RHIC and the Quark Gluon Plasma

Will Link

Abstract

One of the American Institute of Physics's top stories of the year 2005 was the discovery of the quark gluon plasma at RHIC. In this paper, the basic theory of the quark gluon plasma is reviewed, and the experimental evidence from RHIC discussed.

I. INTRODUCTION

The 2004 nobel prize was awarded to David Gross,H. David Politzer and Frank Wilczek for the discovery of asymptotic freedom in the theory of nuclear matter, quantum chromo-dynamics. Asymptotic freedom is a fancy way of saying that as distance scales decrease and energy scales increase the coupling constant for the theory gets smaller and smaller. Soon after this discovery, it was realized that this implies that at very high temperatures or very high densities the interactions between quarks grows smaller and smaller. At very high densities, these interactions could be small enough that the quarks no longer bind together to form nuclei but instead roam freely through the system.[5]

At normal length and energy scales, free quarks are never observed, and hence this prediction of free quarks is essentially a prediction of an entirely new form of matter. These free quarks have free color charges, just as the particles in a traditional plasma have free electric charges. Hence, just as the charged particles in the traditional plasma screen the coulomb interaction, free color charges screen the strong interaction. This screening washes out the long length scale interactions which would grow large for the quarks. This analogy with the traditional plasma lead to the new state of matter being known as the quark gluon plasma.[12][9]

Understanding the quark gluon plasma could lead not only to new understandings of QCD, but also to understandings in cosmology and astrophysics. The conditions right after the big bang would have been ideal for the formation of a quark gluon plasma, and [13] there have also been suggestions that color-charged matter might be important in certain types of stars.[11]

With such a fascinating prediction in hand, clever experimenters were almost certain to figure out ways to probe for the quark gluon plasma. In 2000, after nearly ten years of development and construction, the Relativistic Heavy Ion Collider came online.[1] This experiment collides gold nuclei in the hopes of creating and studying the quark gluon plasma. To the delight of everyone involved, the experiment at RHIC has been very successful. Even more fascinating, the state of matter that was created was far from a weakly interacting gas. In fact, the quark gluon plasma behaves like a nearly ideal fluid.[2]

In this paper, I will first describe the predicted properties of the quark gluon plasma. Next, I will explore the experimental reasons why it is believed that RHIC has actually created a quark gluon plasma, despite the surprising fact that it does not completely match the original prediction. I will then survey some of the theoretical models that have been developed in order to explain this strongly interacting quark gluon plasma observed at RHIC.

[1] from the RHIC website http://www.bnl.gov/RHIC/

II. THE PREDICTION

Due to asymptotic freedom, as the energy scales and densities in nuclear matter increase the strength of the coupling decreases. What this means for theorists is that calculations on the quark gluon plasma can be done perturbatively. These perturbative calculations were thought to, at least qualitatively, describe the quark gluon plasma right from the critical temperature.[14]

The picture of the quark gluon plasma that emerges from this calculation is a simple one. Theorists argued that while an experiment like RHIC would produce many quarks and gluons, these would quickly turn into a cascade of jets not much different than many independent proton-proton collisions. Any small deviations away from independent proton-proton collisions could be calculated using perturbative QCD. [14][9]

Where densities are lower, and perturbative theory breaks down, there is one other important theoretical tool for working with QCD. Known as Lattice QCD, this approach involves putting space-time on a lattice and working to compute the grand canonical ensemble for the system numerically. This method allows computational evaluation of the quark system as the system moves toward the critical temperatures and has been a very important tool in studying the phase transition that is believed to take place.

