remains $> 1$ i.e. in the good liquid regime with low viscosity which nicely agrees with empirical evidences from RHIC experiments. Going to higher $T$ $\Gamma_M$ increases and shows tendency to saturate at a limiting $\Gamma_M^*$ as we expect from the magnetic scaling valid at very high $T$ together with the Dirac condition, i.e. $n_M^* \sim (\alpha_E T)^3$ thus $\Gamma_M^* \sim \alpha_M \cdot (n_M^*)^{1/3}/T \rightarrow$ constant $\sim 5$. 

Figure 1: (a) Monopole density (on Log scale): the diamonds with dashed curve are lattice data [9], and the boxes with solid curve are from model calculation [13]; (b) Magnetic plasma coupling $\Gamma_M$, the grey band indicates $\Gamma_M^*$ at high $T$ limit.
3. LORENTZ TRAPPING EFFECT MAKES THE “PERFECT LIQUID”

In [1] we found that a mixture plasma of both electric and magnetic charges has the smallest viscosity and diffusion (the shortest mean free path, if one wants to use such language) at the E/M density ratio 50%-50% (i.e. maximal mixing), with the values close to the empirical numbers extracted from RHIC data. So, what will be the microscopic origin of such behavior? Due to the E/M ratio dependence, we suggest the Lorentz force between the two types of particles is the mechanism at work in similar way to the “magnetic bottle” effect originally invented by G. Budker in 1950’s for confining hot plasma. In [1] we already showed that in the static electric dipole field a nearby monopole is “focused” by the Lorentz force to collide head-on with the standing charges and bounce back and forth.

We here use a “Gedanken experiment” to elucidate such effect as the microscopic origin of the nearly perfect fluidity. We consider a monopole at the center of a “grain of salt” which has eight static electric charges (with alternating signs) at the corners, and then we “kick” it off with random initial velocity, see Fig. 2(upper left). This can be repeated many times, and what we want to learn include: 1) what the trajectory (as determined by classical equation of motion) will look like; 2) how long it will typically take for the monopole to escape the cube.

Opposite to naive expectation, it turns out most of the trajectories are highly complicated: an example is shown in Fig. 2(upper right). The multiple-folded trajectory shows nontrivial features: apparently the monopole experiences many collisions before finally finding the “door” out; the collisions are strong as can be seen from several complete bouncing back and from its many highly curled parts; also there are a few clearly visible Poincare-cone like structures near the corners (where the electric charges are). From this we see that the monopole, rather than encountering the electric charges at corners by chance, is focused to rotate on the Poincare-cone all the way to the charge and then bounced back, only to be focused toward another corner for the next collision. Such phenomenon is absent if we replace the monopole with an electric charge. The Lorentz force here provides a unique way of enhancing the collision rate and trapping the monopole for long time (not permanent though): thus we may call it a Lorentz trapping effect.
To quantify the effect we choose different values of initial velocity magnitude $v_0$, and for each $v_0$ we repeat the experiment with random initial directions for $10^5$ times and register for each trial the total trajectory length $L_{Esc.}$ before the monopole escapes the cube. The resulting histograms for $L_{Esc.}/(2a)$ (with $2a$ the cube side length) are shown in Fig.2(lower left) for $v_0 = 0.1$(blue diamonds),0.3(red boxes),0.5(black circles) respectively. The plots show that $L_{Esc.}/(2a)$, an estimate of collision numbers, are often much larger than 1. The plots also show that with smaller $v_0$, $L_{Esc.}$ becomes much flatter, i.e. with more probability to be trapped for longer time, because monopole with smaller velocity is more easily curled with smaller Larmor circle to collide with the charges. For comparison we did the same experiment for an electric charge replacing the monopole and found it always exits immediately and never gets bounced back, see the three indistinguishable curves (yellow, green and magenta) very close to the left axis. This study demonstrates that Lorentz force does provide an efficient mechanism that significantly enhances collision rates and traps particles locally for a time scale longer than microscopic motion time scale, i.e. $\tau_{Esc.} \equiv L_{Esc.}/v_0 \gg 2a/v_0$.

