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14. ABSTRACT
All-optical trapping methods are used to produce and study a two-component strongly-interacting Fermi gas near a Feshbach resonance in a unique quasi-two-dimensional regime, where the cloud is far from three-dimensional, but not quite two-dimensional. We measure the radio-frequency spectra and the thermodynamic properties in spin-imbalanced mixtures to explore predictions of the phase diagram and high temperature superfluidity. Our recent measurements reveal that pairing energy and cloud profiles can be explained in part by a polaron model, in which an atom of one spin state is surrounded by a particle-hole cloud of the other

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Final Report: Strongly-Interacting Fermi Gases in Reduced Dimensions

ABSTRACT

All-optical trapping methods are used to produce and study a two-component strongly-interacting Fermi gas near a Feshbach resonance in a unique quasi-two-dimensional regime, where the cloud is far from three-dimensional, but not quite two-dimensional. We measure the radio-frequency spectra and the thermodynamic properties in spin-imbalanced mixtures to explore predictions of the phase diagram and high temperature superfluidity. Our recent measurements reveal that pairing energy and cloud profiles can be explained in part by a polaron model, in which an atom of one spin state is surrounded by a particle-hole cloud of the other spin state. However, a phase separation transition to a balanced central core is not predicted by the model. Our measurements provide the first benchmarks for predictions of the phase diagram for a spin-imbalanced mixtures in a quasi-two-dimensional system.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
07/12/2012	1.00	I. Arakelyan, W. Ong, J. Thomas, Y. Zhang. Polaron-to-Polaron Transitions in the Radio-Frequency Spectrum of a Quasi-Two-Dimensional Fermi Gas, Physical Review Letters, (6 2012): 0. doi: 10.1103/PhysRevLett.108.235302
07/12/2012	2.00	Haibin Wu, J. Thomas. Optical Control of Feshbach Resonances in Fermi Gases Using Molecular Dark States, Physical Review Letters, (1 2012): 0. doi: 10.1103/PhysRevLett.108.010401
07/16/2013	4.00	Haibin Wu, J. E. Thomas. Optical control of the scattering length and effective range for magnetically tunable Feshbach resonances in ultracold gases, Physical Review A, (12 2012): 0. doi: 10.1103/PhysRevA.86.063625
07/16/2013	3.00	Allan Adams, Lincoln D Carr, Thomas Schäfer, Peter Steinberg, John E Thomas. Strongly correlated quantum fluids: ultracold quantum gases, quantum chromodynamic plasmas and holographic duality, New Journal of Physics, (11 2012): 0. doi: 10.1088/1367-2630/14/11/115009
10/19/2015	7.00	W. Ong, Chingyun Cheng, I. Arakelyan, J.?E. Thomas. Spin-Imbalanced Quasi-Two-Dimensional Fermi Gases, Physical Review Letters, (03 2015): 0. doi: 10.1103/PhysRevLett.114.110403
10/19/2015	8.00	J. A. Joseph, E. Elliott, J. E. Thomas. Shear Viscosity of a Unitary Fermi Gas Near the Superfluid Phase Transition, Physical Review Letters, (7 2015): 0. doi: 10.1103/PhysRevLett.115.020401

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Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

