What Quark-Gluon Plasma in small systems might tell us about nucleons

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The origin of flow-like effects in small systems, such as those produced in ultra-relativistic proton-proton and proton-lead collisions, is still widely debated. In this paper the goal is to look at possible consequences if indeed a mini-Quark-Gluon Plasma is formed in these collisions. It is argued that this could indicate a duality between the QGP phase and the color fields in hadrons. A qualitative dense field picture is presented for this duality and discussed.

I. INTRODUCTION

There are indications that a Quark-Gluon Plasma (QGP) is produced even in p-p and p-Pb collisions [1–4]. There is a lot of theoretical and experimental work still to be done, but the goal of this paper is to start speculating on possible implications beyond the collisional regime of mini QGPs. In this paper, it is therefore assumed that a mini QGP is created in each p-p collision, meaning that there is a soft underlying part of the event that forms a QGP (hard jets are not QGP like, but will behave more or less like standard jets in $e^+e^-$ collisions).

The paper is centered around 2 key ideas. In the first part, Sec. II and III, it is argued based on QGP properties in large systems that time reversal could be a good symmetry between the QGP and hadronic state. In small systems, such a symmetry would suggest a duality between QGP and hadrons. In the second part, Sec. IV, a qualitative model of such a duality is explored. Finally, in Sec. V the ideas of the paper is discussed in a broader context.
II. THE QGP PROPERTIES IN LARGE SYSTEMS

Traditionally, small systems have been thought of as the baseline for understanding large systems, e.g., jet quenching and quarkonium melting. However, for bulk effects in small systems it appears that large systems is the baseline because the unexpected effects are easier to identify and isolate there. Here, we shall take the idea a step further and assume that the QGP “standard” model developed for large systems is a baseline for the QGP formation also in small systems.

A heavy-ion collision proceeds through the following stages:

1. Initial scatterings and QGP formation
2. QGP expansion
3. Hadronization
4. Chemical freeze out
5. Kinetic freeze out

The initial scatterings and QGP formation are the least understood and as this will not play a role for the discussion here, this step is skipped.

The QGP phase behaves like a nearly perfect liquid. The expansion of a perfect liquid is reversible, meaning that the expansion, as the QGP cools, generates essentially no entropy (the relative entropy increase is as small as it can be). This behavior is expected to be relatively constant in a reasonable large temperature range above $T_c$, meaning that the QGP behaves as a nearly perfect liquid in the whole phase transition region.

The transition from QGP to hadrons is a crossover transition so it is not a real phase transition. There is no sharp separation between the two phases, instead they coexist in some temperature range around the pseudo-critical temperature, $T_c$. In such a crossover transition there is no entropy generation and so the change between hadronic and partonic degrees of freedom is fast.

On the hadronic side, statistical thermal models have been very successful at describing the particle composition with temperatures similar to $T_c$ (e.g., [5]), and there are so far no

1 These ideas are all fairly standard, see e.g., “NuPECC Long Range Plan 2016/2017”, therefore few references are given.
indication that the hadronic states at $T_c$ are different from those at lower temperatures. A significant amount of hadrons produced are resonances that decay. These decays are not reversible.

Finally, there have been some model results that suggests that both the chemical and kinetic freeze out occurs essentially at $T_c$, e.g. [6]. At the LHC, resonance results indicates effects of hadronic rescattering between the chemical and thermal freeze out [7]. The effect must be less for small systems and is not critical for the ideas here, which focus on the hadronization, so we will not discuss this in any more detail here.

It might seem counterintuitive that large features of these collisions are reversible, but one should recall that this is exactly what allows us to probe the initial state geometry using the final state flow.

