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Phenomenology of Quarkonic Matter

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Phenomenology of Quarkyonic Matter

Research Article

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Abstract: The phase diagram of QCD is richer than often imagined. It may contain a new phase of Quarkyonic Matter that has properties that are both confining and deconfining. Such matter has a perturbative Fermi sea of quarks, but a a Fermi surface and thermal excitations that are confining. Chiral symmetry is broken by a non-translational chiral condensate of quark-hole pairs near the Fermi surface. There are a number of chiral translations associated with how the rotational symmetry of the Fermi surface is broken

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1. The Phase Diagram of QCD

Many times during this meeting we were presented with figures showing the ”Phase Diagram of QCD”. Unfortunately, these figures were not all the same, and had many different features, and even when the same features

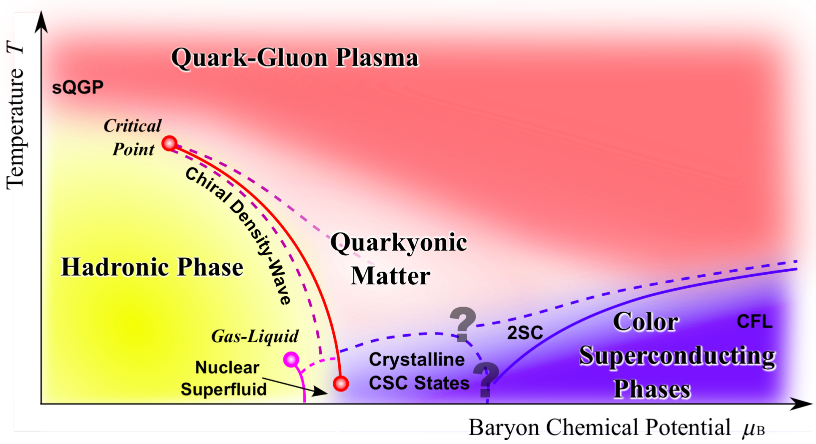

Figure 1. **A hypthetical phase diagram of QCD according to Fukushima and Hatsuda .**

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were shown, the features often appeared at different places. There is a reason for this: Outside a narrow region characterized by a small finite baryon density, and finite temperature, and a region that has baryon density and temperatures parametrically large compared to QCD scales, we do not understand the phase diagram. At finite temperature and small baryon density, methods of lattice gauge theory provide us with a good first principles computation of the properties of strongly interacting matter[1]-[2]. At parametrically high baryon density and temperature, perturbative methods may be used to conclude that matter is an almost free gas of quarks and gluons, with some small effects due to color superconductivity[3]-[4]. In the region where finite baryon density effects are important, there are no rigorous methods of computation, and one must rely on model computations or approximations such as the limit of a large number of colors. For some of us, who do not like to add another decimal point to someone else's computation, or another measurement of someone else's discovery, this "Wild West" frontier provides much amusement.

Of all the phase diagrams presented here, the one that reflects best the uncertainty of our knowledge was that presented by Kenji Fukushima[5]. This diagram has a large region at finite temperature and density labeled Quarkyonic Matter, seen in Fig. 1. This region is the subject of my talk. Its possible existence was argued on the basis of the limit of a large number of colors[6]-[7]. Quarkyonic matter exists at finite baryon density, and in the limit of a large number of colors, this density is parametrically large compared to the typical QCD scale, $1\ Baryon/Fm^3$. At very high density, the degrees of freedom are an almost Fermi gas of free quarks. The Fermi surface is non-perturbative and confining, and gluons and anti-quarks are permanently confined inside of mesons. Hence the name "Quarkyonic" that reflects this Yin-Yang nature of high density matter.

