

The letter “s” (and the sQGP)

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Abstract. Data from the Relativistic Heavy Ion Collider over the last five years have led many to conclude that the medium created is not the expected quark–gluon plasma (QGP), but rather a strongly coupled or strongly interacting quark–gluon plasma (sQGP). We explore the meaning of this possible paradigm shift and the experimental and theoretical arguments that are associated with it. In this proceedings we detail only a small subset of the relevant issues as discussed at the Hot Quarks 2006 Workshop.

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1 Introduction

The goal of this presentation at the Hot Quarks 2006 Workshop was to attempt to develop a consistent understanding of the term “sQGP” and the physics conclusions that result. The first step in achieving such a goal is to detail what the letter “s” actually stands for and what it means. Does the terminology change from quark–gluon plasma (QGP) to sQGP alphabetically symbolize an important paradigm shift in the understanding of high temperature nuclear matter?

First, we detail what various people and collaborations have stated that “sQGP” means. Gyulassy explained: “The name ‘sQGP’ (for strongly interacting quark–gluon plasma) helps to distinguish that matter from ordinary hadronic resonance matter (as described for example by RQMD) and also from the original 1975 asymptotically free QGP (which I dubbed wQGP) that is now theoretically defined in terms of re-summed thermal QCD [1].” Gyulassy and McLerran [2] have argued “Our criteria for the discovery of QGP are (1) matter at energy densities so large that simple degrees of freedom are quarks and gluons. This energy density is that predicted from lattice gauge theory for the existence of a QGP in thermal systems, and is about $2 \text{ GeV}/\text{fm}^3$, (2) the matter must be to a good approximation thermalized, (3) the properties of the matter associated with the matter while it is hot and dense must follow QCD computations based on hydrodynamics, lattice gauge theory results, and perturbative QCD for hard processes such as jets. All of the above are satisfied from the published data at RHIC . . . This leads us to conclude that the matter produced at RHIC is a strongly coupled QGP (sQGP) contrary to original expectations that were based on weakly coupled plasma estimates.”

Although the estimates of the energy density at early times ($t = 1 \text{ fm}/c$) utilizing various methods disagree by more than a factor of two [3], all values are significantly above that predicted for the QGP phase transition for the first few fm/c . For example, the value from the Bjorken energy density equation is up to a factor of four lower than from hydrodynamic calculations, but the Bjorken value is often viewed as a lower limit, since it ignores any effects from longitudinal work. Thus, the first criterion seems to be met. Agreement of hydrodynamic calculations and experimental data on transverse momentum spectra and in particular elliptic flow v_2 (see Fig. 1 [3, 4]) indicates very

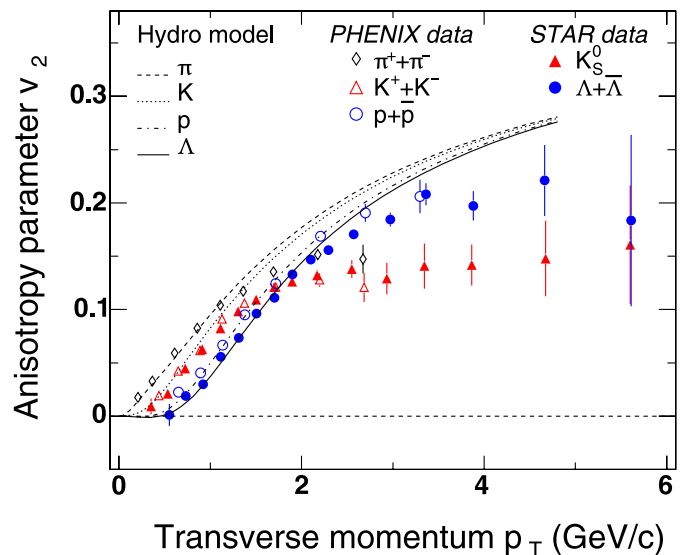


Fig. 1. Azimuthal anisotropy (v_2) as a function of p_T from minimum bias gold–gold collisions. Hydrodynamic calculations are shown as *dashed lines*

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rapid equilibration times of order $t \approx 1 \text{ fm}/c$ [5]. There have been questions raised about the required degree of thermalization [6]; and, the originally stated agreement of hydrodynamics with the lattice equation of state (EOS) appears to be overstated so that no quantitative constraint on latent heat or softness is yet warranted [3, 7]. However, it does appear that equilibration is approached more substantially than one might have expected from perturbative calculations (see later discussion on this point). Thus the first two criteria listed in [2] appear satisfied and might allow one to scientifically conclude that RHIC collisions have created the QGP. However, it is the critical third point that defines the experimental discovery of such.