### III. WHAT DO WE LEARN ABOUT QCD IF THE QGP IS FORMED IN SMALL SYSTEM

Now let us try to consider dilute p-p collisions. The immediate problem is that we do not understand the initial scatterings and QGP formation process and so it can seem hard to pin down exactly what we learn from observing the QGP in these systems. However, as we have seen in the previous section a lot of features in large systems are reversible, which makes it interesting to consider time reversal. If time reversal is applicable, we can get from the final state to the QGP phase through stages that are reasonable well understood as described in the previous section. In this section it will be argued that, if our assumption of large-system-like QGP formation in small systems are true, then time reversal is a good symmetry in small systems. This feature will be used to highlight that QGP formation in small systems in fact suggests that this is not a high energy feature but a general feature of essentially all hadronic collisions.

Since the assumption is that QGP is produced in the underlying event of all p-p inelastic collisions then we can select the simplest to analyze. This means we can suppress the influence of jets and rare events where high mass resonances are produced. We can also focus on dilute p-p collisions where few (tens of) particles are produced in a wide rapidity region around midrapidity. In these dilute collisions we expect final state hadronic rescattering to play an even smaller role than in the previous section and so we can ignore the kinetic freeze
out phase. Furthermore, in these dilute collisions the bulk of the initial kinetic energy of the colliding protons remains at very forward rapidities as fragments that are decoupled from the QGP evolution and so we can neglect them as we just want to go back into the QGP phase. So it is now just the few low-energy particles at midrapidity that we want to use time reversal on to point out that they would reform a QGP if they were recollided by inverting their momentum vectors.

In the time reversal argument we, following the arguments in the previous paragraph, start at chemical freeze out. Resonance decays are non-reversible but as the freeze-out temperature is significantly smaller than the Hagedorn temperature there is no indication that hadron production is dominated by decays of very heavy resonances. Instead it seems likely that we can select p-p collisions where this is not the case. For these collisions, time reversal takes us back through the phase transition and well into the QGP phase itself. What this reversibility exactly means at the Quantum Mechanical level is a bit unclear to the author. Here, the point is not if it evolves back to the exact same state but that it evolves back to a state with similar properties (a QGP).

So, if we do not observe an experimental size threshold for QGP formation then we can use time reversal arguments to argue that there is not really an energy threshold for when the QGP is created - the QGP formation and inelastic thresholds are the same! However, this does not mean that the effects will be easy to observe. In low energy collisions, energy, momentum, and quantum-number conservation could easily hide most of the effects. Another important thing to point out is that even if we at LHC could observe ridge-like effects down to a few particles, as, e.g., ATLAS is pursuing [4], then the origin of the ridge in the perfect liquid picture is the initial state geometry, which spans several units of rapidity. In low-energy collision there is therefore no reason to expect a ridge to appear even the dynamics of the bulk matter is the same because the initial state preparation is very different (and might not even span several units of rapidity).

The lack of an energy threshold also suggests that there will be QGP effects in $e^+e^-$ collisions (after the jets have fragmented) but that these effects are likely hidden by the initial configuration of the system, which is jet driven. To observe these effects one would probably have to look at midrapidity in the thrust system and suppress events with hard radiation.

Let us try to summarize the logic of this section as this is a central idea of the paper. Assuming that a QGP is formed in all p-p collisions we can select particular simple collo-
lisions where non-reversible physics such as resonance decays and elastic scatterings after hadronization is negligible. We can then go reversibly back from the final state at freeze-out and into the QGP phase. The energetic forward going particles are only used for creating the QGP so for dilute events we conclude that just recolliding the few low energy hadrons produced at midrapidity would create a QGP. But if there is no size or energy threshold for QGP formation then it suggests that the QGP is in some sense (to be explored in the next section) present in the hadrons themselves (as opposed to being created and only exist for a short time in high-energy hadronic collisions).

IV. DUALITY BETWEEN QGP AND HADRONS

A fundamental problem in the study of the strong interaction is that QCD describes quarks and gluons while we observe hadrons. If the origin of QGP-like effects in small and large systems is the same, then it would mean that heavy-ion collisions allow the direct study of fundamental QCD dynamics that is difficult to isolate in small systems. This picture is completely opposite to the old idea of parton-hadron duality because it is a lump of dense partonic medium that is now dual to a (dense) hadron. It therefore seems motivated to propose a QGP-hadron duality. The goal in the rest of the section is to explore a concrete idea for the proposed duality.

