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# FAQS ABOUT QUARKYONIC MATTER*

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This paper attempts to answer some frequently asked questions (FAQS) about Quarkyonic Matter.

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## 1. Where does Quarkyonic Matter occur?

Quarkyonic Matter is a hypothetical new phase of matter occurring at high baryon density and temperatures $T \leq \Lambda_{\rm QCD}$. A possible phase diagram in the temperature and baryon chemical potential plane is shown in Fig. 1. In this figure there is a region of de-confined quarks and gluons at high

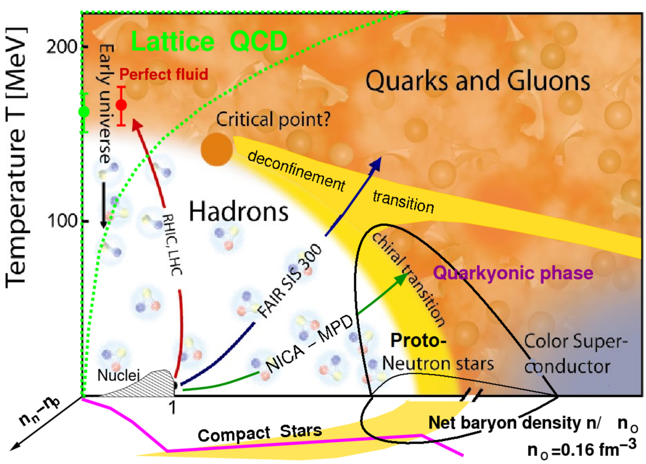


Fig. 1. A conceptualization of the phase diagram of QCD.

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temperatures: the Quark-Gluon Plasma. At low temperature and very small baryon density $\mu_B \leq M_{\text{nucleon}}$, matter is in a hadronic phase composed of nucleons and mesons. Quarkyonic Matter may be thought of as composed of a Fermi sea of quarks with gluons and antiquarks confined. Nucleonic excitations near the Fermi surface are also confined. The quarks are confined near the Fermi surface, but they may be thought of as free quarks deep in the Fermi sea. The word quarkyonic was invented to express this dual nature [1,2].

As one increases the density of baryons to an arbitrarily high value, we would expect that de-confinement would disappear even at low temperatures. Therefore, the region of Quarkyonic Matter in the $\mu_B - T$ plane is enclosed. This enclosed region will be called Happy Island.

## 2. What happened to the phase diagram with only a Hadronic Gas, Quark-Gluon Plasma, and Color Superconductivity?

If Quarkyonic Matter exists, then QCD matter at high energy density has more phases than we had previously imagined. It probably has more phases than we now imagine.

## 3. Is there an approximation to QCD in which Quarkyonic Matter can be rigorously shown to exist?

The large number of colors limit is useful for understanding qualitative features of QCD for $N_c = 3$. In this limit one can ignore the effects of quark loops. This means that quark loops do not affect gluon dynamics. Therefore, the presence of a finite density of quarks will not affect the confining properties of a theory. This is actually so in a finite region of quark chemical potential, since the requirement that loops do not affect the confining potential is

$$\alpha_{\rm S} \mu_{\text{quark}}^2 / N_c \leq \Lambda_{\rm QCD}^2 \tag{1}$$

or $\mu_{\text{quark}} \leq \Lambda_{\rm QCD}/\alpha_{\rm S}\sqrt{N_c}$. This bracketing allows for a region of Quarkyonic Matter where the baryon density is parametrically large compared to the QCD scale.

In the large $N_c$ limit, baryons have a mass $M_{\text{nucleon}} \sim N_c \Lambda_{\rm QCD}$. Therefore the number density of baryons is exponentially small,

$$\rho_B + \rho_{\overline{B}} \sim e^{(\mu_B/T - M_{\text{nucleon}}/T)} \sim e^{-N_c} \tag{2}$$

so long as $T \leq \Lambda$ and $\mu_B \leq M_{\text{nucleon}}$. Note that we require the quark chemical potential, $\mu_{\text{quark}} = \mu_{\text{nucleon}}/N_c$ to be a distance greater than of the order of $\Lambda_{\rm QCD}/N_c$ away from threshold in order for the suppression to occur.

