1. DOE Award # DE-SC0002712 Final Report

Recipient Institution: Duke University

2. Project Title: Simulating strongly correlated electrons with a strongly interacting Fermi gas

PI: Thomas, John E.

3. Report Period: 8/14/2009-8/15/2012

PROGRAM SCOPE

The quantum many-body physics of strongly-correlated fermions is studied in a degenerate, strongly-interacting atomic Fermi gas, first realized by our group with DOE support in 2002. This system, which exhibits strong spin pairing, is now widely studied and provides an important paradigm for testing predictions based on state-of-the-art many-body theory in fields ranging from nuclear matter to high temperature superfluidity and superconductivity. As the system is strongly interacting, both the superfluid and the normal fluid are nontrivial and of great interest. A central part of our program on Fermi gases is the connection between the study of thermodynamics, supported by DOE and the study of hydrodynamic transport, supported by NSF. This connection is especially interesting in view of a recent conjecture from the string theory community on the concept of nearly perfect normal fluids, which exhibit a minimum ratio of shear viscosity to entropy density in strongly-interacting, scale-invariant systems.

4. RESEARCH ACCOMPLISHMENTS

- During this period, we made a major breakthrough in our studies of a strongly correlated, resonantly interacting Fermi gas, as described in our recent *Science* paper on the first measurement of a transport coefficient, the shear viscosity. At resonance, where the gas exhibits universal behavior, we made the first complete measurement of the universal quantum viscosity. Our work was the culmination of a nearly two year effort.
- Measurement of the ratio of the shear viscosity η to the entropy density s is at present of great interest in the context of a recent conjecture from the string theory community that η/s has a universal minimum, $\hbar/(4\pi k_B)$, for a broad class of strongly interacting quantum fields. As both the thermodynamic and hydrodynamic properties can be measured, a strongly interacting Fermi gas offers a nonrelativistic, scale-invariant analog for study. Remarkably, a quark-gluon plasma and our ultracold strongly interacting Fermi gas have nearly the

same ratio, about 5 times the lower bound, despite the fact that the temperatures and densities differ by 19 and 25 orders of magnitude respectively!

- A critical breakthrough was our development a new method of measuring temperature for the viscosity measurements at high temperature, using an image of the cloud profile. In this high temperature regime, we exploited a universal expression for the local energy density in terms of the temperature and density (due to Ho and Mueller), based on the universal second virial coefficient. As the pressure is $2/3$ of the local energy density for a universal gas, we were able to use force balance in the trap to relate the measured mean square size of the trapped cloud directly to the temperature. Further, we used the second virial expansion to calculate the global entropy S and energy E at higher temperatures. Combining this high temperature calculation with our previous model-independent measurements of S and E at low temperature, we were able to obtain a smooth curve for E versus S over the entire range of temperatures used in the viscosity experiments. From this curve, we obtained a new temperature calibration, $T = \partial E / \partial S$, which permitted a measurement of viscosity versus reduced temperature at the trap center.
- We made the first observation of shock waves in a strongly interacting Fermi gas, by colliding two strongly interacting clouds in a long, cigar-shaped optical trap. This system will provide a new paradigm for the study of nonlinear hydrodynamics in quantum matter. Of interest is the interplay between the formation of large density gradients, dispersion arising from quantum pressure, and dissipation arising from the kinetic viscosity, which has a natural unit $\hbar / m$, where m is the atom mass. In this system, we can study shock wave formation and propagation as a function of the speed of the colliding clouds, interaction strength (by tuning away from the collisional resonance), and as a function of temperature. We are working to understand the thermodynamic features, in particular, the effect of heating, when the clouds collide, on the local pressure and shock wave formation.
- We did the first study of pairing interactions in a quasi-two-dimensional trap, where the transverse Fermi energy is comparable to the harmonic oscillator energy spacing in the tightly confining (axial) direction. In this regime, the Fermi energy can be large compared to the dimer pairing energy in the *resonantly interacting* regime. In contrast to previous experiments, where the Fermi energy is large compared to the dimer pairing energy only in the weak pairing, BCS regime, our experiments reveal a major departure from BCS theory in two-dimensions: We observe instead that the data can be fit by assuming the radio-frequency transitions occur between polaronic states.

5. PAPERS PUBLISHED

1) J. E. Thomas, "The nearly perfect Fermi gas," *Physics Today*, pp. 34-37 (May, 2010).

This is a highlight promoting strongly interacting Fermi gases, which incorporates three articles for a broad audience, one written by two quark-gluon plasma experimentalists, one written by a string theorist, and one written by the PI. It was not published at the time of the last report. A central feature of the article is our work on thermodynamics, but we are not permitted to acknowledge support in *Physics Today* articles.

2) C. Cao, E. Elliott, J. Joseph, H. Wu, J. Petricka, T. Schäfer, and J. E. Thomas, "Universal Quantum Viscosity in a Unitary Fermi gas," *Science* **331**, 58 (2011).

This important paper combines studies of the thermodynamic properties of a strongly interacting Fermi gas, studied as a central feature of the DOE grant, with studies of the hydrodynamic transport properties, studied as a central feature of the NSF grant.