Let us first here discuss what such a duality must contain. Since we know that the QGP is strongly interacting the duality must mean that the quarks and gluons inside hadrons are strongly interacting. That is different from the idea of, e.g., the Bag model where the quarks and gluons are a weakly coupled system that is confined by the negative vacuum pressure. As the system is strongly interacting it must be dense in terms of gluons because the strong force needs antiscreening to be strong. It is known that the low $x$ region of the hadronic structure is dense, which have given rise to the so called Color Glass Condensate (CGC) [8]. The CGC gives a universal description of nucleon and nuclei wave functions for $x \leq 0.01$ and $Q > 1 \text{GeV/c}$. If the proton is dense in general then we propose that the CGC is one limit of a more general dense field description.

The task at hand is therefore to come up with a general model for strongly interacting degrees of freedoms that can both describe the QGP and hadrons and can be perceived as a
generalization of the CGC degrees of freedom. We will therefore propose that these degrees of freedoms are dense fields or dense domains. Dense fields mean here that the relevant degrees of freedom are coherent “high occupancy” color fields of a certain size, $1/Q_d$ ($d$ for domain), as opposed to point-like quarks and gluons. For example, it will be argued that the proton at rest is made up of 3 such dense fields.

A. The origin of the dense fields

The origin of the dense fields is assumed to be due to the antiscreening in QCD: when a bare color charge is put in the vacuum, the color field will physically grow into the dense field because of the antiscreening. This growth gives rise to the dense fields in the hadrons and in the QGP, and it is the push to extend the fields that leads to the hydrodynamic expansion.

To understand when this growth stop (the hadron size), the energy in one of these dense fields has to be estimated. We expect that the kinetic energy will grow as $Q_d$, i.e., the smaller the field the more kinetic energy it will contain. Antiscreening in this picture reflects the density of color charge in the dense field and so we assume that the energy stored in the field will therefore also grow as $\alpha_s(Q_d)$, so that the total energy of the dense field is:

$$E \propto \alpha_s(Q_d)Q_d,$$  \hspace{1cm} (1)

$$\propto \frac{Q_d}{\log\left(\frac{Q_d}{\Lambda_{QCD}}\right)},$$  \hspace{1cm} (2)

where $\Lambda_{QCD} \approx 200$ MeV.

This expression has a minimum, $Q_h$, when.

$$Q_h = e\Lambda_{QCD} \approx 544 \text{ MeV},$$  \hspace{1cm} (3)

where $Q_h$ denotes the characteristic size of the dense fields in hadrons.

This means that hadrons will be made up of valence fields with the characteristic size $1/Q_h$ (up to several small factors). In particular the proton will be made up of 3 such fields. Now we want to motivate that this dense field description for a proton at rest can be evolved into the CGC. The word motivate is used because there are several issues, e.g., the proton at rest is a 3D non-perturbative object while the CGC is a 2D perturbative object.
Initial state evolution in rapidity

The basic HERA inspired CGC saturation scale is

$$Q_s^2(x) = 1 \text{ GeV}^2 \left(3 \cdot 10^{-4} \frac{1}{x}\right)^{0.29}.$$  \hspace{1cm} (4)

The goal is now to show that, if the relative evolution with $x$,

$$Q_s^2(x) \propto \left(3 \cdot 10^{-4} \frac{1}{x}\right)^{0.29},$$  \hspace{1cm} (5)

is assumed, one obtains a similar value of the absolute scale in the dense field picture. For the proton at rest there are 3 fields, which shares the mass so that $x = 1/3$ seem reasonable and therefore $Q_d^2(1/3) = Q_h^2$. With this constraint and Eq. 5 one obtains

$$Q_d^2(x) \approx 2.26 \text{ GeV}^2 \left(3 \cdot 10^{-4} \frac{1}{x}\right)^{0.29},$$  \hspace{1cm} (6)

which is similar to Eq. 4. Both $Q_d^2(x)$ and $Q_h$ seem too large, which suggest that an additional common small factor is missing. The dilute image of the proton, which we know from hard scatterings, $Q \gg Q_d$, should then be recovered by evolution in $Q$.