2 Strongly interacting versus strongly coupled

In the literature there is a mixture of terminology of strongly interacting and strongly coupled. If it is strongly coupled, which coupling is being referred to? In many talks and publications, the “strongly coupled” refers to the plasma coupling parameter Γ (often used in the case of electromagnetic EM plasmas).

2.1 Plasma coupling Γ

This coupling is defined as $\Gamma = \langle \text{PE} \rangle / \langle \text{KE} \rangle$, where PE is the average potential energy and KE is the average kinetic energy. This parameter is used as a measure of the interaction strength in EM plasmas. Most EM plasmas that people are familiar with are weakly coupled plasmas where $\Gamma \ll 1$. These behave like gases. However, for $\Gamma \gg 1$ the EM plasmas are strongly coupled and behave as low viscosity liquids and as solids at even larger Γ , as shown in Fig. 2 [8].

Since EM plasmas have been widely studied, it is natural to seek to categorize the quark–gluon plasma (QGP) in a similar fashion. Recently at RHIC, there has been a significant number of publications on the QGP as a “near-perfect liquid.” Thus a question from someone outside the field of heavy ions is whether the matter is in the plasma phase or liquid phase (often thought to be different regimes in the EM matter case). One must be careful about two different definitions of liquid being used here. Liquid can refer to a specific phase of electromagnetic matter, and, secondly, liquid refers to any matter whose dynamic evolution can be described by hydrodynamic equations of motion. An EM plasma in the strong coupling case (large Γ regime) is a plasma in that the electric charges are not confined to atoms but having the liquid-like property (second definition) of low viscosity. At RHIC, the matter produced shows some evidence of low viscosity (though not quantitative yet in terms of an upper limit on the shear viscosity). Thus, it may be a liquid (by the second definition), but may not share other EM liquid phase properties (first definition). For example, many electromagnetic liquids are also highly incompressible. For the QGP, at baryon chemical potential $\mu_B = 0$ the pressure (P) and volume (V) are in-

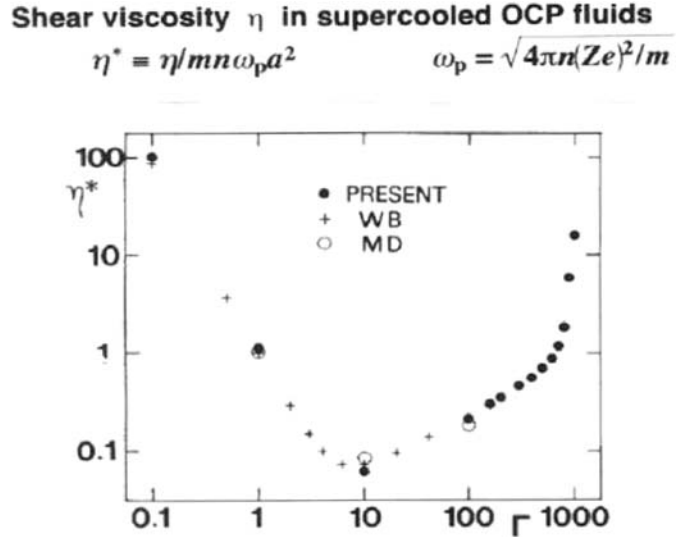


Fig. 2. Plotted is the scaled shear viscosity ($\eta^* = \eta/mn\omega_p a^2$) as a function of Γ for supercooled OCP fluids

dependent. Again, the matter shares a property, but not all.

These analogies are often useful, but only if they lead to new insights rather than just to new declarations and new terminology. One has to be careful to define which properties are analogous. For example, QCD always has screening of long range color magnetic fields, which means that even a weakly interacting (asymptotically free) QGP will be quite different from a weakly coupled EM plasma. Also, on short distance scales, color electric and magnetic fields can be of equal order.

Some in the field have argued the following logic: since the matter produced at RHIC has a large Γ value, it must be a plasma (as a phase). This leads to the very strong conclusion that the matter at RHIC is a plasma (meaning a deconfined plasma of quarks and gluons). However, though EM plasmas are categorized in terms of Γ , not all large Γ (i.e. low viscosity) matter is a plasma at all. As an example, there have been recent experiments with lithium atoms where the mean free paths approach zero under certain conditions [9]. The Feshbach resonance in binary collisions of these alkali atoms at ultra-cold temperatures allow experimentalists to tune the interaction strength. The measurements reveal low viscosity and “flow” reminiscent of that seen in RHIC collisions. However, these atoms are clearly not an EM plasma. Thus, at RHIC, demonstrating low viscosity does not prove that the matter is a plasma.

