Quark Gluon Plasma

Hadronic matter at normal energy densities is composed of confined, color neutral quarks and gluons. At very high energy densities, theoretical models predict a transition should occur wherein the hadrons "melt" together to form a weakly coupled deconfined plasma of quarks and gluons, i.e. quark gluon plasma (QGP). Experimental evidence suggests that the state of matter formed in the high energy Au-Au collisions at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is actually a strongly coupled plasma. In this paper I shall discuss some of the basic features of QGP as well as experimental evidence from the RHIC experiments (PHENIX, STAR, BRAHMS, PHOBOS) that supports its existence.

Introduction

Quark gluon plasma (QGP) is the state of matter formed when one "squishes" hadronic matter together at very high temperatures and densities. The very high energy density causes a phase transition amongst the hadrons; the collection of hadrons "melt" together into a plasma of quarks and gluons [1-5]. This state of matter is thought to be the state of matter a few microseconds after the big bang occurred [6, 7], and so has great importance cosmologically. Additionally, this form of matter may give us an insight into the matter/anti-matter and baryon/meson ratios that are present in our universe [8].

A great deal of experimental evidence has been gathered that supports the formation of quark gluon plasma in Au-Au collisions at the Relativistic Heavy Ion Collider (RHIC). RHIC is a large 3.8 km circumference ring at Brookhaven National Laboratory. It can provide center of mass collision energies of up to 250 GeV per nucleon [2-5]. There are four experiments at RHIC (PHENIX, STAR, PHOBOS, BRAHMS) which all have been working for the past seven years to understand this novel state of matter.

Asymptotic Freedom and QGP

In 2004, Gross, Politzer, and Wilczek received the Nobel Prize for their discovery of asymptotic freedom; essentially this is a theory that showed a decrease in the strong coupling constant with an increase in momentum transfer or distance scales between quarks. This result was (and still is) very significant for both its physical meaning and calculational applicability. From a calculational standpoint, it says that at high energies we can perform perturbative QCD calculations, while at low energies QCD calculations will be very difficult. Physically, it means that at low energies one cannot find de-confined quarks, but must always find pairs or trios of quarks coupled together by gluons. However, at high energies, one can essentially neglect these gluonic interactions and consider quarks "free".

Because RHIC collisions have a very high energy density (and therefore a high temperature) it was thought that the QGP created there would be one such that its constituent partons would be asymptotically free and would only very weakly interact and thus behave similar to a Fermi gas. However, at the energy densities of collisions at RHIC, it has been shown by experiment that the plasma behaves more like a perfect liquid of strongly interacting quarks and gluons than a gas [10]. This makes some theoretical sense because the strong coupling constant is still of order unity and any perturbative calculation is quite suspect in this regime (it is suspect until one reaches ~ 1000 times the critical temperature) [11]. At higher temperatures, it is still believed that a gaseous state of quarks and gluons can be found [11, 13].

So how can we categorize QGP with known forms of matter? PHENIX spokesperson Bill Zajc in his 2006 DNP talk [12] said that instead of QGP we should call the plasma SGP (sui generis plasma), which means unique, or of its own kind. What he means is that QGP does not fall into any category of matter we have before encountered. So how is exactly do we characterize this form of matter? It is done by using many of the familiar thermal properties that are used in matter at ordinary densities and temperatures, e.g. energy density, pressure, chemical potential, viscosity, entropy. Many of these properties have been calculated by using lattice QCD calculations, wherein a functional integral for the partition function is calculated and thermodynamic properties are calculated from this partition function [6]. In Figure 1, I show the energy density as a function of temperature. It is predicted that above the critical temperature ($\underline{\varepsilon}$ = 1 Gev/fm^3, or T = 170 MeV) there will be a plateau corresponding to a region where the energy density scales like the Stefan-Boltzmann equation [15]. This corresponds to what one might expect from an ultra-relativistic Fermi gas (the pressure and entropy behave according to this prescription as well) [15]. However, as briefly mentioned before, RHIC probes a strongly interacting liquid of quarks and gluons which have essentially zero viscosity [2-5]. How are these two ideas consistent? It turns out that both that both the lattice QCD calculation result (less than the Stefan-Boltzmann equation prediction by ~ 20%) and an extremely small viscosity can be predicted by gravitation phenomena in N=4 supersymmetric theories [12]. Quark gluon plasma is a very new state of matter and we are only now beginning to elucidate some of the features of the plasma created at RHIC. Theorists' predictions have not yielded definitive results as to the order of the transition from ordinary hadronic matter to QGP [2-5, 15]. A phase diagram is shown in Figure 2 for the phases of hadronic matter. On the x-axis the baryon chemical potential is plotted which basically scales with the density of baryonic matter. In addition to quark gluon plasma, there are other exotic states of matter such as a cold color superconducting phase.