3) J. E. Thomas, "Unitary Fermi gases," in "Ultracold Fermi and Bose Gases," "Contemporary Concepts of Condensed Matter Science" (A. Fetter, K. Levin and D. Stamper-Kurn, Editors), (Elsevier, 2012).

This paper is an overview of our strongly interacting Fermi gas studies, written for an audience in condensed matter science and contains results from all of our programs, which are acknowledged.

4) J. A. Joseph and J. E. Thomas (with M. Kulkarni and A. G. Abanov), "Observation of shock waves in a strongly interacting Fermi gas," *Phys. Rev. Lett.* **106**, 150401 (2011).

This paper is mostly concerned with the hydrodynamic properties of the strongly interacting gas, but is of interest to condensed matter theorists for its connection to recent theory on shock waves in electron gases. The new paper was a result of a collaboration with condensed matter theorists Sasha Abanov and his student Manas Kulkarni at Stonybrook. Their specialty is nonlinear dynamics.

5) C. Cao, E. Elliott, H. Wu, J. E. Thomas "Searching for perfect fluids: Quantum viscosity in a universal Fermi gas," *NJP special issue on strongly correlated matter*, *New J. Phys.* **13** 075007(2011).

The topic of correlated many-body systems is of central interest for the DOE program. I assumed responsibility with several other researchers as an associate editor for the special issue that combines research on strongly correlated systems from cold atoms to nuclear matter and string theory.

6) J. E. Thomas, "Spin drag in a perfect fluid," *Nature, News and Views*, **472**, 172 (2011).

This is a highlight article written by the PI on a recent transport experiment by the MIT group.

7) H. Wu and J. E. Thomas, "Optical control of Feshbach resonances in Fermi gases using molecular dark states," *Phys. Rev. Lett.* **108**, 010401 (2012).

This paper proposes a new method of controlling interactions in ultracold gases using two optical fields to suppress spontaneous scattering by quantum interference. This work is supported primarily by AFOSR, but has a synergistic relation to our DOE program on the thermodynamics.

8) Y. Zhang, W. Ong, I. Arakelyan, and J. E. Thomas, "Polaron-to-polaron transitions in the radio-frequency spectrum of a quasi-two-dimensional Fermi gas," *Phys. Rev. Lett.* **108**, 235302 (2012).

This paper reports on our studies of many-body physics in two dimensions. This work was supported by our ARO program on Fermi gases in reduced dimensions and our DOE program on the thermodynamics in 2D strongly interacting Fermi gases.

6. PERSONEL

Chingyun Cheng—Duke graduate student 50%.

Ethan Elliott—Duke graduate student 25%.

Nithya Arunkumar—NCSU graduate student 50%.

Yingyi Zhang- Duke graduate student 50%.

Ilya Arakelyan—postdoctoral associate 50%.

Haibin Wu—postdoctoral associate 8.3%

7. PLANNED ACTIVITIES (new program)

- Develop a bichromatic lattice system for controlling dispersion.
- Develop radio-frequency methods to measuring pairing energy for clouds with linear dispersion along one or two directions.
- Study the thermodynamics in expanding gases.

8. OTHER SUPPORT (Within the grant period, PI: J. E. Thomas)

1) **Strongly-Interacting Fermi Gases in Reduced Dimensions**

ARO # W911NF-11-1-0420

9/01/2011-8/31/2014: Award total \$517,191. Annual: \$172,397.

Location: North Carolina State University

Person-Months Per Year Committed to Project: $\frac{1}{2}$ Person Month Acad.;

$\frac{1}{2}$ Person Month Sumr.

This program explores an interacting Fermi gas confined in a standing wave CO₂ laser trap. The resulting pancake geometry has a transverse Fermi energy which is less than the harmonic oscillator energy in the axial direction, producing a two-dimensional system. Radiofrequency spectroscopy is used to study pairing interactions. Synergy with the DOE program arises in studies of thermodynamics and control of dispersion in reduced dimensional systems.

2) **Quantum Transport in Strongly Interacting Fermi Gases**

NSF # PHY-1067873

8/15/2011-7/31/2014: Award total \$535,756. Annual: \$167,390.

Location: North Carolina State University

Person-Months Per Year Committed to Project: $\frac{1}{2}$ Person Month Acad.;

$\frac{1}{2}$ Person Month Sumr.

This program studies minimum viscosity hydrodynamics to test theories of strongly interacting fields and quark-gluon plasmas. Current research focuses on measurement of bulk viscosity and shear viscosity away from resonance.

Synergy with the DOE program arises in studies of thermodynamics, which are an essential part of understanding the hydrodynamic flow.

3) Non-Equilibrium Fermi Gases

AFOSR # FA9550-13-1-0041

3/1/2012-2/28/2015: Award total \$516,740. Annual: \$211,192.

Location: North Carolina State University

Person-Months Per Year Committed to Project: $\frac{1}{2}$ Person Month Acad.;

$\frac{1}{2}$ Person Month Sumr.

This program is developing methods for optical control of the scattering length and effective range to rapidly change the interaction parameters in a Fermi gas. The goal is to change the interactions fast compared to the Fermi time, to study non-equilibrium dynamics. Synergy with the DOE program arises in potential studies of non-equilibrium thermodynamics of systems with linear dispersion.

9. COST STATUS

There is no unexpended balance for this Duke program.