One can push the plasma analogy further and attempt to estimate the value of the Γ parameter for the QGP and then attempt to infer other properties of the medium. One such estimate [10, 11] yields

$$\Gamma = \frac{\langle \text{PE} \rangle}{\langle \text{KE} \rangle} \approx \frac{\alpha_s/r}{3T} \approx \frac{\alpha_s T}{3T} \approx \alpha_s; \quad (1)$$

then utilizing the relation $\alpha_s = g^2(T)/4\pi$ and putting back in d the characteristic inter-particle distance, one obtains

$$\Gamma = \frac{Cg^2}{4\pi dT} \approx 1.5-5. \quad (2)$$

Note that this result is different from an earlier much larger estimate which had a factor of 4π unit error and was without a factor of two scale-up for the approximately equal strength color magnetic interaction [10, 11]. Thoma notes that for EM plasmas “the phase transition to the gas phase, assumed to happen at $\Gamma_c \approx 1$, takes place now at a few times the transition temperature from the QGP liquid to the QGP gas [10, 11].” Note the title of this article is “The quark–gluon plasma liquid.” In the PHENIX whitepaper it states that “considerations such as these have led some to denote QGP in this regime as ‘sQGP’ for strongly interacting QGP [3].”

In a recent set of papers [12, 13], the authors invoke a model referred to as cQGP where they calculate the shear viscosity as a function of the dimensionless Γ parameter. The calculation seems to show a QGP with liquid-like behavior (low viscosity) at large Γ and an indication of solid behavior at even larger Γ , as was seen in the EM plasma case. There has been speculation that the QGP formed in heavy ion collisions could have crystalline or polymer chain type solid structures [14]. However, it is critical to note that the letter ‘c’ stands for classical. Thus, the entire calculation is done in the non-relativistic, non-quantum regime and thus the possible insights gained have to be viewed with skepticism.

The entire utilization of Γ raises some significant questions. The potential energy is taken as the Coulomb (short range) part of the QCD potential as α_s/r . Unfortunately, if one has a system of (nearly) massless, relativistic particles, then the potential energy is not a well defined concept in a relativistic quantum field theory (QFT). This issue applies to a QFT for QED or QCD, but is of particular concern for the QGP case here, since anywhere near the transition temperature the light quarks are relativistic. The fundamental problem is that there is no unique distinction between the particles and the fields and thus no unique manner of separating potential energy and kinetic energy. In which category do the gluons belong for example? In the case of heavy quarks, one might approximate them as static source charges and thus have made a reasonable attempt to separate the potential energy. However, this is not the case for the QGP overall, and the assumption of a non-relativistic limit in the cQGP case discussion above is not close to the real case for the QGP even near the critical temperature $T = 170$ MeV. There are attempts to formulate an alternative for calculating Γ [15].

Many people are interested in the Γ calculation, since it is about how many EM plasmas are categorized. However, other perfectly well defined measures of the interaction strength in hydrodynamics and in a QFT do exist that can alternatively be used.

2.2 Shear viscosity over entropy density η/s

There is a well defined measure of the interaction strength. It is the ratio of the shear viscosity (a measure of the

mean free path of particles) and its entropy density (measure of the inter-particle distances). It is in fact this ratio, η/s , that may be very small in the QGP as inferred from hydrodynamic calculations and their comparison to experimental data. Recent measurements of charm quark suppression at moderate $p_T \approx 2-5$ GeV/ c and non-zero elliptic flow v_2 , may give the best constraint on the diffusion coefficient from heavy quarks and subsequently η/s [20, 21]. Full three-dimensional viscous hydrodynamic calculations in comparison with precision data are needed to set a quantitatively reliable limit on η/s . Lattice simulations are presently unable to make reliable predictions of most dynamical properties of the quark–gluon plasma. The calculation of phenomenologically relevant transport properties, such as the shear viscosity or collective modes, remains an important challenge [16].

However, recently there has been important progress in calculating these dynamical properties perturbatively in a dual quantum field theory involving black holes in anti-de Sitter (AdS) space [17]. This approach is based on the insight derived from string theory that weakly coupled gravity theories in higher dimensions can be dual to four-dimensional gauge theories in the strong coupling limit [18, 19]. It must be emphasized that these AdS/CFT (conformal field theory) techniques presently have the limitation that no higher-dimensional gravity or string theory is known which is dual to QCD. Work by Son et al. indicates that there may be a lower viscosity bound $\eta/s > 1/4\pi$ applicable for all systems including the quark–gluon plasma. A critical goal for the field is to put the QCD matter data point on a plot like the one shown in Fig. 3 for other systems [17].