1) J. E. Thomas, ``From Strongly-Interacting Fermi Gases to Nuclear Matter," Quark-Gluon Plasma meets Cold Atoms-Episode III (Hirshegg, Austria, August 25-31, 2012).
2) J. E. Thomas, ``Perfect Fluidity in Fermi Gases and Quark-Gluon plasmas," (Rice University, October 24, 2012).
3) J. E. Thomas,``Perfect Fluidity in Fermi gases and Quark-Gluon plasmas," (University of North Carolina, November 5, 2012).
4) J. E. Thomas, ``Perfect fluidity: From Strongly-interacting Fermi gases to Quark-gluon plasmas," (SESAPS Meeting, Tallahassee, Fla., November 14-17, 2012).
5) J. E. Thomas, ``Connecting Ultra-cold Fermi Gases and Quark-gluon Plasmas," (National Nuclear Physics Summer School 2013, Stonybrook University, July 15-26, 2013).
6) J. E. Thomas, ``Bowls made of Laser Light to Corral Ultra-Cold Atoms," (NCSU, September 9, 2013).
7) J. E. Thomas, ``Quantum Viscosity and Perfect Fluidity in Fermi gases," (BC, April 23, 2014).
8) J. E. Thomas, ``Measuring Scale Invariance and Viscosity in Fermi Gases," (INT, Seattle, May 13-15, 2014).
9) J. E. Thomas, ``Layered Strongly Correlated Fermi Gases," (IUPUI, March 12, 2015).
10) J. E. Thomas, ``Scale-Invariant Hydrodynamics and Quantum Viscosity in Fermi Gases," (DAMOP, Columbus, Ohio, June 7-12, 2015).
11) J. E. Thomas, ``3D Hydrodynamics and Quasi-2D Thermodynamics in Strongly Correlated Fermi Gases," (Cold atoms meet quantum field theory, Bad-Honnef, Germany, July 6-9, 2015).
12) J. E. Thomas, ``Emulating Layered Materials with Ultra-cold Fermi Gases," (Fitzpatrick Center, Duke University, October 7, 2015).

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(d) Manuscripts

Received Paper

07/10/2014 5.00 E. Elliott, J.?A. Joseph, J.?E. Thomas. Observation of Conformal Symmetry Breaking and Scale Invariance in Expanding Fermi Gases,
Physical Review Letters (1 2014)

07/10/2014 6.00 Ethan Elliott, James A. Joseph, John E. Thomas. Anomalous Minimum in the Shear Viscosity of a Fermi Gas,
(07 2014)

TOTAL: **2**

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

1) Jessie Beams Award for Research (SESAPS 2011).
2) Outstanding Referee Award, American Physical Society (2013).
3) John S. Risley Distinguished Professor of Physics (NCSU, 2013)

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Willie Ong	1.00	
Chingyun Cheng	0.50	
Jayampathi Kangara	0.50	
FTE Equivalent:	**2.00**	
Total Number:	**3**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Ilya Arakelyan	0.50
FTE Equivalent:	**0.50**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
John E. Thomas	0.04	
FTE Equivalent:	**0.04**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 1.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 1.00

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The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 1.00

Names of Personnel receiving masters degrees

NAME	
Total Number:	

Names of personnel receiving PHDs

NAME	
Willie Ong	
Total Number:	**1**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

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Scientific Progress

See attached pdf.

Technology Transfer

FINAL REPORT

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2. TITLE: Strongly-Interacting Fermi Gases in Reduced Dimensions
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5. AUTHORS OF REPORT: J. E. Thomas
6. LIST MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORT PERIOD, INCLUDING JOURNAL REFERENCES:

1) 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).
21) J. E. Thomas, "Spin drag in a perfect fluid," Nature, *News and Views*, **472**, 172 (2011).
3) H. Wu and J. E. Thomas,"Optical control of Feshbach resonances in Fermi gases using molecular dark states," Phys. Rev. Lett. **108**, 010401 (2012).
4) 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).
5) A. Adams, L. D. Carr, T. Schäfer, P. Steinberg, and J. E. Thomas, "Strongly correlated quantum fluids: ultracold quantum gases, quantum chromodynamic plasmas and holographic duality," New J. Phys. **14**, 115009 (2012).
6) H. Wu and J. E. Thomas, "Optical control of the scattering length and effective range for magnetically tunable Feshbach resonances in ultracold gases," Phys. Rev. A **86**, 063625 (2012).
7) E. Elliott, J. A. Joseph, and J. E. Thomas,"Observation of Conformal Symmetry Breaking and Scale Invariance in Expanding Fermi Gases," Phys. Rev. Lett. **112**, 040405 (2014).
8) E. Elliott, J. A. Joseph, and J. E. Thomas, "Anomalous Minimum in the Shear Viscosity of a Fermi Gas," Phys. Rev. Lett. **113**, 020406 (2014).
9) W. Ong, C.-Y. Cheng, I. Arakelyan, and J. E. Thomas, "Spin-Imbalanced Quasi-Two-Dimensional Fermi Gases," Phys. Rev. Lett. **114**, 110403 (2015).
10) J. A. Joseph, E. Elliott, and J. E. Thomas, "Shear viscosity of a unitary Fermi gas near the superfluid phase transition," Phys. Rev. Lett. **115**, 020401 (2015), selected

