**A New Era of Matter**

Recent experiments at CERN and at Brookhaven’s Relativistic Heavy Ion Collider have realized a state of matter with such high energy that quarks and gluons cannot form fundamental nuclear particles like protons and neutrons. Unbound quarks and gluons form plasma that has fantastic experimental and theoretical importance. Quark-gluon plasma is thought to have been the state of matter very shortly after the Big Bang, and thus is thought to have had an important impact on the early evolution of our universe. It is also suspected to exist at the core of neutron stars.

Quark-gluon plasmas remain exceptionally difficult to study experimentally. The plasmas exist for 10-15 seconds before the energy density decreases enough for protons and neutrons to re-form, so observational methods are indirect and plagued with statistical uncertainty. These challenges make the theoretical study of quark-gluon plasmas particularly important. My research involves the use of fluid dynamics to calculate values for the material properties of quark-gluon plasmas, like the viscosity, that determine how it flows and expands after a heavy ion collision. In the absence of definitive experimental data, some characteristics of quark-gluon plasmas can be understood through the fluid dynamics of related physical systems.

The observation of elliptic flow in quark-gluon plasmas was a major step forward because it demonstrated that quark-gluon plasmas have similar dynamics to several other fluids. Elliptic flow is a phenomenon in which the wide dimension of an elliptical density profile changes with time, and is a characteristic of strongly-coupled quantum fluids with anomalously low viscosity. The observation of elliptic flow in quark-gluon plasmas implies that analogies can be drawn with other systems that exhibit elliptic flow, but which are easier to study experimentally. Fluids that flow elliptically exhibit similar fluid transport and diffusion characteristics and therefore are expected to have similar material properties [1].

Several strongly-coupled atomic fluids exhibit elliptic flow and are promising parallels for the study of quark-gluon plasmas. One such system is the unitary Fermi gas, which is an ultra-cold collection of fermions (often Lithium) in the limit (called unitarity) where the Fermi gas exhibits the strongest coupling. Experimental data suggests that quark-gluon plasma may have the lowest viscosity of any fluid yet observed, and the unitary Fermi gas has the second lowest [2]. Hydrodynamics is a natural method for studying the relationship between the material properties of unitary Fermi gases and quark-gluon plasmas because it deals explicitly with the fluid transport and diffusion on which our analogy is based.

Under the direction of Dr. Paul Romastchke, I am developing a set of hydrodynamic simulations of unitary Fermi gases from which to extract their material properties (such as viscosity). The expansion and elliptic flow of unitary Fermi gases has been observed in several experiments (e.g. [3]) and occurs on the scale of hundreds of microseconds. Density profiles of the fluid can be imaged many times over the lifetime of the expansion, and so the data is thorough and has relatively low experimental uncertainty. Studying the unitary Fermi gas allows me to compare the results of my simulations with experiment, analyze deviations, and revise my algorithms if necessary. The limited experimental data set for the expansion of quark-gluon plasmas does not make a similar analysis possible for this system.

Although quark-gluon plasmas and unitary Fermi gases share analogous material properties, heavy ion collisions and quark-gluon plasmas are a relativistic system while unitary Fermi gases are not. The behavior of matter that has exceptionally high mass or energy is not described accurately by classical physics and must be analyzed using Einstein’s theory of relativity. Quark-gluon plasmas are expanding at a significant fraction of the speed of light, and the energy density in these collisions is also very large. For these reasons, an accurate model of quark-gluon plasmas will incorporate the effects of relativity.

Relativistic hydrodynamics is a developing field with important applications across several branches of physics, including astrophysics, magneto-hydrodynamics, and high-energy condensed matter physics. It describes how fluids behave near very massive objects (like stars) or when they are exceptionally high in energy. In non-relativistic hydrodynamics, viscous flows are typically modeled by the Navier-Stokes equations. These methods are well understood and strike a balance between computability and accuracy. Unfortunately, relativistic formulations of the Navier-Stokes equations are not useful because they violate causality, the directionality of time [4]. Various techniques for re-working this model have been proposed, but the equations remain very complicated and numerical solutions are prohibitively computationally-intensive in most cases. Advances in hydrodynamic modeling of quark-gluon plasmas and other high-energy matter will require improvements in the computational efficiency of relativistic hydrodynamic methods.

In order to apply my study of elliptic flow in unitary Fermi gases to the study of quark-gluon plasmas, I will need to incorporate relativistic hydrodynamics into my simulations. Solving the issue of computability and accuracy in relativistic hydrodynamics will be central to the effective simulation of quark-gluon plasmas, and is also an open problem across several other areas of physics. I hope to contribute to the resolution of this important issue in my undergraduate thesis.

As I move forward toward graduate school in physics and mathematics, a wider diversity of methods will become available to me for the study of high-energy matter and plasmas. Relativistic hydrodynamics is an important field with promising applications in high-energy and plasma physics, but there are also many other approaches to understanding these problems. My undergraduate research has given me a unique perspective on high-energy physics because hydrodynamics is a non-traditional method in the field. It has given me a strong background in computational methods and theoretical mathematics that will be great assets as a graduate student and researcher. Most importantly, it has given me the opportunity to contribute to an important and fascinating problem in physics. I look forward to further research and education as an opportunity to explore these issues on a deeper level, and to use this depth of knowledge to help solve some of these exciting problems in high energy physics.

**References**

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