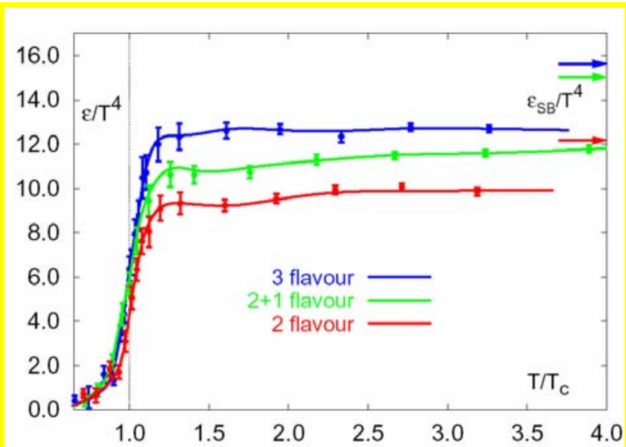

Figure 1: ε/T^4 vs Tc [14]. The region from approximately T/T_c is range of temperatures that RHIC is believed to probe.

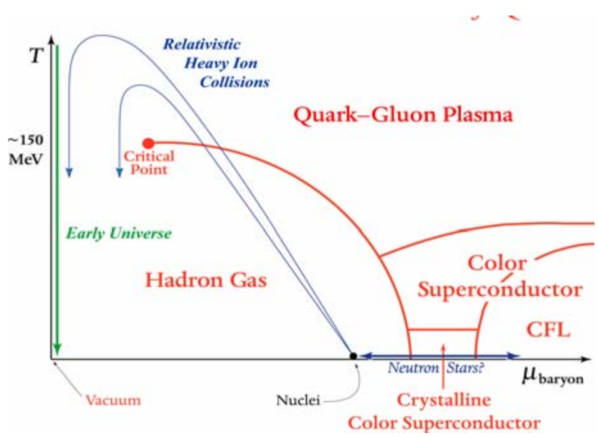

Figure 2: Phase Diagram for QGP [12]

It is very natural to introduce some of the features of quark gluon plasma as a discussion of the experimental signatures proceeds and hence these will be delayed until the experimental signatures are discussed.

Dynamical Considerations of Au-Au collisions

Now, one may ask what makes the energy densities in Au-Au collisions larger than in p-p collisions. After all, if we strip one electron from the protons and one electron from the gold atoms the energy will end up being the same. The first thing one must understand about the collisions at RHIC is that *every* electron is stripped from each gold atom by running them through a series of aluminum foils [8]. Thus each nucleon in the gold atom contributes to the net charge of the atom and results in an extremely high

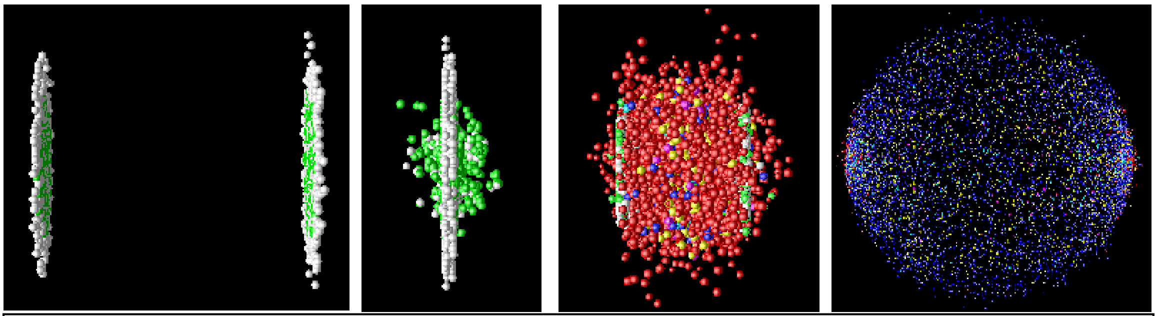

Figure 3: The Stages of an Au-Au collision at RHIC [16]

