

Theory Summary

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I provide a short summary of many of the theoretical talks given at "The Critical Point and the Onset of Dconfinement Conference", "CPOD 2018", held in Corfu, Greece, September, 2018. I also include some remarks on a possible interpretation of the recent observation that the sound velocity squared may be of the order or exceed $1/3$ at a few times nuclear matter density, as determined by neutron star observations.

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1. Introduction

During this scientific meeting, you have been shown many times "The Phase Diagram of QCD". Problem is you were shown many different phase diagrams! There is a reason for this. Outside of a small region around zero baryon density, we do not know the phase diagram. The region around small baryon density and finite temperature has been well studied by lattice gauge theory computations that provide reliable results at such small baryon density, and by many experimental results of the highest quality from both the LHC and RHIC. Non-perturbative computations at finite baryon density on the lattice are unreliable because there is no convergent method to provide convergent results. Simulations of the properties of lower energy nuclear collisions are rapidly improving, but much remains to be done both in experiment and theory to develop reliable and compelling understanding of high density matter. In a somewhat surprising development, data from neutron star observations now provide the best experimental constraints on the equation of state for zero temperature finite density strongly interacting matter.

It is of course great fun to be an experimentalist or a theorist exploring an area where little is known. Oftentimes, in such conditions, wrong ideas became widely and strongly held, simply because there is no compelling way to refute them. We must remember that we are dealing with speculative science, and I strongly recommend the famous quote by Mark Twain to you all:

It is not what you know that gets you in trouble, but what you think you know but you do not.

An interesting result that has come from analysis of experimental data are the decoupling curves where final state multiplicities of various flavors of particles are used to infer a decoupling temperature and chemical potential. See Ref. [1] for reference to original material. See the presentation of Galatyuk[2]. (References are to conference presentations unless otherwise noted.) A result of such a determination is shown in Fig. 1. I have drawn a blue line and a red line on the figure. The blue line would be the case if the de-confinement cross-over transition occurred at a fixed temperature and the straight red line would be the case for

$$(M - \mu_B)/T = \text{const} \quad (1.1)$$

Such behaviour is suggested by large N_c arguments[3]. While one can seriously question the decoupling interpretation of these curves, at least at high baryon density and low temperature, it is clear that something changes at baryon chemical potential of about 400 MeV. This simple observation provides a partial justification of the excitement about the low energy run as an attempt to understand the properties of matter at finite density, and that this matter may have different properties from that of high temperature and low baryon density matter. The point at which the two straight lines intersect is approximately the point at which baryons dominate the energy density of strongly interacting matter.

We were also presented with data from NA61 by Grabieskow[4] that showed in the region of this transition that various ratios of particle abundances show distinctive changes in their dependence on collision energy, and that there are intriguing structures associated with intermittancy. The first is associated with the so-called Horn originally observed by Gazdzicki[5]. Some computations using three flavor NJL models were shown to reproduce such behavior by Freisen[6].

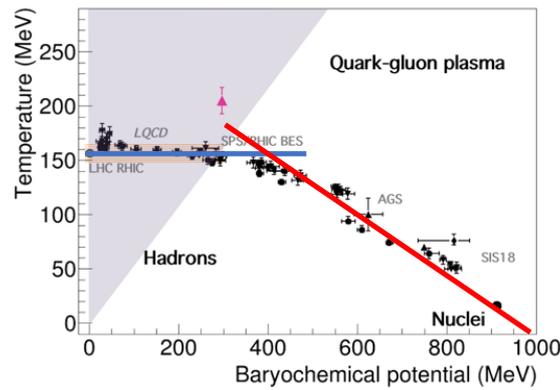


Figure 1: Data on decoupling temperature and density.

In seminal work by Antoniou and Diakonov[7] it was argued that intermittency might be a signal for a critical end point. They used a sigma model to simulate the approach to criticality. The approach to masslessness of the sigma field in such a theory generates scale invariant correlation functions that might be responsible for the observed effect in NA61[4]. The effect is localized in energy, A , and collision centrality since one has to be very near to critical point to get a sizable signal. How does this emerge in collisions at neighboring centrality, energy and A ? If it is a real effect it should have a maximum somewhere and it should be possible to follow in the multidimensional space of energy, impact parameter and A .

