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RPPR Final Report
as of 14-Dec-2022

Agency Code: 21XD

Proposal Number: 65677PE

Agreement Number: W911NF-14-1-0628

INVESTIGATOR(S):

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Final Report for Period Beginning 05-Sep-2014 and Ending 04-Aug-2019

Title: Many-body Physics in Two-dimensional Fermi Gases

Begin Performance Period: 05-Sep-2014

End Performance Period: 04-Aug-2019

Report Term: 0-Other

Submitted By: John Thomas

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Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees:

STEM Participants:

Major Goals: This program broadly explores a strongly-interacting Fermi gas of 6-Li atoms, confined in quasi-two-dimensional pancake geometries, simulating layered materials. Our work includes: 1) Studies of spin-imbalanced Fermi gases in quasi-2D, 2) The crossover from true 2D to quasi-2D geometries. 3) Pairing of Fermi gases in bichromatic superlattices. 4) New studies of Fermi gases in the extreme, weakly interacting regime, near the zero crossing of the scattering length below a broad Feshbach resonance, where spin-energy correlation naturally emerges.

Accomplishments: See attached pdf for a detailed description of the results and publications.

Training Opportunities: During the period of this grant, 6 graduate students, 2 of them female, completed their Ph.D. theses. In this research, students acquire theoretical background in optical and quantum physics. They are broadly trained in experimental methods, including optical, electronic, mechanical, and vacuum system design, computer control and interfacing, and data acquisition and analysis. These students are particularly well equipped to tackle quantum physics problems, which are currently of national interest.

Results Dissemination: Our results have been presented at DAMOP conferences and in invited colloquiums and published in Physical Review A and Physical Review Letters.

Honors and Awards: During the period of this grant, the PI received the following honors:

1) Davison Germer Prize in Atomic or Surface Physics, APS 2018.

(For the creation and study of strongly interacting Fermi gases)

2) Fellow of the American Association for the Advancement of Physics 2018.

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

RPPR Final Report
as of 14-Dec-2022

Participant: Ilya Arakelyan

Person Months Worked: 6.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Jayampathi Kangara

Person Months Worked: 12.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Saeed Pegahan

Person Months Worked: 6.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Chingyun Cheng

Person Months Worked: 6.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Willie Ong

Person Months Worked: 6.00

Project Contribution:

National Academy Member: N

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ARTICLES:

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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review Letters
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevLett.115.020401
Volume: 115 Issue: 2 First Page #: 0
Date Submitted: Date Published:
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Article Title: Shear Viscosity of a Unitary Fermi Gas Near the Superfluid Phase Transition

Authors:

Keywords: viscosity, strongly-interacting, Fermi gas

Abstract: We measure the shear viscosity for a resonantly interacting Fermi gas as a function of temperature from nearly the ground state through the superfluid phase transition into the high temperature regime. Further, we demonstrate an iterative method to estimate the local shear viscosity coefficient $\eta_S(\mu)$ versus reduced temperature μ from the cloud-averaged measurements $\langle\eta_S\rangle$, and compare η_S to several microscopic theories. We find that η_S reveals features that were previously hidden in $\langle\eta_S\rangle$.

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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review Letters
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Article Title: Spin-Imbalanced Quasi-Two-Dimensional Fermi Gases

Authors:

Keywords: layered materials, strongly interacting Fermi gas, polarons

Abstract: We measure the density profiles for a Fermi gas of ^6Li containing N_1 spin-up atoms and N_2 spin-down atoms, confined in a quasi-two-dimensional geometry. The spatial profiles are measured as a function of spin imbalance $N_2=N_1$ and interaction strength, which is controlled by means of a collisional (Feshbach) resonance. The measured cloud radii and central densities are in disagreement with mean-field Bardeen-Cooper-Schrieffer theory for a true two-dimensional system. We find that the data for normal-fluid mixtures are reasonably well fit by a simple two-dimensional polaron model of the free energy. Not predicted by the model is a phase transition to a spin-balanced central core, which is observed above a critical value of $N_2=N_1$. Our observations provide important benchmarks for predictions of the phase structure of quasi-two-dimensional Fermi gases.