as an *Editor's Suggestion*.

7. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

J. E. Thomas
Ilya Arakelyan (Post doctoral associate)
Willie Ong (Graduate Student)
Chingyun Cheng (Graduate Student)

8. REPORT OF INVENTIONS (BY TITLE ONLY):

None.

BRIEF OUTLINE OF RESEARCH FINDINGS

Overview

Optically-trapped, strongly-interacting Fermi gases are models for exotic strongly-interacting systems in nature. For this reason, tabletop experiments with strongly-interacting atomic Fermi gases can provide measurements that are relevant to all strongly-interacting Fermi systems, thus impacting theories in intellectual disciplines outside atomic physics, including materials science and condensed matter physics (superconductivity), nuclear physics (nuclear matter), high-energy physics (effective theories of the strong interactions), astrophysics (compact stellar objects), the physics of quark-gluon plasmas (elliptic flow), and most recently, string-theory (minimum viscosity hydrodynamics).

This program has focused on strongly-interacting Fermi gases confined in a standing-wave CO_2 laser trap. This trap produces a periodic quasi-two-dimensional pancake geometry, with confinement induced pairing between fermions of opposite spin, many-body pairing arising from the Pauli exclusion principle, and quantum pressure arising from the tight axial confinement. This geometry provides a rich new paradigm for testing state of the art many-body theories of strongly correlated systems. In addition to this research, we continue to be interested broadly in the thermodynamic and hydrodynamic transport properties of strongly interacting Fermi gases.

Findings

In the past funding period, we made a major breakthrough in our studies of quasi-two-dimensional Fermi gases, producing the first spin-imbalanced quasi-2D Fermi gas and measuring its thermodynamic properties.

A. Spin-Imbalanced Quasi-Two Dimensional Fermi Gases.

In the experiments, by using a standing wave, as noted above, we produce a periodic pancake-shaped trapping potentials with a $5.3\,\mu$ spacing. With 200-800 atoms per site, we use site-resolved imaging to study a quasi-two-dimensional geometry. For a true two-dimensional (2D) system, the Fermi energy E_F in the weakly confining transverse direction should be small compared to the harmonic oscillator energy level spacing $h\nu_z$ in the tightly confining axial (z) direction, i.e., $E_F << h\nu_z$ for a true 2D system. Here, the atoms occupy a quasi-continuum of transverse states, but they are all in the ground axial state. In contrast, when $E_F >> h\nu_z$, a quasi-continuum of axial as well as transverse states is occupied, and the gas becomes three-dimensional (3D). Our recent experiments are performed in the intermediate regime, where $E_F \simeq h\nu_z$. In this case, the system is far from 3D, but is not quite 2D. Enhanced superfluid/superconducting transition temperatures are predicted for condensed matter systems in this regime, as well as for quasi-2D Fermi gases, making measurements in this regime particularly important for comparison with predictions.

Our previous work on radio-frequency spectroscopy, [Zhang et al, Phys. Rev. Lett. **108**, 235302 (2012)], revealed that the spectra are not explained by 2D-BCS theory. Instead, a polaron model of the two-component gas could explain the spectra. However, it was unclear how the system evolved from true 2D behavior, where 2D-BCS theory is valid, to behaving as a gas of spin-up and spin-down polarons, where each spin is surrounded by particle-hole cloud of the opposite spin. We believed that measuring the cloud profiles in a spin-imbalanced mixture would shed light on this problem.