Let me shortly here discuss how this model compares to the Bag model and the CGC. The arguments leading to Eq. 1 are reminiscent of the arguments in Bag models with the Bag pressure replaced by the field strength $\alpha_s$, but as stressed in the introduction to this section, the Bag model is a weakly coupled picture while the dense field picture is a strongly
interacting model. We finally note that while the vacuum Bag pressure makes sense from Quantum Mechanical arguments there exists no quantitative understanding of the vacuum pressure of the Universe and therefore this pressure might not be confining the hadrons.

The CGC is a model for the initial state of hadrons in high-energy hadronic collisions [8]. It is in principle derived from first principles, but in reality several approximations have to be done to obtain results. The main idea is that bulk production is driven by semi-hard interactions of low $x$ gluon fields. The gluon densities at low $x$ can become very large for momentum scales smaller than a saturation scale $Q_s$, so that they can be treated as classical fields. A semi-hard approach can be taken when $Q_s$ is so large that $\alpha_s(Q_s)$ is small, which one expects at LHC where $Q_s$ is estimated to be of order a few GeV. The CGC when combined with PYTHIA fragmentation can reproduce many features of small systems [9]. It should be clear that the QGP is a real model whereas the picture proposed here is a qualitative sketch. Still, it is important to stress in what fundamental way this sketch differs from the CGC model. Firstly, the CGC is is a model of the initial state and not a model of the QGP. It is only applicable at high energies as $Q_s$ has a strong rapidity dependence whereas the proposed initial state effect here is expected to affect all energies. Secondly, the CGC description of the QGP-like effects in small systems [9] does not require a QGP, nor ideal hydrodynamics, to describe the ridge and so there is no reversible QGP phase. This means that the whole argument chain put forward in Sec. III collapses. The initial state description proposed here is a fundamental non-perturbative picture, which, if true, would suggest that the limits in which the CGC approximations (semi-hard and classical) is valid are not yet dominating bulk production.

B. The dense fields in the QGP

In this section the goal is to explore the dense field description in the QGP. In the QGP we assume that the dense fields eventually form and it is their push to expand, to decrease their energy cf. Eq. 1, that gives rise to the hydrodynamic expansion.

Let us first try to understand how the domain size depends on the energy density. While the systems formed in hadronic collisions will typically have small momenta transversely they will have significant longitudinal momenta. Here, it is first assumed that the system is
at rest when the dense fields are formed and then the effect of the longitudinal momentum on observables is guesstimated. For a homogenous system the domain size, $1/Q_d$, must be the same for all domains. The density of domains, $\rho$, is then

$$\rho \propto Q_d^3 \quad \text{(7)}$$

and the internal energy (mass) of each domain is proportional to $Q_d$ cf. Eq. 1. The energy density, $\varepsilon$, will therefore scale with $Q_d$ as

$$\varepsilon \propto Q_d^4 \quad \text{(8)}.$$

The constant of proportionality can be found for a region where $\alpha_s$ is constant ($Q_d \sim Q_h$) since the same equation has to be valid for nucleons. For the QGP one knows from Lattice QCD that $\varepsilon \propto T^4$ so this suggests that $Q_d \propto T$.

As the QGP expands and cools the domain size will increase ($Q_d \rightarrow Q_h$) and eventually reach the hadronization size where the domains will be confined inside the hadrons.