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Publication Location:

Article Title: Fermi Gases in the Two-Dimensional to Quasi-Two-Dimensional Crossover

Authors: Chingyun Cheng, J. Kangara, I. Arakelyan, and J. E. Thomas

Keywords: Fermi gases, two dimensional

Abstract: We tune the dimensionality of pancake-shaped strongly-interacting ^6Li Fermi gas clouds from two-dimensional (2D) to quasi-2D, by controlling the ratio of the radial Fermi energy E_F to the harmonic oscillator energy $\hbar\nu_z$ in the tightly confined direction. In the 2D regime, where $E_F \ll \hbar\nu_z$, the measured radio frequency resonance spectra are in agreement with 2D-BCS theory. In the quasi-2D regime, where $E_F \simeq \hbar\nu_z$, the measured spectra deviate significantly from 2D-BCS theory. For both regimes, the measured cloud radii disagree with 2D-BCS mean field theory, but agree approximately with predictions using a free energy derived from the Bethe-Goldstone equation.

Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: Y

RPPR Final Report
as of 14-Dec-2022

Partners

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I certify that the information in the report is complete and accurate:

Signature: John E. Thomas

Signature Date: 12/14/22 3:08PM

PROGRESS REPORT

1. PERIOD COVERED BY REPORT: 05 September 2014 - 04 August 2019
2. TITLE: Many-body Physics in Two-dimensional Fermi Gases
3. CONTRACT OR GRANT NUMBER: 2015-0274 / W911NF-14-1-0628
4. NAME OF INSTITUTION: North Carolina State University
5. AUTHORS OF REPORT: J. E. Thomas
6. LIST MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORT PERIOD, INCLUDING JOURNAL REFERENCES:
 - 1) W. Ong, C.-Y. Cheng, I. Arakelyan, and J. E. Thomas, “Spin-imbalanced quasi-two-dimensional Fermi gases,” *Phys. Rev. Lett.* **114**, 110403 (2015).
 - 2) 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), *Editor’s Suggestion*.
 - 3) A. Jagannathan, N. Arunkumar, J. A. Joseph, and J. E. Thomas, “Optical control of magnetic Feshbach resonances by closed-channel electromagnetically induced transparency,” *Phys. Rev. Lett.* **116**, 075301 (2016), *Editor’s Suggestion*.
 - 4) Chingyun Cheng, J. Kangara, I. Arakelyan, and J. E. Thomas, “Fermi gases in the two-dimensional to quasi-two-dimensional crossover,” *Phys. Rev. A* **94**, 031606(R) (2016).
 - 5) J. Kangara, Chingyun Cheng, S. Pegahan, I. Arakelyan, and J. E. Thomas, “Atom pairing in optical superlattices,” *Phys. Rev. Lett.* **120**, 083203 (2018), *Editor’s Suggestion*.
 - 6) N. Arunkumar, A. Jagannathan, and J. E. Thomas, “Probing Energy-Dependent Feshbach Resonances by Optical Control,” *Physical Review Letters* **121**, 1630404 (2018).
 - 7) N. Arunkumar, A. Jagannathan, and J. E. Thomas, “Designer Spatial Control of Interactions in Ultracold Gases,” *Physical Review Letters* **122**, 040405 (2019).
 - 8) S. Pegahan, J. Kangara, I. Arakelyan and J. E. Thomas, “Spin-Energy Correlation in Degenerate Weakly-Interacting Fermi Gases,” *Phys. Rev. A* **99**, 063620 (2019), *Editor’s Suggestion*.
 - 9) Lorin Baird, Xin Wang, Stetson Roof and J. E. Thomas, “Measuring the Hydrodynamic Linear Response of a Unitary Fermi Gas,” *Phys. Rev. Lett.*, **123**, 160402 (2019), *Editor’s Suggestion*.

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

J. E. Thomas

Ilya Arakelyan (Research Scholar)

Willie Ong (Graduate Student, Ph. D., July, 2015)

Chingyun Cheng (Graduate Student, Ph. D., May, 2017)

Jayampathi Kangara (Graduate Student, Ph. D., Dec. 2018)

Saeed Pegahan (Graduate Student, Ph D., Dec., 2020)

8. REPORT OF INVENTIONS (BY TITLE ONLY):

None.

9. HONORS AND AWARDS:

1) Davisson Germer Prize in Atomic or Surface Physics, APS 2018.

2) Fellow of the American Association for the Advancement of Physics 2018.