We see that in the large $N_c$ limit, the baryon number density is an order parameter for a phase transition.

The hadronic world in the large $N_c$ limit is confined and has no baryons. The quarkyonic world has baryons and is confined. The Quark-Gluon Plasma degrees of freedom are quarks and so the baryon number is not suppressed. It is also deconfined.

Although Quarkyonic Matter is confined, the effect of confinement on quarks deep in the Fermi sea cannot be big, if $\mu_{\rm quark} \gg \Lambda_{\rm QCD}$. This is because the interaction of these quarks is not sensitive to long range interactions, and can be treated using perturbation theory.

## 4. How do bulk properties of matter reflect the Quarkyonic Phase?

In the large $N_c$ limit, there must be a very strong change in the properties of matter between a Hadron Gas, the Quark-Gluon Plasma, and Quarkyonic Matter. The Quark-Gluon Plasma has of the order of $N_c^2$ degrees of freedom. Hadronic Matter has $O(1)$ degrees of freedom. At low baryon density, it is known that the transition to a Quark-Gluon Plasma is a first order phase transition. At low temperature and high baryon density we expect a transition in a region of the order of $\delta\mu_B \sim O(1/N_c)$, or perhaps a discontinuous change, between a Hadron Gas and Quarkyonic Matter. The number of degrees of freedom is $O(N_c)$.

## 5. How good is the large $N_c$ limit?

The honest answer to this question is that we simply do not know. There are some reasons to expect it might be good, however.

The de-confinement transition can be computed as a function of $T$ and $\mu_{\rm quark}$ for $\mu_{\rm quark} \ll T$ for $N_c = 3$. The curvature is very small and to a good first approximation, and the effects of finite density are very small.

The heavy quark potential can be computed in lattice gauge theory, and it is known to be linear in the vacuum out to distances of about 2 Fm. The effects of quark loops are quite small.

For $N_c = 3$, we expect that the number of degrees of freedom of a low temperature Hadron Gas are those of pions, $N_{\rm dof} = 3$. For a Quark-Gluon Plasma for three flavors of light quarks, $N_{\rm dof} \sim 40$. For Quarkyonic Matter and three light mass flavors, $N_{\rm dof} \sim 18$. There should, therefore, be quite significant changes in the bulk properties of matter.

The transition from Hadron Matter to Quarkyonic Matter should take place in a narrow range of $\mu_B$. If the transition is between non-relativistic nucleons and Quarkyonic Matter with a typical Fermi momentum of the order of $\Lambda_{\rm QCD}$, the width should be of the order of $k_{\rm Fermi}^2/2M \sim \Lambda_{\rm QCD}/N_c$, and is quite narrow. However if we think in terms of the baryon number density, it is of course continuous as the baryon number density changes between a small value and $N_{\rm dof}\Lambda^3_{\rm QCD}$.

## 6. Are there special points in the phase diagram?

There should be some region where there is a triple point, where all three phases might coexist [3]. There may also be a critical end point. In Fig. 1, a possible critical end point is shown. There might be a triple point at the intersection of the two yellow lines. It is possible that the triple point is at the same position as the critical point. There may be other possibilities as well.

## 7. What happens in the large $N_c$ limit with $N_f/N_c$ fixed?

In large $N_c$ with $N_f/N_c$ fixed, confinement is no longer an order parameter for a phase transition. Baryon number remains an order parameter. Quarkyonic Matter becomes the phase with baryon number non-zero [4]. In this case, the Quark-Gluon Plasma and Quarkyonic Matter live in the same phase.