energy particle. The energies in these collisions usually range from center of mass energy per two nucleons of 130 GeV < $s_{NN}^{1/2}$ < 200 GeV [2-5]. The p-p collisions at RHIC also run at 200 GeV, and so these can be used to make important comparisons with the Au-Au collisions (discussed in the jet quenching section). One may also argue that in Au-Au the collisions are just nucleon-nucleon collisions, and the density of nucleonic matter is no greater in Au-Au than in pp. However, one must realize that the nucleons in Au-Au collisions move at ~99.95% the speed of light, and participate in relativistic collisions in which the nuclei are contracted along their directions of motion. Hence we must essentially contract "columns" of nucleons together to a single point. Instead of having two spherical atoms collide, we in fact have two flat disks colliding together, and all atoms essentially collide at the same instant in time [6]. The number of nucleons present is greatest in the center of the atom and decreases as one moves radially outwards; therefore, the energy density is the largest at the center. A corollary to this fact is that we expect peripheral collisions to have a lower energy density than central collisions. This is an important point that will be re-iterated in the discussion of jet quenching.

Jet Quenching

One of the major indicators for quark gluon plasma is jet quenching [2-5, 13, 16]. The basic idea is that if QGP is present then the jets of final state baryons and mesons that are emitted from the plasma will lose some of their energy due to strong interactions with the plasma (gluon brehmstralung, or scattering [6]), which will result in a lower energy of the resulting particles. Since this is difficult to interpret in the longitudinal direction (the direction the beams are initially moving in), the transverse momentum/energy spectrum is used [8]. Specifically, if QGP is actually formed, one expects to see a suppression in the yields of high transverse momentum particles. A difficulty arises because one needs a reference Au-Au collision that does not evolve to QGP in order to see a suppressed p_t spectrum. The reference is created by looking at p-p collisions, and using a process known as binary scaling to essentially match the number of nucleon-nucleon collisions to proton-proton collisions. A skeptical reader would ask is this actually an acceptable

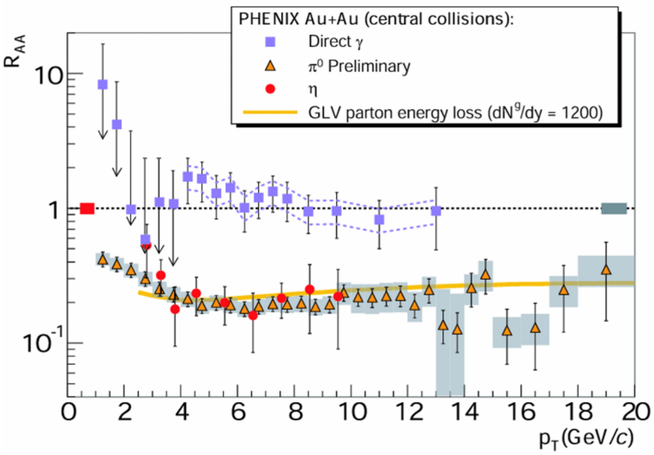

Figure 4: R_{AA} for hadrons and direct photons [16]

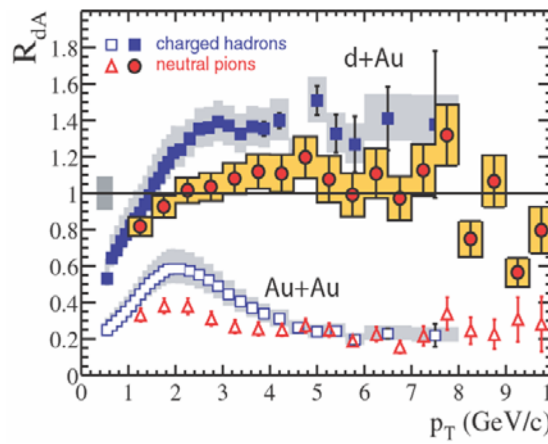

Figure 5: R_{AA} for hadrons and D-Au [17]