**Final state evolution in time**

![Final state evolution of the dense fields. Note that the number of dense fields is the same at all times. The figure is meant as a schematic illustration. Importantly, some of the fields will have anticolors (antiquarks) to form mesons and antibaryons.](image)

Let us now look at the system in more details. The initial domain size are fixed by the energy density, cf. Eq. 8; the domains cannot be larger, even it would be energetically favorable, and conserve energy at the same time. Now we assume that the number of domains is fixed during the expansion to conserve entropy (reversibility). This assumption means that the domains are valence-quark-like degrees of freedom, i.e., they grow 1-to-1
into the valence quarks in the final state hadrons. As entropy is essentially conserved, the expansion of the domain sizes must be adiabatic. Figure 2 illustrates the final state evolution of the dense fields as a function of time. Let me be clear that the domain size at a given rapidity in the initial and final state do not have to be related. In both cases the important things is that domains are dense, which can have different meaning in the initial and final state. In fact one would expect that the domain sizes in the final state are larger because the smaller the domains get in the initial state the less likely they will be to interact.

If \( N_d \) is constant then it means that the total final multiplicity, \( N \), is \( N \propto Q_d^3 \). Furthermore, as a domain expands its energy (mass) decreases. This difference in energy must therefore be converted to kinetic energy so that for the final state total energy, \( E \), one has \( E \propto Q_d^4 \). Let us now compare this to data from heavy-ion collisions. At the LHC the \( dN/d\eta \) is approximately twice that at the maximum RHIC energy for the most central collisions. To account for the difference in the longitudinal direction it is estimated that \( dN/d\eta \propto Q_d^2 \) (while \( N \propto Q_d^3 \)). As the initial overlap region is supposedly the same at the LHC and RHIC, this suggest that initial domains are \( \approx 40 \% \) smaller at the LHC than at RHIC. The transverse energy (2D) at midrapidity is for similar reasons expected to scale with \( Q_d^3 \). The dense field model presented here suggests that transverse energy should therefore increase by \( \approx 40 \% \) more than \( dN/d\eta \) going from RHIC to the LHC. The increase reported by CMS at \( \sqrt{s_{NN}} = 2.76 \) TeV was \( \approx 42 \pm 15 \% \) [10] while the same increase measured by ALICE was found to be \( \approx 18 \pm 12 \% \) [11]. Recent preliminary results from ALICE for \( \sqrt{s_{NN}} = 5.02 \) TeV, where the lever arm is longer, seem to suggest that the increase is likely closer to the top end of the ALICE limit.

Studies of \( dN/d\eta \) and \( E_T \) as a function of beam energy at RHIC [12] in general show a smaller rise than suggested by the dense field picture. One could suspect that the reason for this is that collisions at lower energy are only semi-transparent, meaning that significant baryon number is transported to midrapidity, which biases the \( E_T \) per particle.

Finally, let me first give some thoughts on equilibration and thermalization and then discuss why the dense fields would repel each other. For the final state to behave as a medium, i.e., for a collective expansion to take place, it must be required that a domain is formed so it can act as a coherent entity and that the same is true for its neighbors. As the initial domains are assumed to be coherent objects and as the final state formation merely
requires these domains to form a dense final state, this suggests that the collective expansion can take place for early times/small collisional systems. As previously noted, the scaling of energy density implies $Q_d \propto T$, but as the domain size does not require a full system in equilibrium one could think of the proposed dense fields as useful structures for describing the pre-equilibrium physics, e.g., for Debye screening where one expects effects on scales of $1/T$.

Now let us go on to the bigger problem of why the domains would repel each other. In the CGC, the gluons are treated as stochastically distributed sources but realistic correlations between gluons have been studied in CGC like models [13, 14]. Importantly, in both works they found that the state is color neutral for gluon wavelengths larger than $1/Q_s$ due to active shielding from other gluons (while color appears randomly distributed for wavelengths less than $1/Q_s$). If the same kind of shielding takes place for the proposed color domains then this would explain why the domains are stable and also suggest that they interact in a similar way as magnetic field lines repelled by a superconducting magnet. This seem to have some relation to the Debye screening length, not as a screening caused by uncorrelated high color charge densities but rather as an active screening process enforcing color neutrality on scales larger than $1/Q_d$.