There is not consensus about the chiral properties of Quarkyonic matter. Computations that assume a spatially homogenous chiral condensate conclude that chiral symmetry is restored in quarkyonic matter[8]-[9]. However, if one allows for inhomogenous condensates, there may be a lattice formed of rotating chiral spirals, associated with the nonperturbative degrees of freedom near the Fermi surface[10]-[11]. Chiral spirals are a configuration of the chiral condensate $< \overline{\psi}\psi >$ and a condensate of a Goldstone degree of freedom that rotates between the two as a function of position. These one dimensional structures form a crystal, and the rotational symmetry of this crystal can change as a function of density, leading to a number of different phase transitions associated with the change of this order. There are also now a variety of additional conjectures associated with the Quarkyonic phase, and how crystallization might occur[12]. There are also strong coupling arguments based on the AdsCFT correspondence that such Quarkyonic Phase would exist[13], although it is difficult to extend these arguments to densities parametrically large compared to the QCD scale.

If it is true that there is a crystallization phase transition or transitions associated with Quarkyonic matter, then Quarkyonic matter is surrounded by a line of phase transitions in the $\mu_B - T$ plane. There may also be a triple point where the Quarkyonic, Confined, and Deconfined phase coexist.

2. Intuitive Arguments for Quarkyonic Matter

In the large N_c limit, quark-antiquark pairs do not affect the confining potential. Gluon loops are of order $\alpha_{'tHooft} \sim \alpha_S N_c$ which is held finite in the large N_c limit. Quark loops are of order α_S and vanish in such a limit. At finite density, finite temperature gluon loops can short out the quark-antiquark potential, if the temperature gets to be larger than of order Λ_{QCD}. On the other hand, quark loops generate a Debye length that is of order $R_{Debye} \sim \sqrt{\alpha_{'tHooft}/N_c}/\mu$, and the Debye mass only becomes of the order of a Fermi distance scale when

$$\mu \sim \sqrt{\frac{N_c}{\alpha_{'tHooft}}}\, \Lambda_{QCD} \tag{1}$$

This means that confinement remains until densities that are parametrically high compared to the QCD scale. At such densities, baryons are overlapping on size scales much less than a Fermi!

In addition to confinement, there is another way to characterize matter at large N_c. The baryon number is itself an order parameter. Since the baryon density is of order $\rho_B \sim e^{-M_B/T+\mu_B/T}$, we see that the baryon density is exponentially small unless the baryon number chemical potential is $\mu_B \geq M_B$. Since the baryon mass is of order $M_B \sim N_c\Lambda_{QCD}$ and the baryon chemical potential is related to the quark chemical potential by $\mu_B = N_c\mu_Q$, we see that there are no baryons in matter until $\mu_Q \geq \Lambda_{QCD}$

These arguments mean that in large N_c, there are three phases of high energy density matter: Confined which is baryon-less, confined matter that has baryons in it, and deconfined matter with baryons. These three regions correspond to the “Quark Gluon Plasma”, “Hadronic Gas” and “Quarkyonic Matter” on the Hatsuda-Fukshima diagram.

Because the intrinsic distance scale separating quarks in the Fermi sea is much less than a Fermi, their interactions should be weak, and the quarks thought of as an almost free Fermi gas. Anti-quark, gluonic and Fermi sea excitations are sensitive to long distance interactions, and will be confined.

The issue of chiral symmetry restoration is delicate. It is impossible to make a low energy particle hole excitation, since the minimum energy of a quark is the Fermi energy. However, we can make a pair that has small relative separation if we take a particle hole pair of opposite momentum, corresponding to a quark-antiquark pair of zero relative momentum but large total momentum, $E \sim 2\mu_Q$. This costs little energy because we can simply move a quark from a small momentum below the Fermi surface to a momentum above it. Such a particle has a finite DeBroglie wavelength, so making a condensate from such particle will break translational invariance. Such a mechanism allows for chiral symmetry breaking in very high density quark matter.