An interesting side note is that in the figure these systems have a minimum in the ratio η/s . In fact, for helium, superfluidity sets in at approximately 2 K, which is below the minimum. The minimum occurs around 4 K which is the gas to liquid phase transition point. Thus the mini-

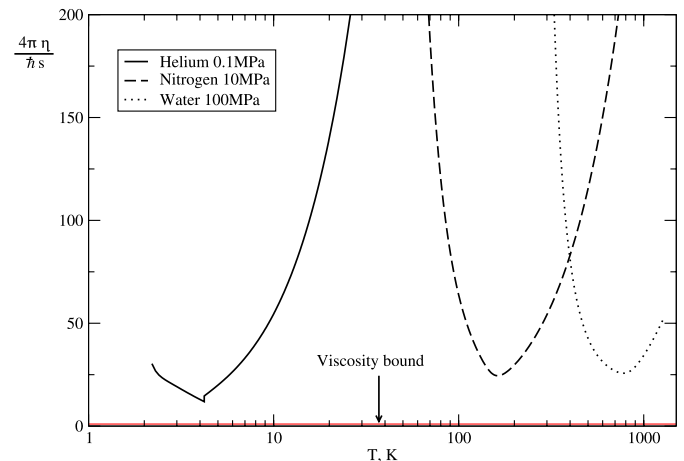


Fig. 3. Plotted are the shear viscosity to entropy density ratios (η/s) divided by the conjectured lower bound as a function of temperature in kelvin. Shown are curves for helium, nitrogen and water

mum is not a minimum in viscosity, but rather the sudden change in entropy associated with the phase transition. Note the recent paper on the subject of [24].

The most common example of a very low viscosity (or near-perfect) fluid are the cases shown in Fig. 3 which are referred to as superfluids. In most cases this superfluidity comes about from quantum mechanical effects dealing with the limited excitations at low temperature. This seems quite different from the system at RHIC, and thus, though there are many examples in the literature describing the matter at RHIC as a near-perfect fluid, it is not termed a superfluid.

2.3 Strong coupling α_s

Another interpretation of the letter “s” is strongly coupled in the sense of a large QCD coupling α_s . Clearly α_s is always, in any experimentally accessible energy range, much greater than $\alpha_{EM} = 1/137$. The wQGP, where the letter “w” stands for weak coupling, implies that perturbative expansions should converge as $\alpha_s \ll 1$. By contrast, sQGP would simply imply that perturbative techniques would not be applicable. Heinz observed that “perturbative mechanisms seem unable to explain the phenomenologically required very short thermalization time scale, pointing to strong non-perturbative dynamics in the QGP even at or above $2 \times T_c$.” [27].

Specifically, analytic calculations utilizing perturbative expansions of gluon scattering lead to long equilibration times (> 2.6 fm/c) and thus rather modest elliptic flow (i.e. small v_2) [28]. There are also numerical simulations that give similar results utilizing a $2 \rightarrow 2$ cross section of approximately 3 mb, as shown in Fig. 4 [29,

30]. One can artificially increase the cross section (or transport opacity) to match the data and it requires an order of magnitude increase in the cross section. In this sense, it is not a wQGP. There are two important caveats on these calculations. One is that the equation of state is too hard relative to lattice results for the QGP. More importantly is that there is some controversy over the inclusion of $2 \rightarrow 3$ and $3 \rightarrow 2$ processes. Greiner and Xu [31, 32] claim that their inclusion results in a dramatic decrease in the equilibration time and thus a large increase in v_2 . At this conference it became clear that the critical part of their result is that in the $2 \rightarrow 3$ case the resulting gluons are emitted isotropically. Under this assumption it is easy to see why it leads to rapid isotropization. Other implementations of these processes show much smaller effects, in large part due to forward peaking of the emission distribution. This issue needs to be resolved.