C. Jet quenching in the QGP

Let us try to do a qualitative estimate of how jet quenching depends on $Q_d$ for a static source. If one considers a purely geometrical cross section then one expects $\sigma \propto 1/Q_d^2$ and this is also somewhat motivated from calculations of valence quarks interacting with a CGC [15]. The energy loss in each interaction, $\delta E$, is supposedly also of order $Q_d$. For incoherent scatterings one therefore obtains the total energy loss

$$\Delta E \propto \rho L \sigma \delta E$$

$$\propto Q_d^3 L \frac{1}{Q_d^2} Q_d$$

$$\propto Q_d^2 L$$

$$\propto \sqrt{\varepsilon} L$$

$$\propto T^2 L,$$

where $L$ is the path length.
This rough estimate has several caveats as it does not take into account the expansion of the medium as the probe traverses it or the effect of the initial longitudinal momentum. It is still useful to highlight that, in the same way as saturation limits the particle production in the initial state, the dense fields in the final state will limit the quenching and make it rise less than linear with the energy density. Furthermore, it is interesting that the scale of the dense fields, $Q_d$, naturally couples to the idea of the medium being unable to resolve the jet structure so that the jet is quenched coherently [16].

V. DISCUSSION

In this section the two main ideas of the paper will be discussed in a broader context.

The first idea is centered around the remarkable observation that many phenomena we observe in the QGP are nearly reversible. This is by no mean a trivial observation as the prediscovery expectations for the QGP was that it would be weakly coupled. There were several reasons to expect this: asymptotic freedom, lattice QCD energy densities in the QGP were consistent with expectations for a relativistic quark-gluon gas, and the general result that the free energy is eventually dominated by entropy at large temperatures. Similarly, if Hadronization would proceed via very heavy hadronic states, as is the underlying idea of the Hagedorn limiting temperature, then there would be a clear separation between the QGP and hadronic phases.

This conflict between expectations and observations points to a fundamental lack in our understanding of QCD. The proposed solution in this paper is a duality between QGP and hadrons that would give some insights into QGP properties: QGP and hadrons are fundamentally strongly coupled, the expansion is driven by asymptotic freedom, and the phase transition is driven by the energy density cf. Eq. 1.

In the second half of the paper, the idea of Universal color domain-like degrees of freedom was presented. Here, it will be outlined how a full generator building on these ideas could look. The initial state would involve CGC-like calculations of domain scatterings followed by a non-CGC requirement that the scattered domains are dense in the final state (similar to the idea of the EKRT model [17]). Similarly to CGC longitudinal glasma fields [8] and Lund string models as implemented in PYTHIA [18], there would have to be structures that
are long range in rapidity to get long range correlations. These intermediate long range structures does not have to be dense fields as long as they break up early to form the QGP (dense field phase). To get the proper strangeness scaling with multiplicity [19] one could consider to use color ropes for the initial “strings” [20]. One would need to implement something like the p-p core-corona model in EPOS [21] to separate the hard (e+e− like) and soft (QGP) components. The microscopic implementation of the hydrodynamics is very similar to the “shoving” model [22]. Note that the basic picture of the expansion in the domain model is similar to the experiments done with strongly interacting lithium atoms [23] because the order of the domains must to first order be preserved for the liquid to be perfect. Hadronization will proceed via recombination of the domains as they achieve the size $Q_h$.

VI. SUMMARY

In this paper we have tried to speculate on QCD implications of mini-QGP formation in proton-proton collisions. It has been proposed that, due to the reversible nature of the QGP, time reversal could be a powerful tool to understand the relationship between the QGP and hadrons. We have tried to extend the CGC ideas to the full initial and final state as a dense field picture. This QGP-hadron duality would suggest that there should be relations between initial and final state p-p physics. It is the hope of the author, that better qualitative and quantitative tests can be devised to validate or falsify the proposed picture.

Finally, a goal for me in pursuing such a picture has been that it should, if correct, help explain to non-physicists why we collide heavy-ions:

Each nucleon contains a snapshot of how the Universe looked a few microseconds after the Big Bang. In this way we are not only children of the stars but carries within ourselves also an imprint of the Big Bang itself. When we collide nuclei, they replay for us the movie of creation.

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