In both the 2D-BCS and 2D-polaron regimes, the effective interaction strength is determined by the 2D confinement-induced dimer-pairing energy E_b and the transverse Fermi energy E_F. Since $E_F \propto \hbar^2/(mL_\perp^2) \propto \hbar^2 n_\perp/m$, with $L_\perp$ the transverse interparticle spacing and $E_b \propto \hbar^2/(ml_d^2)$, with l_d the dimer size, the ratio E_F/E_b sets the ratio of the $L_\perp$ to l_d. For $E_F << E_b$, the dimer is small compared to the interparticle spacing. In this case, we expect the dimers to behave a small independent molecules, without many-body effects. Increasing E_F/E_b, the dimer size becomes larger than the interparticle spacing. In this case, we expect to see many-body changes in the pairing energy and in the thermodynamic properties. For pairing in the weakly interacting regime, we expect 2D-BCS theory to be valid. However, we find that 2D-BCS theory predicts that the pairing energy will be exactly E_b and that the spatial profile for a 50-50 mixture of two spin states will be identical to that of an ideal gas! No many-body effects are predicted for measurements of the radio-frequency spectra nor for the spatial profiles in the 2D-BCS regime.

In our experiments, we use a mixture of the two lowest hyperfine states of fermionic ^{6}Li. We hold the number of atoms in the majority state N_1 constant, at $N_1 = 800$. We choose the number of atoms in the minority state N_2 to be $0 \leq N_2 \leq 800$, so that $0 \leq N_2/N_1 \leq 1$. Defining the 2D-Fermi energy of the majority, $E_F = h\nu_\perp\sqrt{2N_1}$, which is held constant in the experiments, we control the ratio E_F/E_b by tuning the bias magnetic field near a Feshbach resonance. We begin by measuring the column density of one transverse dimension x, as a function of spin-imbalance N_2/N_1. Fig. 1 shows the results for two different bias magnetic fields, at the Feshbach resonance (832 G) and below the Feshbach resonance (775 G), where the 2D-dimer pairing energy is increased by an order of magitude.

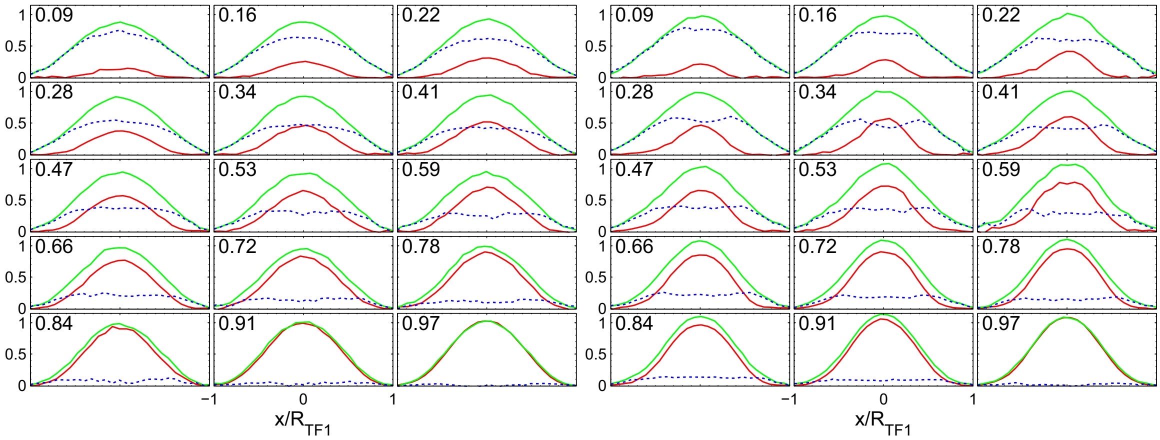

Figure 1: Measured column density profiles in units of N_1/R_{TF1} at 832 G, for $E_F/E_b = 6.6$ (left panel) and at 775 G, for $E_F/E_b = 0.75$ (right panel) versus N_2/N_1. Green: 1-Majority; Red: 2-Minority. Blue-dashed: Column density difference. Each profile is labeled by its N_2/N_1 range. For the density difference, the flat center and two peaks at the edges are consistent with a fully paired core of the corresponding 2D density profiles. These features are more prominent for the higher interaction strength (right panel).