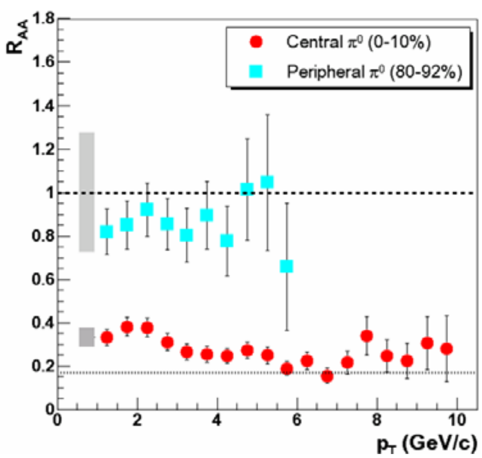

Figure 6: R_{AA} for hadrons in central and peripheral collisions [17]

method? In order to test the method, the same comparison was done for photons which only interact via the electromagnetic forces. The ratio R_{AA} is the essentially the ratio of the particle yields of Au-Au collisions to the binary scaled p-p collisions. $R_{AA} < 1$ implies suppression, while $R_{AA} > 1$ implies enhancement. In Figure 4 one can clearly that for high transverse momentum there is a large suppression for the π^0 meson, whereas there is no suppression for the photons. Note that one needs to look above 2 GeV, because the low transverse momentum hadrons and photons are subject to other effects.

Another competing effect one needs to consider is an initial state effect called the color glass condensate which has to do with initial state gluon screening [15]. However, this effect should also be present in the deuteron-Au (d-Au) collisions (though not as strong as in Au-Au). By looking at the suppression in the d-Au spectra (Figure 5), we see that the suppression is in fact a final state effect and does not result from the initial state CGC.

Additionally, we can look at R_{AA} as a function of collision centrality. We expect central collision to have the largest suppression, and hence the smallest R_{AA}. Figure 6 shows that indeed this is confirmed for π^0's (and other particles as well. Below I show diagrams of central and peripheral Au-Au collisions.

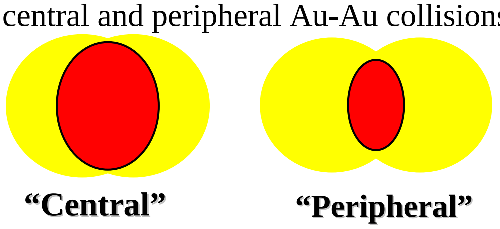

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Figure 7: Central and Peripheral collisions at RHIC

Another aspect of jet quenching is that most processes are 2 → 2 processes in which two particle are formed from the resulting collisions. Thus one has back-to-back jets that form from the collisions. For Au-Au collisions at RHIC, it has been shown by the STAR collaboration that the away-side jet actually disappears at a given cutoff p_t as is shown in Figure 8 (bottom plot). The comparison with pp (binary scaled) and d-Au are also shown in this plot. In these plots one can clearly see the away side jet. In Au-Au, the away side jet actually is still present (at a lower energy) and it seems possible that the interaction with the QGP fluid resembles that of a QCD sonic boom [12] as shown in Figure 9.

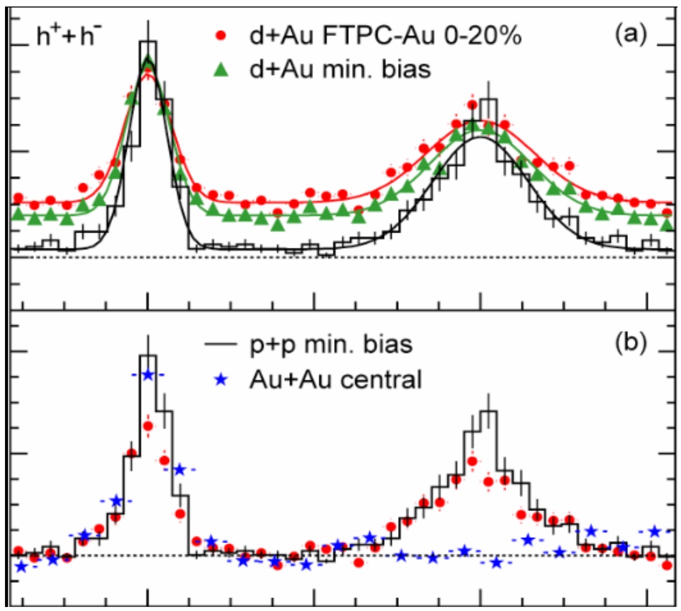

Figure 8: Correlations between Jets for pp binary scaled (red, bottom) Au-Au (red, bottom) [18]

