In 2000, CERN announced that the first quark-gluon plasmas had been created in collisions between lead and gold nuclei [1]. This discovery is of fundamental importance to high-energy physics and is revolutionizing modern physical thought. However, progress has been slowed by the difficulty of experimental procedures and data analysis, which make it challenging to study the physical and material properties of quark-gluon plasma. I am exploring a relationship between the fluid properties of quark-gluon plasma and a similar fluid, the cold Fermi gas, which may allow us to calculate values for the material properties of quark-gluon plasma with more precision than experimental data for quark-gluon plasma itself would allow.

Quarks are bound together with gluons to form protons and neutrons, which in turn are bound in the atomic nuclei that form molecules and macroscopic matter. At temperatures exceeding K however, matter is too high in energy for even neutrons and protons to be stable and they break apart into free quarks and gluons; the resulting state of matter is called quark-gluon plasma. Quark-gluon plasma provides a unique opportunity for the study of individual quarks, as opposed to the study of composites of several quarks. Quark-gluon plasma is also important to the study of the early universe because it is thought to have been the state of all matter shortly after the Big Bang.

The interactions between free quarks and gluons are of great importance to our understanding of the fundamental forces governing these particles. The flow characteristics of a fluid convey abundant information about the microscopic interactions between fluid particles. In this case, the flow of quark-gluon plasma is indicative of the forces between free quarks and gluons. Thus, fluid dynamics is a promising method for the theoretical study of quark-gluon plasmas.

Quark-gluon plasmas currently are exceptionally difficult to study experimentally. They 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. The formation of quark-gluon plasma in a collision cannot be determined directly and must be inferred from the statistical presence of other particles in the collision aftermath. One of the few properties observed in experiment was that of elliptic flow, first seen in quark-gluon plasmas in 2005 [2]. Elliptic flow is a phenomenon in which a fluid expands non-uniformly. A fluid with these characteristics that initially has an elliptical shape will expand much more quickly in one direction than the other, thus changing shape over time. Elliptic flow is a relatively rare flow pattern and is characteristic of strongly-coupled quantum fluids with anomalously low viscosity. There is therefore reason to believe that fluids both exhibiting elliptic flow share other physical properties.

A particularly strong relationship has been developed ([2], [3]) between quark-gluon plasmas and unitary Fermi gases. Unitary Fermi gases are ultra-cold collections of fermions (typically Lithium) under the conditions in which the atoms exhibit the strongest coupling. In addition to both exhibiting elliptic flow, experimental data suggests that quark-gluon plasma has the lowest viscosity ever observed and the unitary Fermi gas has the next lowest [3]. The unitary Fermi gas has been studied with low experimental uncertainty (e.g. [4]), so the fact that it obeys very similar fluid dynamics to quark-gluon plasmas is very useful to the study of quark-gluon plasmas.

Although quark-gluon plasmas and unitary Fermi gases have many similarities, quark-gluon plasmas have the added complexity of being a high-energy, relativistic fluid. Relativistic hydrodynamics is a developing field with important applications across several branches of physics, including astrophysics and magneto-hydrodynamics, and is essential to the fluid dynamics of quark-gluon plasma. It describes how fluids behave near very massive objects (like stars) or when they are exceptionally high in energy. Current methods in relativistic fluid dynamics are much more complicated than their non-relativistic counterparts, and in many cases are too difficult for computers to solve numerically in a practical amount of time. The issue of computability and accuracy in relativistic hydrodynamics is central to the effective simulation of quark-gluon plasmas.

In my current research, I am using non-relativistic fluid dynamics to develop simulations of unitary Fermi gases. I write computer simulations using a discrete fluid dynamics algorithm called the lattice Boltzmann method, which approximates microscopic fluid particles as being able to move only on a discrete “lattice” of points in space, instead of in the infinite directions of continuous space.

Simulating any physical fluid on the computer involves many approximations, including how temperature varies or how the fluid dissipates energy or relaxes to equilibrium. I am in the process of writing a set of simulations that make different sets of assumptions about these types of parameters. I compare the results of each simulation to published experimental data for unitary Fermi gases (e.g. [4]) and will determine the set of physical approximations that provide the best fit to experimental data.

The fluid assumptions that are most accurate for cold Fermi gases are supposed to also be nearly correct for quark-gluon plasma. Because of this, it is hoped that developing simulations of quark-gluon plasmas based on the fluid dynamics of cold Fermi gases will be more precise than trying to fit simulations directly to the uncertain experimental data on quark-gluon plasma. The goal of my research is to use computational relativistic fluid dynamics to calculate values for the material properties of quark-gluon plasma, like viscosity, that determine how it flows and expands after a heavy-ion collision. The first step is to determine a set of fluid assumptions based on simulations of the unitary Fermi gas, and next to use similar assumptions in relativistic fluid dynamics to develop simulations of quark-gluon plasmas. In my future work, I hope to contribute to the efficient computer implementation of relativistic hydrodynamics, and to use these methods to calculate theoretical bounds for the viscosity of quark-gluon plasma.

Graduate school in physics and mathematics promises exciting new opportunities to explore my interests in high-energy matter and plasma. 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, as well as 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.

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