We see in the figure a curious behavior in the column density difference, which appears to oscillate for $N_2/N_1 \simeq 0.34$ for the larger pairing energy E_b. To examine the behavior further, we measure the cut-off radii of the cloud, in units of the Thomas-Fermi radius of the majority $R_{TF1} \equiv \sqrt{2E_F/(m\omega_\perp^2)}$, which is held fixed in the experiments. When the minority fraction is small, the cutoff radius of the majority density approaches R_{TF1} as it should. However, as the minority concentration is increased, both the minority and majority spatial profiles are substantially distorted, due to the strong interactions between the two components, Fig. 2.

We find that the cloud radii deviate strongly from predictions for an ideal Fermi gas, where $R_1/R_{TF1} = 1$ and $R_2/R_{TF1} = (N_2/N_1)^{1/4}$. Further, the spatial profiles predicted by 2D-BCS theory for a balanced mixture are identical to that of an ideal Fermi gas, black circle, upper right in Fig. 2, which is in strong disagreement with the data.

As a polaron model explained the radio-frequency spectra obtained in our previous program [Zhang et al, Phys. Rev. Lett. **108**, 235302 (2012)], we again resorted to a physically-motivated polaron model to explain the cloud profiles. At zero tem-

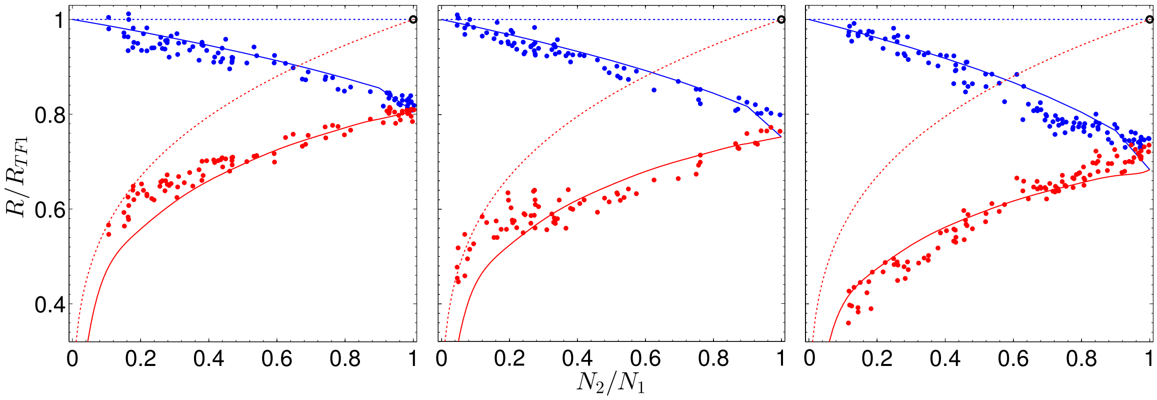

Figure 2: Majority radii (upper-blue) and minority radii (lower-red) in units of the Thomas-Fermi radius for the majority for $E_F/E_b = 6.6$ (left panel), $E_F/E_b = 2.1$ (middle panel) and $E_F/E_b = 0.75$ (right panel). Dots: Data; Dashed lines: Ideal Fermi gas prediction; Black circle upper right: 2D-BCS theory for a balanced mixture; Solid lines: 2D polaron model.

perature, the free energy density f is equal to the energy density. For an imbalanced mixture, with $N_2 << N_1$, we assume the 2D energy density is

$$f = \frac{1}{2} n_1 \epsilon_{F1} + \frac{1}{2} n_2 \epsilon_{F2} + n_2 E_p(2). \tag{1}$$

