Research Description

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Introduction and Motivation

In the first few microseconds following the Big Bang, the very hot and dense Universe was thought to be in a state of matter known as the *quark gluon plasma* (QGP). The QGP is rather different from the normal matter we observe everyday; protons and neutrons are examples of particles in which quarks and gluons are bound. It is said that quarks and gluons are *confined* in Nature; we do not observe them individually as free particles, but only in composite objects which are composed of quarks and gluons bound together tightly. For example, while we observe the proton (a particle consisting of two up quarks and one down quark), we do not observe those three quarks individually in Nature. However, it is thought that at sufficiently hot and dense conditions, one can "liberate" quarks and gluons from the confined state. The state in which quarks and gluons are not confined, but quasi-free or *deconfined*, is known as the QGP.

Why is the QGP useful to study? It will not only give us insight into how the medium of the Early Universe behaved, but will help us understand how nuclear matter behaves under extreme conditions. Scientists at many high energy accelerators, including the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory on Long Island, New York attempt to recreate the QGP by colliding heavy nuclei (such as Copper, Lead, and Gold) at speeds very close to the speed of light. The hope is that colliding sufficiently heavy particles at very fast speeds will compress and heat the matter to the degree necessary to produce the QGP. However, one of the biggest challenges involved in analyzing the QGP is that the state is transient; it is so short lived (lifetime is on the order of $\sim 10^{-23}$ s), that the quarks and gluons recombine to from bound states (known as *hadrons*), and the particle detectors in such experiments measure properties of the final-state hadrons rather than the free quarks themselves.[2] As a result, there is a great deal of detective work in phenomenology and theoretical modeling involved in identifying possible signatures for the existence of a QGP, and investigating such properties.

One of the top science stories of 2005 was the discovery of a "near perfect fluid" at RHIC.[1, 2, 3] It was previously expected that if a QGP were to be created at RHIC energies, the resulting matter would be a gas. However, a great deal of experimental evidence exists suggesting that the state created at RHIC is not only not a gas, but a nearly ideal fluid.[4, 5, 6, 7] The resistance to flow in a fluid is characterized by a quantity known as the shear viscosity (η). Traditionally, an ideal fluid has been defined as having $\eta = 0$. However, such a fluid is unphysical, and there has been a paradigm shift in defining an "ideal fluid." The related quantity proposed for this definition is the viscosity to entropy ratio $\frac{\eta}{s}$, where s is the *entropy density*. A crude way to think about the entropy is that it characterizes the amount of disorder in the system; how many possible configurations a system can take at a given time. In particular, a revolutionary technique in string theory, which has long been criticized in the scientific community as failing to produce any concrete, falsifiable results, has predicted a possible minimum bound for a class of fluids: $\frac{\eta}{s} \geq \frac{\hbar}{4\pi k_B}$, where $\hbar$ is Planck's constant divided by 2π, and k_B is Boltzmann's constant.[8] This famous result, known as the Kovtun-Son-Starinets (KSS) bound, conjectures that the most "ideal fluid" should have a value corresponding to $\eta{=}s\left(\frac{\hbar}{4\pi k_B}\right)$. Thus, understanding the QGP created at RHIC will also help us better understand the nature of near perfect fluidity. It should also be noted that a program for performing such collisions of heavy ions at very high speeds is also planned for the Large Hadron Collider (LHC), which has recently opened near Geneva, Switzerland. There further exists speculation that a QGP created at the LHC would actually be a fluid with a higher viscosity, and the current relativistic heavy ion community is anxiously awaiting the heavy ion experiments due to begin in 2010.[9]

A cartoon of a relativistic heavy ion reaction is shown in Figure 1. The two pancake-shaped objects in the "initial state" panel represent heavy nuclei (such as gold nuclei) colliding at very fast speeds. The "pre-equilibrium" phase refers to the process where the nuclei collide and "mesh", and scattering among the quarks and gluons takes place. The "QGP and hydrodynamic expansion" phase is where the QGP thermalizes, and then expands like an ideal fluid. "Hadronization" refers to when the quarks and gluons of the QGP reorganize into bound states called hadrons (protons and neutrons are examples of hadrons). "Freezeout" refers to when the hadrons stop colliding with each other, and travel to the particle detectors. When discussing the "ideal fluid" behavior of the QGP, the relevant question to ask is "What is the viscosity to entropy ratio of this mystery medium?" In order to get a real quantitative estimate of this quantity, one must do a separate calculation of $\frac{\eta}{s}$ of the hadronic phase, as this quantity is what is relevant when theorists and phenomenologists perform the detective work to backtrace from the data measured in the particle detectors to the QGP state in a relativistic heavy ion collision.