Through both of the methods above methods, some understanding of the confined/quark gluon plasma phase transition has been made. Figure 1 shows a sketch of the phase diagram determined by one such calculation. From these lattice calculations, $Tc \approx 150 - 180$ MeV and the phase transition is second order. [8][7]

III. EXPERIMENTAL EVIDENCE

Having discussed a few theoretical predictions of the quark gluon plasma, let us now turn to actually detecting such a thing. There are a number of experimental obstacles making it hard to directly observe the phase transition. It is important to realize that the timescales over which the collisions at RHIC take place are on the order $\sim \frac{10fm}{c}$. Hence, its not at all clear that what is taking place is a phase transition between two states in thermal equilibrium. This, unfortunately, obscures the signatures of the phase transition.[2]

Hence, experimenters have to be more clever in order to see the signatures of the quark gluon plasma. One of these clever approaches is looking at how the properties of particles are modified by their interactions with the quark gluon plasma.

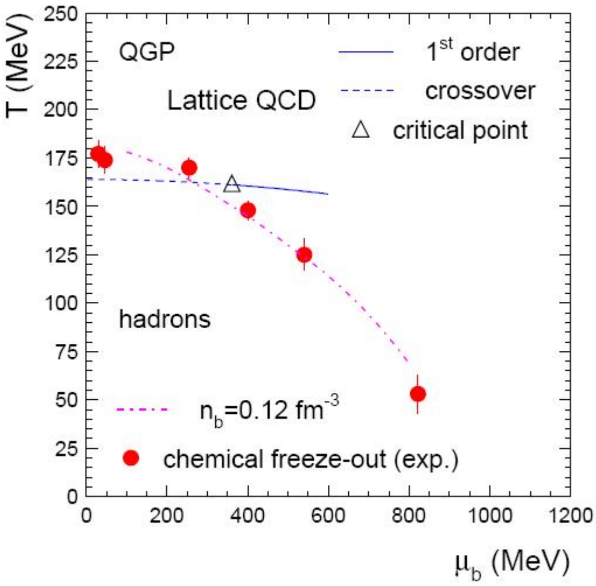

FIG. 1: A Lattice QCD calculation of the phase diagram of hadronic matter. The Red Dots are experimental measurements of the hadron freeze out. Temperature is plotted against baryon chemical potential.Figure taken from[4]

One such interesting modifications of particle properties is that vector mesons are expected to melt in the plasma. These mesons are pairs of quark/anti quarks. Because of this melting, it is expected that if a quark gluon plasma is present in the system, fewer such particles will be produced in the collisions. One such vector meson, the J/ψ particle decays fairly often into two muons. These heavy leptons are particularly easy to detect, and hence measuring J/ψ cross production and comparing it to a normal proton-proton collision gives one potential signature of the existence of the plasma. This J/ψ suppression is confirmed in data from RHIC.[2][16]. Figure 2 shows the suppression in one such experiment. There is similar suppression in other mesons such as pions.

Suppression of vector mesons isn't the only, or even the most important, signature of the quark gluon plasma. As particles travel through the quark gluon plasma, they interact with the free color charges in the color-equivalent of bremsstrahlung. Hence, we can expect in a quark gluon plasma that we will not have many high transverse momentum particles, as the momentum will be dissipated through this interaction.[2][16] Figure 3 shows that just such a transverse momentum suppression is seen. Particularly surprising is the failure of perturbative QCD to explain the suppression.

While looking at modified particle properties has provided some evidence for the plasma, there is yet another method in which experimenters can search for evidence of the quark gluon plasma. Instead of looking at individual particles and how they react with the quark gluon plasma, experimenters can look for collective behavior.