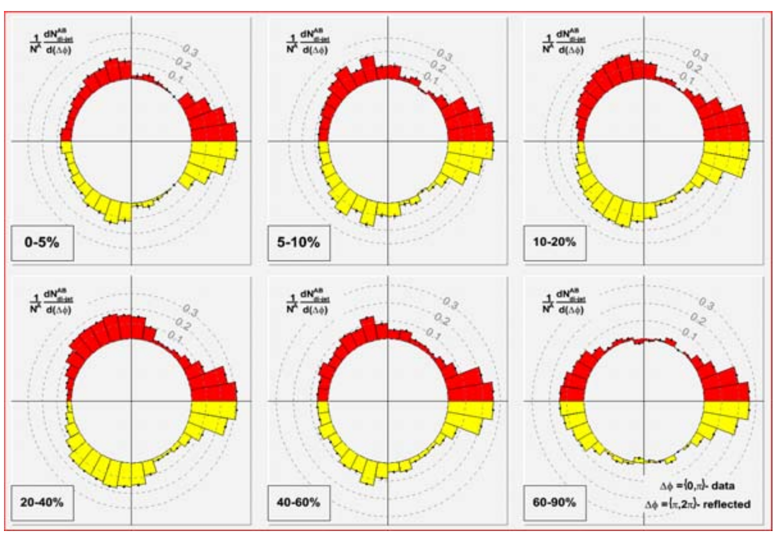

Figure 9: Mach Cone-like behavior as a function of centrality for Au-Au collisions [12]

A Perfect Liquid

What exactly does a liquid quark gluon plasma mean? Surely we cannot pour it into a cup and feel the "wetness" of the liquid. In the case of quark gluon plasma, this refers to the elliptic flow of the small p_t outgoing hadrons. This elliptic flow is a consequence of the overlap between the two gold nuclei in the collision. Their overlap creates an elliptical shape. Now, assuming the pressure to be zero at the edges of this ellipse, we see that the pressure gradient from the center of the ellipse is greater to the semi-minor axis than to the semi-major axis. From hydrodynamical calculations, one can show that a fluid with these initial conditions would approximately exhibit the following Fourier decomposition [15]