We can define an effective collision number for the monopole with each given $v_0$ by averaging out the histogram for $L_{Esc.}$: $C(v_0) \equiv \langle L_{Esc.}(v_0)/(2a) \rangle$. If we “pretend” the monopole is taken as a representative of a plasma with $\Gamma = PE/KE$, then $v_0 \propto KE^{1/2} \propto 1/\Gamma^{1/2}$. Thus we obtain a plot showing how $C$ changes with $\Gamma$, see Fig.2(lower right). It shows a linear relation in the Log-Log plot, which is nicely fitted by $C \propto \Gamma^{-0.47}$. The monopole mean free path is then $L_{MFP} \propto 1/C \propto 1/\Gamma^{0.47}$. One may image that there is a whole crystal with periodically repeating electric cube and the monopole is jumping from the original cube to the neighboring cubes and eventually diffuses away. A hand-waving argument leads to the diffusion constant for such a monopole: $D \propto L_{MFP} \propto 1/\Gamma^{0.47}$ which is close to the power law obtained both from our MD $(1/\Gamma^{0.63} [1])$ and from the AdS/CFT calculation $(1/\lambda^{0.5} [12])$.

Finally consider a dynamical mixture plasma with each charge surrounded by the charges of the other type, so the Lorentz trapping effect both types of charges are spatially interlocked for much longer time than microscopic motion and diffuse away only after even longer time. This may be the underlying picture of the QCD fluid near $T_c$.

**Acknowledgments**

This work was supported in part by the US-DOE grant DE-FG-88ER40388. JL thanks the hospitality of the Institute for Nuclear Theory and the organizers of the QCD Critical Point Workshop during which part of this write-up was done. He is also grateful to M. Baker for interesting discussion.

**References**

[1] J. Liao and E. Shuryak, Phys. Rev. C **75**, 054907 (2007) [arXiv:hep-ph/0611131].
[2] M. N. Chernodub and V. I. Zakharov, Phys. Rev. Lett. **98**, 082002 (2007) [arXiv:hep-ph/061228].
[3] A. Di Giacomo, [arXiv:hep-lat/0610102]. J. A. Harvey, [arXiv:hep-th/9603086].
[4] E. Shuryak, [arXiv:0804.1373 [hep-ph]; arXiv:0807.3033 [hep-ph]].
[5] P. Petreczky, F. Karsch, E. Laermann, S. Stickan and I. Wetzorke, Nucl. Phys. Proc. Suppl. **106**, 513 (2002).
[6] E. V. Shuryak and I. Zahed, Phys. Rev. C **70**, 021901 (2004); Phys. Rev. D **70**, 054507 (2004).
[7] J. Liao and E. V. Shuryak, Phys. Rev. D **73**, 014509 (2006); Nucl. Phys. A **775**, 224 (2006).
[8] N. Seiberg and E. Witten, Nucl. Phys. B **426**, 19 (1994) [Erratum-ibid. B **430**, 485 (1994)].
[9] A. D’Alessandro and M. D’Elia, [arXiv:0711.1266 [hep-lat]].
[10] J. Liao and E. Shuryak, Phys. Rev. Lett. **101**, 162302 (2008) [arXiv:0804.0255 [hep-ph]].
[11] A. Nakamura, T. Saito and S. Sakai, Phys. Rev. D **69**, 014506 (2004); M. Baker, Phys. Rev. D **78**, 014009 (2008); M. N. Chernodub and E. M. Ilgenfritz, [arXiv:0805.3714 [hep-lat]].
[12] J. Liao and E. Shuryak, Phys. Rev. Lett. **102**, 202302 (2009) [arXiv:0810.4116 [nucl-th]].
[13] J. Liao and E. Shuryak, [arXiv:0804.4890 [hep-ph]]; Phys. Rev. C **77**, 064905 (2008) [arXiv:0706.4465 [hep-ph]].
[14] H. B. Meyer, [arXiv:0808.1950 [hep-lat]].
[15] J. Casalderrey-Solana and D. Teaney, Phys. Rev. D **74**, 085012 (2006).