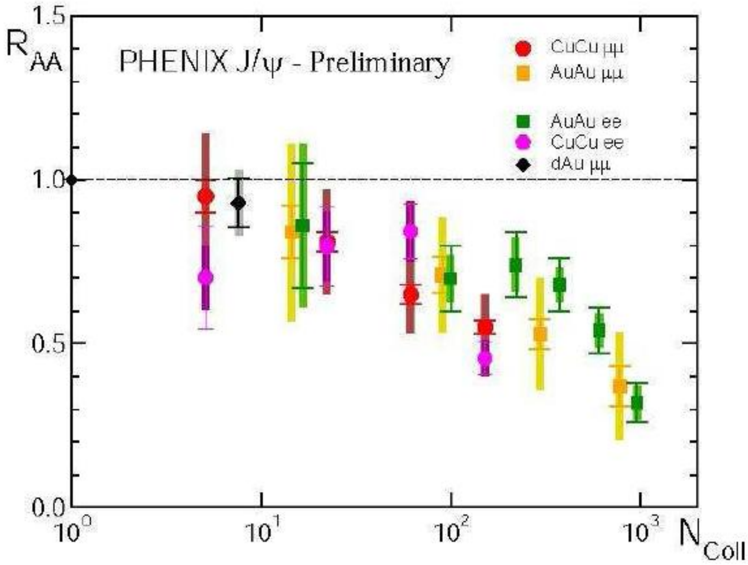

FIG. 2: J/Ψ production, normalized to a proton-proton collision. Figure taken from [1]

While perturbative calculations would suggest otherwise, it is this collective behavior that makes the quark gluon plasma extremely interesting.[10][13]The results from RHIC, surprisingly, do show collective behavior. In fact, results from RHIC match very well with a fluid. Figure 4 shows data taken from RHIC along with calculations made using a fluid model.[13][15] This is significant, because a fluid implies strong interactions.

Even more surprising is the viscosity to entropy ratio observed in this fluid. $\frac{\eta}{s} = .1 - .2 << 1$ This ratio is one measurement of how "ideal" a fluid is. By this measure, the fluid at RHIC is the most ideal fluid thus far discovered. Exactly why this should be the case remains quite a mystery.[13][2]

The astute reader could ask the question, if this matter is strongly interacting how do we know it really is a quark gluon plasma? The BRAHMS collaboration suggests that the "smoking gun" that indicates the formation of the quark gluon plasma is the transverse momentum suppression discussed above. This transverse suppression/Bremsstrahlung effect indicates that the particles are interacting with color charges over length scales longer than nucleons. Free color charges imply free quarks, which are the fundamental property of the quark gluon plasma. [2]

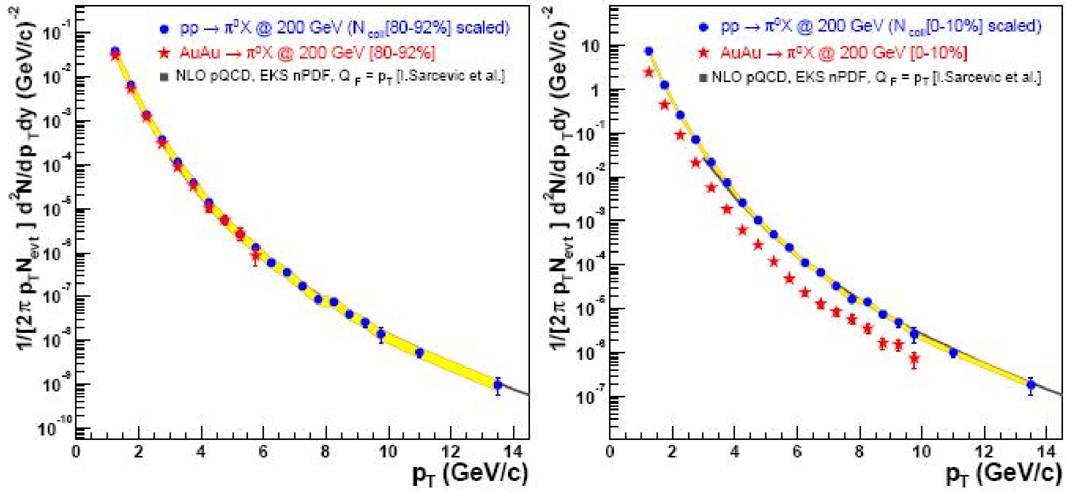

FIG. 3: Transverse cross sections from data taken by PHENIX, plotted against proton proton measurements and a perturbative QCD calculation. Notice both the suppression and that perturbative QCD fails to predict the results. On the left we have peripheral collisions, on the right we have central collisions. The Figure taken from [6]

IV. TOWARDS THE STRONGLY INTERACTING QUARK GLUON PLASMA

Now that the results from RHIC have started to come in, theorists are left with an interesting challenge. How can this strongly interacting quark gluon plasma be explained?