$$dN/d\theta \sim 1 + v_2 \cos 2\theta.$$

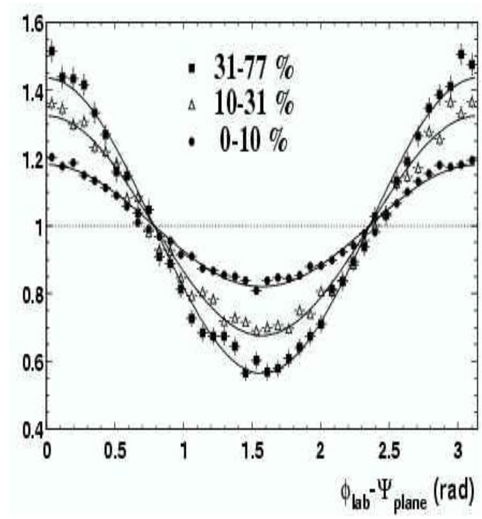

Figure 10: Angular distribution of elliptic flow

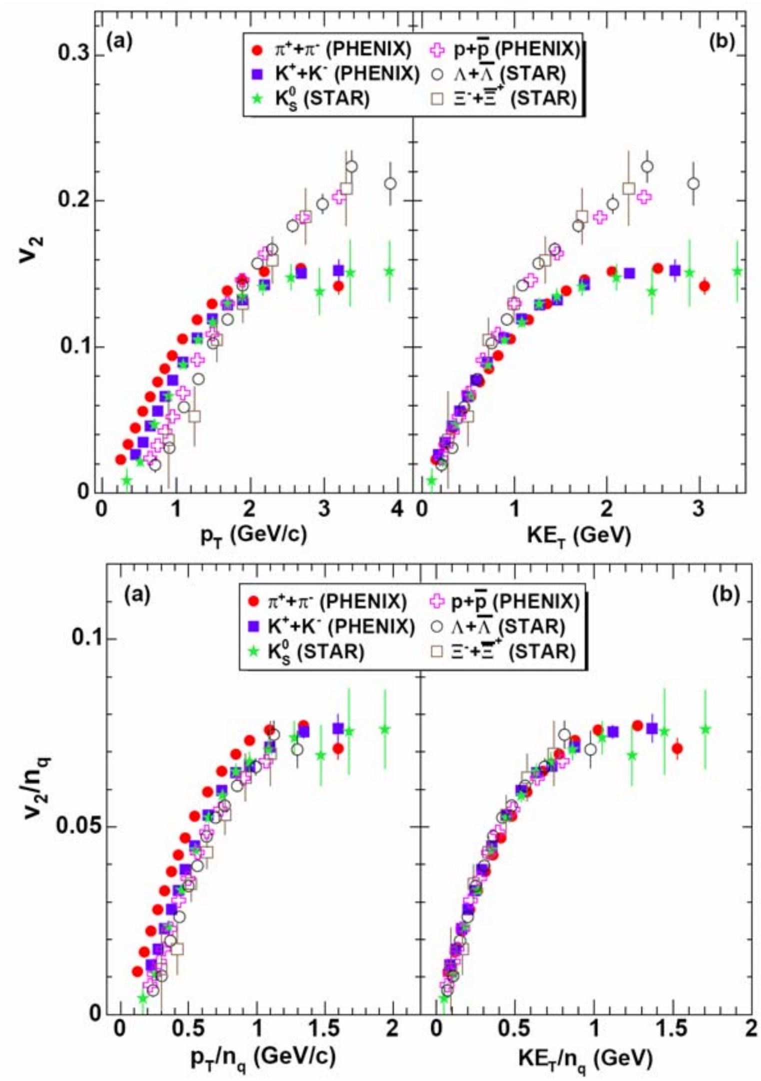

Figure 11: v_2 as a function transverse momentum, Energy and scaled for particle number [12]

When we measure this component in RHIC, find very good agreement with this theory. The results for the distribution and for v_2 are shown Figures 10-11. Specifically considering Figure 10, when we view the results for v_2 as a function of p_t, we find a fairly good agreement between the different hadrons. However, if we scale the results as function of transverse energy, we find better agreement, but with two different curves, one for baryons and one for mesons. When we further divide by the number of quarks in each particle (2 in mesons 3 in baryons), we find the striking result that our calculation yields the same value of v_2 for all particles. What exactly does this mean? It first shows that we are dealing with something that is like a liquid. Additionally, it seems as though each individual parton is interacting with the fluid in a strong manner, and it is not the mesons or baryons that are interacting; hence this gives evidence for the strongly interacting nature of the plasma [8].

Now, not only does QGP show the behavior of a liquid, it exhibits characteristics of a perfect liquid (almost as perfect as is allowed by the quantum limit [12]). This has extremely important consequences in how we describe QGP. In the weakly coupled limit, estimates show that the ratio of viscosity to entropy density should be large; however, we have found this ratio is nearly zero [15]. This implies that the strong coupling constant cannot be small in this regime, which is in disagreement with QGP behaving as a deconfined state of quarks and gluons. Hence there has been both a major experimental and theoretical paradigm shift in how we view quark gluon plasma in RHIC. It is actually called sQGP (strong quark gluon plasma), and is modeled as a liquid instead of a gas. One should note that QGP in the deconfined state is predicted to exist at much higher temperatures.

Conclusion

In conclusion, the quark gluon plasma formed at the RHIC is a very interesting, novel phase of matter that has yet to be fully understood. The QGP at RHIC is not what was at first expected – a collection of deconfined quarks and gluons, but it instead a strongly interacting plasma of these constituents. As both the theory and experiments develop, the study of QGP has great potential to increase our understanding in the fields of cosmology, astrophysics, QCD/high energy physics, nuclear physics, string theory, etc, and is a very interesting topic of study (I spent one summer doing research in this field).

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