We can imagine the transition to Quarkyonic matter as a change in the particle number degrees of freedom. In a low temperature and density hadronic bass, the degrees of freedom are 3 pions. For a quark gluon plasma (I will treat the two flavor case) there are $N_{dof} \sim 2(N_c^2-1)+8N_c \sim 40$. Quarkyonic matter would have $N_{dof} \sim 4N_c \sim 12$. The number of degrees of freedom scale as $O(1), N_c^2$ and N_c for the three phases. In the large N_c limit, this implies large changes in the internal energy across transitions between these forms of matter. There

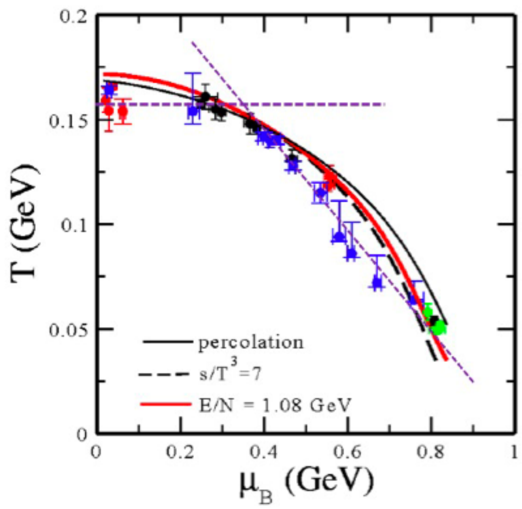

Figure 2. **A simple fit to the deoupling data from heavy ions The fit corresponds to the dashed line..**

should also be a triple point where these three phases of matter meet.

The deonfinement transition temperature should be independent of N_c in the large N_c limit. The Quarkyonic transition should occur when the baryon number equals some finite value or when $e^{-M_B/T+\mu_B/T} \sim 1$, or

$$T \propto M_B - \mu_B \tag{2}$$

3. Hints of Quarkyonic Matter from Heavy Ion Experiments

If we accept that data on decoupling temperatures and chemical potential corresponds to a phase boundary separating Quarkyonic, Hadronic and Deconfined phases, we can use $T = constant$ and $T = const'(M_B - \mu_B)$ as a parameterization of data[14]. This is shown in Fig. 2.

On Fig. 2, there is a triple point where there is coexistence of the three phases. At this point, the decoupling curve changes branches. We would here expect discontinuities in the derivative of various quants as a function of energy. This indeed occurs[15], as seen in Fig. 3 This plot is called Marek's Horn, in honor of Marek Gazdzicki.

4. Acknowledgements

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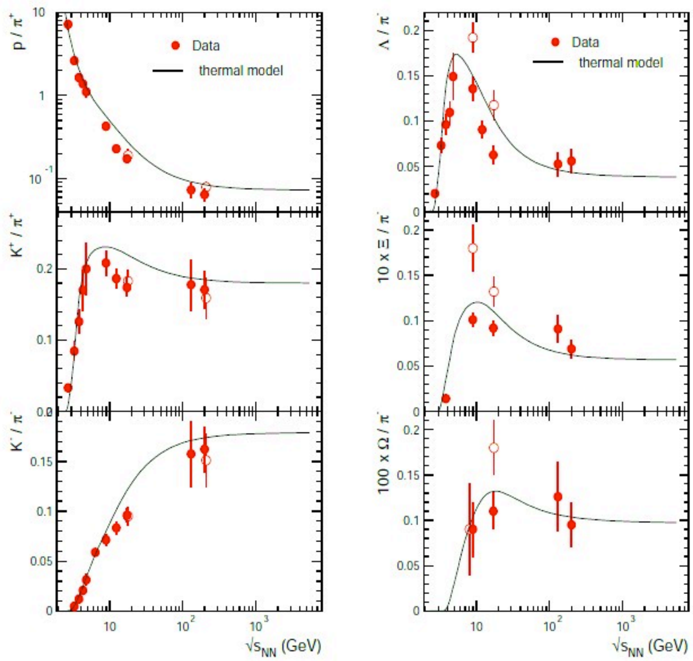

Figure 3. **Particle ratios at decoupling as a function of energy**

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