Some theorists have decided that the quark gluon plasma must be weakly interacting, and that what RHIC is actually seeing can be explained without the need for strong interactions. For instance, it has been suggested that for an anisotropically expanding quark gluon plasma could give rise to an anomalous viscosity as thermal quarks interact with the color fields of the plasma. This viscosity could dominate over the collision-based viscosity for weak coupling. The hope is to rescue the gas description of the plasma.[3]

However, most theorists believe that what RHIC is seeing is a strongly interacting quark gluon plasma. They believe this because, in addition to the experimental evidence mentioned above, theoretical lattice QCD work also suggests this should be the case. In the lattice models, many bound states are present, which could help enhance transport properties and lead to the fluid-like behavior seen at RHIC.[7][13]

Having these strong reasons, where does this leave theorists? Theorists have been

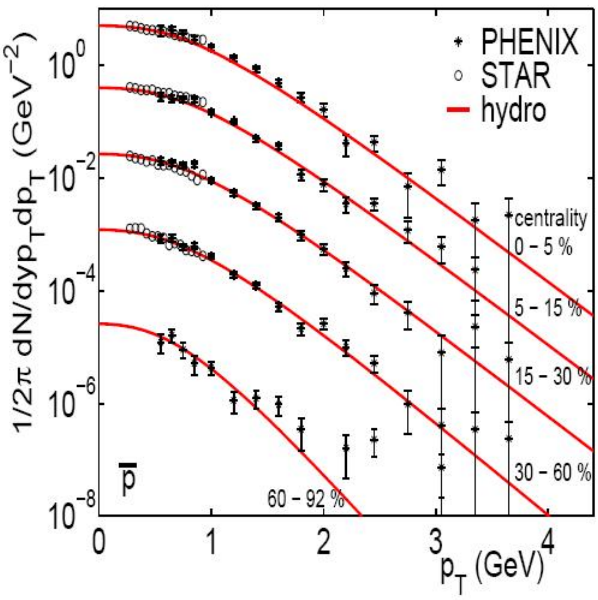

FIG. 4: A plot of calculations made from hydrodynamic calculations plotted against experimental data from RHIC. Notice how good the fit is. Taken from[13]

able to make progress by comparing the strongly interacting quark gluon plasma to other strongly interacting systems, such as strongly coupled traditional plasmas. In fact, strong traditional plasmas are fairly good fluids, just like the quark gluon plasma.[13][15] Other strongly interacting systems that have been suggested for comparison are cold, trapped atoms.[13]

Other areas for potential theoretical exploration include the super-symmetric Yang-Mills field theory/Anti-de Sitter Spacetime correspondence.[15][13] This idea is beyond the scope of this paper.

V. CONCLUDING REMARKS

To conclude, the experimental evidence indicates that not only has the quark gluon plasma been seen at RHIC, but that it is surprisingly strongly interacting. These results give theorists new questions, questions that could lead to the resolution of the now decades old problems of confinement of quarks, and a better understanding of the nuclear matter that makes up our everyday world.

So important, and so startling are these results that in just the few years that RHIC has taken data, the discovery of this new form of matter has caused a paradigm shift in the field of quark gluon plasma research, to paraphrase Edward Shuryak.[14] This paradigm shift could lead to dramatic new understanding not only of the everyday matter around us, but also of the conditions that prevailed shortly after the big bang. In a very real sense, the scientists at RHIC are probing the nature of the universe both as we know it today, and as it was at the very beginning.

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