## 8. How is chiral symmetry broken in Quarkyonic Matter?

Quarkyonic Matter is confined and we would expect that chiral symmetry is broken for confined matter. It is however possible to have a parity doubled phase where chiral symmetry is restored and the matter remains confined, as first shown by Glozman and Wagenbrunn [2]. Explicit computation in QCD models suggests, however, another possibility that chiral symmetry is broken through the condensation of charge density waves [5].

The argument for charge density wave condensation is very simple. To make a chiral condensate, one needs a particle–hole pair to make a scalar meson condensate. In the presence of a Fermi surface, this costs the least energy if the particle and hole are taken from near the Fermi surface so that both have an energy $E_{\rm Fermi}$. It costs little energy to move such a quark or quark hole above the Fermi energy. To make a scalar meson requires little relative momentum since otherwise the confining potential requires a big interaction energy. Therefore, the quark–antiquark pair has low relative momentum, but a big total momentum of the order of $2E_{\rm Fermi}$. This configuration has a DeBroglie wave vector, and breaks translational invariance.

Explicit computation shows that the condensate involves a linear combination of the sigma meson $\overline{\psi}\psi$ and a spin one meson $\overline{\psi}\sigma^{03}\psi$ where the third component is the direction of condensation. This means that the condensate forms a chiral spiral, and this condensate breaks parity.

## 9. What is Happy Island?

Happy Island is the region where there is Quarkyonic Matter and chiral symmetry breaking. If chiral symmetry breaking occurs by a translationally non-invariant parity breaking condensate, then Happy Island must be surrounded by a line of phase transitions.

## 10. How do the charge density waves interweave?

The charge density waves have a one spatial dimensional structure. They condense in a three dimensional world. Surely there can be more than one condensate pointing in different directions. What is the optimal configuration of condensates?

The answer must depend upon density. It was suggested by Kojo, Pisarski and Tsvelik [5], that the condensates form by segmentation of the Fermi sea. The number of segments depends upon the density. This segmentation violates rotational invariance, and each segmentation corresponds to a different discrete breaking of rotational invariance. At lowest density, there is the largest change in the symmetry of the Fermi sea upon going from one segmentation to the other. Within Happy Island there are, therefore, a number of phase transitions associated with this segmentation.

## 11. What is the geography of Happy Island?

The answer to this is not known. Happy Island is largely unexplored. It may turn out also that the chiral properties play a minor role compared to, as yet, unthought physical processes.

My current best guess about the geography is that on the side facing Hadron Matter, there is either a very steep hill or a cliff corresponding to a first order phase transition or an approximation to it. There are then stairs which go down to a beach that border on the Quark-Gluon Plasma. The steps of the stairs correspond to the segmentation of the Fermi surface.

## 12. Is there experimental evidence for Happy Island?

In low to intermediate heavy ion collisions, one can make freeze out curves for the abundances of produced particles. These curves presumably correspond to regions where there were rapid changes in the number of degrees of freedom. One finds a freeze out boundary which corresponds qualitatively with the region of transition of Hadronic Matter to a Quark-Gluon Plasma and Hadronic Matter to Quarkyonic Matter [3].

In such a plot, there is a region that corresponds to the triple point. In fact ratios of some particle abundances in this region show properties expected for such a triple point. The center of mass energy per nucleon where this occurs is about 10 GeV/$A$.

Happy Island might be studied experimentally in low energy nuclear collisions at RHIC, and possible at future facilities such as FAIR and NICA. Little is known about signatures for such matter, nor what systematic theoretical or experimental studies need to be done to reliably extract the properties of such matter.

## 13. Is Happy Island really fantasy island?

Again, the answer here is not known. Surely such a construct exists in the large $N_c$ limit. However even in the limit of large $N_c$, there is room for much controversy concerning the precise nature of chiral symmetry breaking, and the existence of translationally non-invariant and parity breaking condensates. There is also the possibility, which often occurs in discovery, that Happy Island exists, but the reasons for its existence are quite different than what we have imagined.

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