The masslessness of a sigma field mode might generate long range attractive forces and induce large scale baryon number fluctuations as argued by Torres-Rincon[8]. This might generate clustering effects in baryons. Such effects should persist below the critical end point since first order phase transitions have large fluctuations in baryon number.

As argued a long time ago by Stoecker[9], it is in this region that various hydrodynamic flow signatures, in particular directed flow, show non-monotonic properties.

2. Proton Number Fluctuations

In the talk of Galatyuk[2], various measures of proton number fluctuations were presented. Baryon number fluctuations and correlations are among the strongest potential signatures for phase transitions since if the transition is related to chiral symmetry breaking, the nucleon mass might be strongly affected during such a transition. Many times, experimentalists and theorists have looked for signatures in two particle baryon number correlations without success. It was however recently argued by Bzdak, Koch and Skokov[10], that while 2 particle correlations give small deviation from statistical fluctuation, two particle correlations give a moderate effect and three 4 particle correlations a very large effect. The 2, 3 and for particle correlations as a function of energy are shown for the Star experiment in Fig. 2, and for the Hades experiment for the fluctuations as a function of hadron multiplicity, Fig. 3.

While it is tempting to speculate that the correlation seen in these experiments might be tied to a phase transition, detailed computations such as those of Bzdak, Koch and Skokov[10] cannot

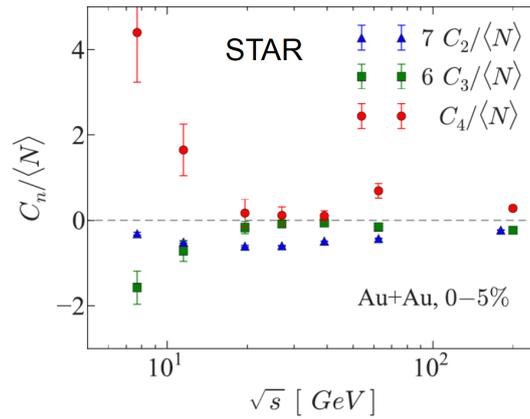


Figure 2: Multiparticle proton correlations as a function of energy in the STAR experiment[2].

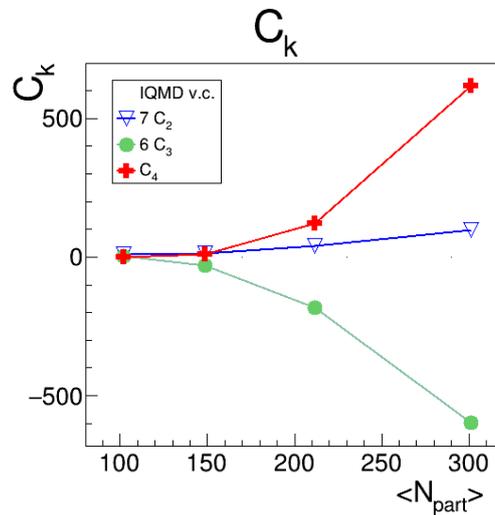


Figure 3: Multiparticle proton correlations as a function of multiplicity in the Hades experiment[2].

successfully describe these correlations by a model with such a transition as an underlying property. It appears that one needs two distinctive event classes, each with a Poisson distribution centered around a different value. This is difficult to resolve with an underlying theory where for example one had a first order phase transition since in such a circumstance one would produce a mixed phase, and the underlying fluctuation spectrum would be a product of two Poisson distributions which is itself Poisson, and not a sum of two Poisson distributions. While the data is suggestive and provocative, a fundamental understanding is at this time lacking.

3. Thermalization and Critical Behaviour

The classic work developed by Braun-Munzinger, Redlich and Stachel[11],[12], demonstrates that to a very good approximation, the ratios of abundances of particles produced in heavy

ion collisions is described as a thermal distribution with a baryon number chemical potential. The temperature and chemical potential is a function of multiplicity and energy. This result is interpreted as that the system quickly freezes out at some temperature and density close to the line of crossover in the μ_B and T plane. This can be strongly motivated at low baryon density, but such an interpretation is controversial at high baryon density.