Here, the first two terms are the energy density for a noninteracting gas and the last term is the energy density for minority polarons in state 2, which arises from scattering in the bath of majority atoms in state 1; $n_{1,2}$ and $\epsilon_{F1,2}$ are the corresponding 2D-densities and 2D-local Fermi energies. The 2-polaron energy per particle $E_p(2) \equiv y_m(q_1)\,\epsilon_{F1}$, where $q_1 \equiv \epsilon_{F1}/E_b$. For simplicity, we use an analytic approximation for $y_m(q_1) = -2/\log(1 + 2\,q_1)$, due to Klawunn and Ricatti [Phys. Rev. A **84**, 033607 (2011)], which interpolates between the Fermi-polaron and Bose-dimer regimes. From Eq. 1, we directly obtain the local chemical potentials, $\mu_1 = \partial f/\partial n_1$ and $\mu_2 = \partial f/\partial n_2$ and the corresponding local 2D pressure $p = n_1\,\mu_1 + n_2\,\mu_2 - f$. The local chemical potentials determine the spatial profiles in the trap, since $\mu_{1,2}(\rho) + U_{trap}(\rho) = \mu_{1,2}(0)$. The solid curves in Fig. 2 show the predictions of the polaron model, which captures most of the features of the data.

We find that the simple polaron model fails to predict a phase-separation transition that we observe in the 2D density profile as N_2/N_1 is increased beyond a critical value. For $N_2/N_1 < (N_2/N_1)_{crit}$, the cloud is a uniform, spin-imbalanced mixture. For $N_2/N_1 > (N_2/N_1)_{crit}$, the 2D-density profile changes to a balanced core region, where the densities become equal near the cloud center, with the excess majority spin component expelled to the edges. A better model of the pressure is needed to explain the transition, which provides an important benchmark for new predictions of the phase diagram in this interesting quasi-2D regime.

B. New Results on Strongly Interacting Fermi Gases.

Recently, we have made new measurements of the radio-frequency spectra for a balanced mixture, as a function of the transverse Fermi energy. Here, we tune the ratio $E_F/h\nu_z$ from $<< 1$ where the system is truly 2D to $\simeq 1$, where 2D-BCS theory breaks down. Our initial measurements show that the 2D-BCS theory prediction is correct for $E_F/h\nu_z << 1$, but that the polaron model is needed to fit the data for $E_F/h\nu_z \simeq 1$. Our hypothesis is that in the strongly interacting regime near the Feshbach resonance, atoms inside the dimer pair dimension l_b, can collide with each other, rendering a Cooper-like pairing picture incorrect. Instead, the atoms of each species become surrounded by a particle-hole cloud of the other species, i.e., a polaron gas. These new experiments are made possible by an optical lattice system, constructed in part using support from DOE, which unites our ARO and DOE programs.

We also made a major breakthrough in our studies of *shear viscosity*, J. A. Joseph, E. Elliott, and J. E. Thomas, "Shear viscosity of a unitary Fermi gas near the superfluid phase transition," Phys. Rev. Lett. **115**, 020401 (2015), which was selected as an *Editor's Suggestion*. In these experiments, we made the first attempts to extract local shear viscosity from cloud-averaged data and provide the most precise measurements to date of the shear viscosity from nearly the ground state to the high temperature regime. These experiments are spurring new theoretical efforts to understand hydrodynamic transport in the strongly interacting regime.

We made the first study of *scale invariance* in the hydrodynamic expansion of a unitary Fermi gas in E. Elliott, J. A. Joseph, and J. E. Thomas, "Observation of Conformal Symmetry Breaking and Scale Invariance in Expanding Fermi Gases," Phys. Rev. Lett. **112**, 040405 (2014). In this work, we also made the first precision measurement of the *bulk* viscosity, showing that it is consistent with zero, as predicted for a scale-invariant system.