In the third category used by Gyulassy and McLerran for discovery of the QGP, they cite utilizing perturbative methods to understand jet probes. Radiative energy loss calculations are done perturbatively to describe the jet quenching phenomena. In fact, the calculations are effectively leading order. GLV [25], for example, assume the correct pQCD interaction strength (noting that some calculations use a fixed coupling α_s and others running), and then determine the color charge density. One obtains a result of $dN/dy(\text{gluons}) = 1000$ or $dN/dy(\text{quarks, gluons}) = 2000$. The final entropy density dS/dy is of order 5000, and thus since the entropy cannot be larger at earlier times it translates roughly into a limit $dN/dy(\text{quarks, gluons}) < 1300$ [26]. One possibility is that more than just radiative energy loss contributes as has been highlighted by recent heavy quark results (perhaps indicating collisional energy loss). However, another approach is to say: you know the color charge density and can then infer the coupling strength. This then implies that the coupling strength is much larger than predicted from the effectively leading order perturbative calculation – which may be consistent with the sQGP description.

2.4 Bound states

This strong coupling α_s is taken by Shuryak and collaborators [22] to imply that the interaction between quasi-particles is strong enough to bind them. Thus the sQGP is composed of bound (not necessarily color neutral) qq , $q\bar{q}$, gg , qg , etc. states. However, recent lattice calculations for baryon number–electric charge correlations show no such quasi-particles with these quantum numbers [23]. It appears that lattice QCD is ruling out qq and $q\bar{q}$ states, though the results can say nothing about states without these quantum numbers, like qg and gg states.

2.5 Expectations

A reasonable question is why there was an original expectation for a wQGP or perturbative plasma. “For

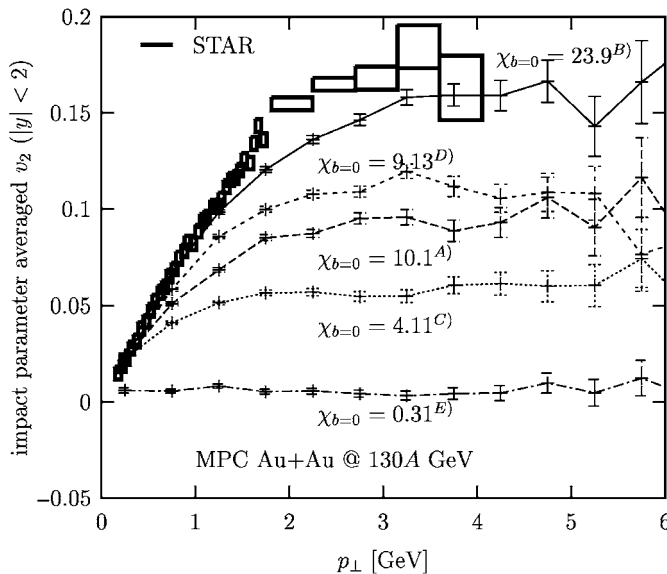


Fig. 4. Impact parameter averaged gluon elliptic flow as a function of p_T for Au+Au reactions at $\sqrt{s_{NN}} = 130$ GeV from MPC with various values of the transport opacity for $b = 0$. Also shown are data points from the STAR experiment

plasma conditions realistically obtainable in nuclear collisions ($T \approx 250$ MeV, $g = \sqrt{4\pi\alpha_s}$) the effective gluon mass $mg^* \approx 300$ MeV. We must conclude, therefore, that the notion of almost free gluons (and quarks) in the high temperature phase of QCD is quite far from the truth. Certainly one has $mg^* \ll T$ when $g \ll 1$, but this condition is never really satisfied in QCD, because $g \approx 1/2$ even at the Planck scale (10^{19} GeV).” [33]. Despite this observation, many people noted that from lattice gauge theory results the value of ε/T^4 approaches 80% of the non-interacting gas limit. Some viewed this as indicating only weak interactions, while some in the lattice community already thought that this 20% difference from the Stefan–Boltzmann limit was the effect of strong residual interactions in a non-perturbative system. Also, recent results from AdS/CFT have shown that one can be at the 80% limit and still be in the very strongly interacting limit.

3 Summary

Exciting results of emergent phenomena at RHIC such as strong flow and jet quenching have sparked a great deal of very positive new thinking about the medium created in these collisions. It appears to represent a paradigm shift, although the earlier paradigm of a perturbatively describable (asymptotically free) plasma seems to have been poorly motivated. Karsch puts it best: “I do not really care what the ‘s’ in sQGP means. However, I am worried and partly also disappointed about the way this new name is used. The disappointment, of course, arises from the fact that suddenly a new name seems to be necessary to describe the properties of QCD in a temperature regime which lattice gauge theory since a long time has identified as ‘not being an ideal gas’ and ‘impossible to be described by perturbation theory [1].”

As the field of heavy ions progresses, a coherent picture of the medium created may be emerging. At this point there are many ideas, some commensurate and other incommensurate with each other. Hopefully the future will tell us which are correct.

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