At high energies, there is some tension between optimizing thermal fits for strange and non-strange baryons. Noronha-Hostler argued that there may be a different freeze out temperature for strange vs non-strange baryons[13].

The particle abundance curve also works well in small systems where the assumption of chemical equilibrium might be questioned. In the talk of Bellwied it was argued that perhaps this thermal spectrum might be a consequence of quantum entanglement, and not due to thermalization as in the conventional way of thinking[14].

In the talk of Rennecke the effects of strangeness neutrality were considered for various fluctuation measures[15].

The position of the cross over transition as a function of baryon number density can be quantitatively explored using lattice gauge theory methods up to a baryon number chemical potential of order 250 MeV[16]. The position of this crossover is semi-quantitatively similar to the values of μ_B and T measured by particle abundances. In analysis presented by Karsch, Mukherjee, Goswami and Vovchenko, computations were shown that also argued that there is no evidence for a critical endpoint for temperatures below 300 MeV.[17],[18],[19],[20]. The dependence of the crossover temperature on chemical potential is very weak in this region, consistent with large N_c expectations.

Glozman reminded us that there is no confinement phase transition nor even sharp cross over. He asks how does one conceptualize the degrees of freedom on either side of the cross over? Perhaps Euclidean correlation functions are sensitive to confining effects even beyond the crossover[21]?

The crossover transition seen in lattice gauge theory computations is a remnant of a chiral phase transition in the limit that the light quarks masses go to zero. In a true phase transition, there would be a singularity along a line of in the μ_B, T plane. This singularity would appear in the derivatives of various measurable quantities, and these derivatives correspond to operators that measure fluctuations of various quantities such as baryon number density or energy density. For finite quark masses there is no true singularity, but sharp behaviour. This work has been most strongly developed by Karsch and Redlich[17].

In a number of presentations by Herold, Nahrgang, Wink, Bluhm, Yin, Ridgway, Sochorova, Tomasik and Rustamo, it was shown how such underlying behaviour might be measured and computed in heavy ion collisions[22],[23],[24],[25],[26],[27],[28] [29],[30]. In particular, one needs to understand for various initial conditions how close does one evolve to a hypothetical critical end point and how does such an evolution affect the extraction of underlying fluctuation measures.

4. The Chiral Magnetic and Chiral Vortical Effect

Heavy ion collisions allow one to probe matter in the presence of high magnetic fields and at high angular momentum.. Such magnetic fields and angular momenta may generate topological

excitations of the underlying field theory. For example, if there is a fluctuation in the underlying helicity of quarks, then an external magnetic field will generate an electromagnetic current. This is the Chiral Magnetic Effect[31]. High angular momentum can generate vortices[32]. Mao discussed the general problem of QCD in external magnetic fields[33]. Sorin discussed the chiral magnetic and chiral vortical effect, and presented beautiful simulations of velocity and vortex fields that might be produced in collisions at NICA energies[34].

5. Varying the Baryon Number Density at High Energy

Most of the discussion of high baryon number density concerns collisions at low energy. Some thought needs to be given to the proposal described by Brewster[35]: Are we better to change baryon density by varying rapidity at fixed energy or by varying the energy over a fixed region of rapidity? In principle one could study the high baryon density region by going to very high energy and looking in the target fragmentation region. There are arguments that T/μ_B is approximately beam energy independent at fixed rapidity. This means that one can start with very high T and μ_B and it evolves with this roughly fixed rapidity[36]. After expansion, one has produced a baryon rich system like that produced at low energy, except that it is expanding very slowly. To properly set up this problem, one needs a good theoretical treatment of initial conditions.

