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**Nominee Essay, Goldwater 2014**

Recent experiments at CERN and at Brookhaven’s Relativistic Heavy Ion Collider (RHIC) 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 is of fantastic experimental and theoretical importance for many reasons. Among these, quark-gluon plasma is thought to have been the state of matter very shortly after the Big Bang and is also suspected to exist at the core of neutron stars.

Quark-gluon plasmas remain exceptionally difficult to study experimentally. The plasmas exist for femtoseconds before the energy density decreases enough for protons and neutrons to re-form, so observational methods are indirect. If the creation of quark-gluon plasma in a collision corresponds to changes in the production of some other particles, then the statistical presence of those particles in the collision aftermath can determine whether or not quark-gluon plasmas were created [1]. Making these measurements with statistical certainty has proven to be quite the challenge.

The experimental observation of elliptic flow in quark-gluon plasmas was therefore a major success and sparked significant theoretical interest. Elliptic flow is a phenomenon in which the wide dimension of an elliptical density profile changes as time evolves, and is a characteristic of strongly-coupled quantum fluids with anomalously low viscosity. In fact, experimental data suggests that quark-gluon plasma may have the lowest viscosity of any fluid yet observed [2]. Particularly in light of an absolute lower bound on fluid viscosity proposed recently through string-theoretic methods [3], there is much interest in finally constraining the viscosity of quark-gluon plasma. Hydrodynamics is one promising method for the theoretical study of viscosity in quark-gluon plasmas.

The observation of elliptic flow in quark-gluon plasma allows analogies to be drawn with other systems that exhibit elliptic flow, which include several strongly-coupled cold atomic fluids. 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. This system is a non-relativistic, but has analogous material properties to quark-gluon plasmas. Both are strongly-coupled quantum fluids, and so are expected to obey similar transport and diffusion characteristics (that both exhibit elliptic flow is evidence of this). Besides the quark-gluon plasma, the unitary Fermi gas is also observed to have the next lowest viscosity ([2], [4]).

Relativistic hydrodynamics is a developing field with important applications in astrophysics, magneto-hydrodynamics, and high-energy condensed matter. The Navier-Stokes equations are a first-order diffusion relation typically used in non-relativistic hydrodynamics to model viscous flows. Unfortunately, relativistic formulations of the Navier-Stokes equations violate causality [5]. Various techniques for re-working this model exist in the literature, but the equations for relativistic viscous hydrodynamics 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. This problem certainly has not been solved and is an issue I hope to contribute to in my undergraduate thesis.

My current contribution to the study of quark-gluon plasmas is to study the material properties of unitary Fermi gases through hydrodynamic simulations. The advantage of studying this system is that it is experimentally-verifiable: elliptic flow in Fermi gases is observed on the scale of hundreds of microseconds ([6], [7]), which is about 12 orders of magnitude longer of a time scale than the one on which the expansion of quark-gluon plasmas can be observed. Developing simulations of quark-gluon plasmas out of simulations of Fermi gases that have been verified through experiment puts the non-relativistic limit on a solid experimental foundation.

Moving forward in my physics and mathematics education into graduate school, a wider diversity of methods will become available to me for the study of high-energy matter and plasmas. Relativistic hydrodynamics is a promising model for studying particular aspects of these experiments, but high-energy physics is centrally based on quantum field theories that are not typically taught on an undergraduate level. I look forward to my future research and education as an opportunity to appreciate these issues on a deeper level, and to use this diversity of knowledge to more effectively solve problems in high energy physics.

**References**

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