My research is specifically concerned with extraction of *transport coefficients* of the hadronic and QGP phases of a relativistic heavy ion reaction. Transport coefficients are physical quantities which characterize the nature of medium interactions. The "transport" refers to the transfer of physical properties through the medium. In particular, the transport coefficients relevant to my research are the shear viscosity coefficient and the diffusion coefficient. The shear viscosity coefficient is relevant for momentum transfer in the medium, and the diffusion coefficient is relevant for transfer of particle concentration in the medium. The media created in these relativistic heavy ion collisions involves a large number of different particle species, and traditional theoretical methods in nuclear and high energy physics give at best very crude approximations for describing the media created in such collisions. However, with the multiple advances in computational power and modeling, sophisticated models have been successfully developed (known as *microscopic transport* models)and tested which provide fairly accurate descriptions of the deconfined and hadronic media created in relativistic heavy ion collisions. My research exploits such microscopic transport models, and involves calculating the shear viscosity, viscosity to entropy ratio, and the diffusion coefficients for a system which resembles an equilibriated QGP and hadron gas. Our hope is that when such sophisticated, state of the art calculations are completed, verified for self-consistency, and systematic uncertainties properly assessed, one could obtain a much better constraint on the values for the transport coefficients of the elusive state of matter sought after at RHIC and the LHC. Knowledge of the transport coefficients of hot and dense nuclear matter is not very well known, and must be improved if one is to gain a better understanding not only of the medium interactions in the Early Universe, but also of systems which are thought to be "near-ideal" in Nature.

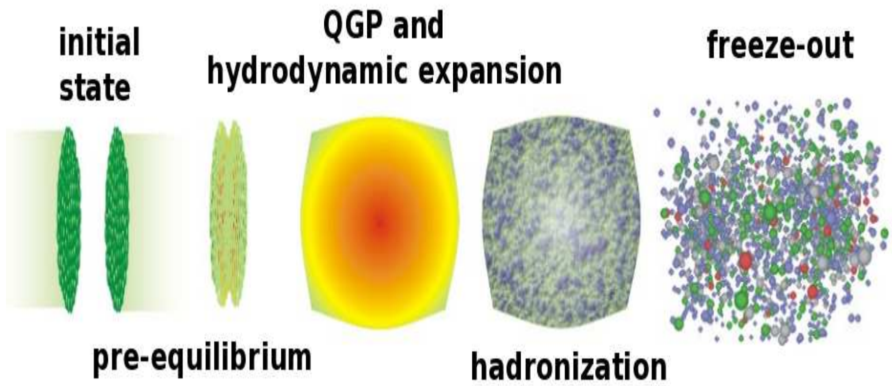

Figure 1: Graphical depiction of a relativistic heavy ion collision.

Summary of Research Completed

My calculations of $\frac{\eta}{s}$ in a hot, dense, equilibriated hadronic gas have been submitted to Europhys. Journal C for publication, and in addition a Letter is being prepared to be sent to Physical Review Letters. Another more detailed paper containing calculations of other transport coefficients, such as the diffusion of baryon number and the bulk viscosity coefficient is in progress, and to be submitted to Physical Review C. We are also involved in a comparison project dealing with calculations of viscosity coefficients in hot, dense deconfined matter, where we compare our results to those of the Institute for Theoretical Physics in Frankfurt University, Germany.

Upcoming Projects and Estimated Timetable for Completion

The first of the two upcoming projects involves an actual calculation of the $time - dependence$ of the viscosity coefficients in the hadronic phase of a relativistic heavy ion collision, and this computation must first involve the accurate extractions of the timescale in which the system depicted in Figure 1 alters its macroscopic thermal quantities (i.e. how long it takes for the system to cool its temperature a given amount). The goal is to extract such a timescale accurately, and afterwards the actual calculation of the time-evolution should be straightforward, since our group already has the computational technology for such a calculation. Our estimate is that the time-dependence of shear viscosity project be completed by Summer of 2009.

The other upcoming project involves extracting the diffusion coefficient of heavy quarks (most of the quarks in the QGP are light, but there also exist much heavier quarks which are produced much more rarely in relativistic heavy ion collisions). It should be noted that "light" and "heavy" in this context refer to the specific quark's position in the mass hierarchy of quark flavors. Investigating the diffusion of such heavy quarks is also a very important quantity to be assessed, and another important theoretical signature for QGP production. A distinguished Japanese collaborator of ours, Professor Masayuki Asakawa, will be visiting Duke at the conclusion of November 2008, and will also be of great help in developing the formalism of this approach. However, there also remains much work to be done on the calculational end of this project. The project itself is estimated to be completed in the course of the 2009-2010 academic year.

References

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