6. Neutron Stars

The recent measurements of neutron star properties such as mass radii and gravitational radiation from neutron star collisions has led to a better understanding of the equation of state of high baryon density matter. As argued by Stoeckle, shown in Fig. 4, neutron star collisions occur over a range of temperature and density that might be accessible to laboratory experiment

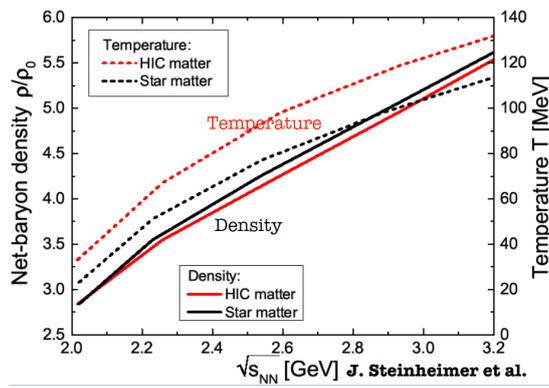


Figure 4: Temperature and density accessible in lab experiment and probed in neutron star collisions

Constraints from neutron star mass radius relations have led to a very interesting constraint on equation of state of nuclear matter. For a recent article on such determination and references to the original literature, see Ref. [37]. At energy densities only a few times nuclear matter densities, these analyses agree that the sound velocity squared should become (in units of the speed of light)

$$v_s^2 \geq 1/3 \quad (6.1)$$

This is a truly remarkable result, The sound velocity for a zero temperature gas is determined by

$$v_s^2 = \frac{N_B}{\mu_B dN_b/d\mu_B} \quad (6.2)$$

This can be reexpressed as

$$\frac{\delta\mu_B}{\mu_B} = v_s^2 \frac{\delta N_B}{N_B} \quad (6.3)$$

In this equation, the baryon chemical potential or Fermi energy includes the effect of the nucleon mass. If the sound velocity is of order one, then an order one change in the baryon density induces a change in the Fermi energy of nucleon that is of the order of the nucleon mass! This is far different from the situation of nuclear matter where the Fermi energy (minus the nucleon mass) is of the order of 10's to at most 100 MeV.

While it may be true that even at such high chemical potential, the energy density of nuclear matter might still be computed using conventional nuclear many body theory, the assumptions of such computations are surely open to doubt. In presentations of Blaschke, Motornenko and Fischer, various quark model computations were described[38], [39], [40].

We can easily see that understanding a relativistic sound velocity for nuclear matter is not so easy. It would be tempting to say it was due to chiral symmetry restoration. The Fermi momentum of a nucleon is $k_F = \sqrt{\mu_B^2 - M_B^2}$. If M_B shrinks to zero as the chemical potential increases, then at zero M_B , the Fermi momentum will be $k_F^B \geq M_B$. This corresponds to a huge baryon density $\rho_B \sim k_F^3 \sim M_B^3$ that is about 100 times larger than that of nuclear matter. This is too high a density to be relevant for neutron stars.

To avoid this problem we can introduce quark degrees of freedom[41]. In this case if we make a transition between a system dominated by nucleons to one dominated by quarks, effectively the baryon chemical potential, which at nuclear matter density corresponds to a Fermi momentum of order $k_F^B \sim 300 \text{ MeV}$, can become of order $k_F^B \sim M_B$. However if during this transition, the degrees of freedom are entirely transferred into quarks, the density does not go up so high, because $k_F^Q \sim k_F^B/3 \rightarrow M_B/3 \sim 300 \text{ MeV}$. Therefore the baryon density in quarks does not increase by a huge amount.

This feature of QCD can be understood in the large N_c limit and the ability to transform continuously nucleon degrees of freedom into quark degrees of freedom is a characteristic of Quarkyonic Matter[3].

Such a transition means that the baryon chemical potential may increase by a large amount without the baryon number density much changing. The pressure therefore goes up rapidly. The energy density (that is dominated by the nucleon mass times the density) also does not rapidly change. The transition to quarks in Quarkyonic Matter does not involve a phase transition. It is quite the opposite. In the large N_c limit, the baryon chemical potential and pressure jumps by a huge amount at almost constant energy density and baryon number density. This is the precise opposite of what occurs for a phase transition. This is precisely what is needed to generate the hard equation of state needed to support neutron stars.

7. Acknowledgements

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