BRIEF OUTLINE OF RESEARCH FINDINGS

Abstract

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, non-equilibrium dynamics, and scale invariant non-relativistic systems). This program explores a strongly-interacting Fermi gas of ${}^6\text{Li}$ atoms, confined in quasi-two-dimensional pancake geometries, simulating layered materials. We have extended our work to include new studies of Fermi gases in the extreme, weakly interacting regime, near the zero crossing of the scattering length below a broad Feshbach resonance, where spin-energy correlation naturally emerges.

Highlights of the publications

1) Spin-Imbalanced Quasi-Two-Dimensional Fermi Gases

- Willie Ong completed his Ph. D. dissertation (publication 1 above) by creating the first spin-imbalanced quasi-two-dimensional Fermi gas. His work provided the first benchmarks for predictions in the quasi-2D regime. In our experiments, a mixture of N_1 spin-up and N_2 spin-down ${}^6\text{Li}$ atoms is confined in a standing-wave CO_2 laser trap, creating an array of pancake-shaped sites, each of which provides tight confinement along the z axis and relatively weak confinement along the perpendicular \perp directions x and y . The atoms vibrate in an approximately harmonic potential, for which $h\nu_z \gg h\nu_\perp$, with $N_1 = 800$ atoms per site and $N_2 \leq N_1$. In a true 2D gas, the transverse Fermi energy $E_{F\perp} = h\nu_\perp\sqrt{2N_1} \ll h\nu_z$, and the atoms are all in the ground z -vibrational state. For $E_{F\perp} = h\nu_\perp\sqrt{2N_1} \gg h\nu_z$, the cloud is in a quasi-continuum of z -vibrational states, and the cloud is three dimensional.

Our experiments are done in the regime where $E_{F\perp} = h\nu_\perp\sqrt{2N_1} \simeq h\nu_z$, where the gas is not truly a 2D system, but it is far from 3D. For this regime, it has been predicted that the superfluid transition temperature is enhanced, especially in spin-imbalanced systems. This quasi-2D gas is a paradigm for layered materials,

which are not usually true 2D and for which the phase diagram is complicated and not well-understood. Further, the quasi-2D gas accesses a new strongly correlated many-body regime: At the 3D Feshbach resonance, the dimer size is comparable to the spacing between free atoms, which collide with a mean free path comparable to the interparticle spacing. This is quite different than the true-2D regime, where the dimers are large compared to the inter-atom spacing, but the atoms collide with a large mean free path.

Willie first measured the cutoff radii for the majority N_1 and minority N_2 spatial profiles, as a function of N_2/N_1 and interaction strength. We observed strong interaction-dependent modification of the cloud radii. The cloud radii are not fit by ideal gas predictions, nor are they fit by BCS theory for a true 2D gas, which predicts ideal gas spatial profiles for balanced mixtures. Here, 2D-BCS theory predicts dimer spectra: Many-body physics has no effect. However, we found that a *polaron* model could fit the observed spectra, where a *polaron* is a minority spin atom surrounded by a cloud of majority particle-hole pairs.

By simply writing the free energy of the gas a sum of ideal gas contributions and a polaron term, we derived simple equations for the local chemical potentials and the pressure. In a harmonic trap, the known variation of the local chemical potential with position determines the density profiles of both species. We found very good agreement with these predictions, using no free parameters. Further, we found that the polaron model nicely fits the measured 2D pressure, which is related to the central density.

We also determined the 2D central densities as a function of N_2/N_1 from the measured column densities. On comparing the predicted ratio of the central densities of the minority and majority components, we found a *surprise*. As the interaction strength was increased toward the BEC side of the 3D Feshbach resonance, the polaron model failed in a spectacular way: The central densities abruptly changed from imbalanced to balanced, above a critical ratio of N_2/N_1 . More complete theory is needed to predict these observations, which serve as important markers for a predictions of the phase diagram for spin-imbalanced 2D Fermi gases.

2) Crossover between Quasi-2D and 2D Fermi Gases

- Chingyun Chen completed her Ph. D. thesis on the study of the cross over between atom dimers and polarons in two-dimensional systems (publication 4 above). She employed CO₂ laser trap to provide transverse confinement for atoms trapped in a 1064 nm standing wave. Varying the transverse confinement enabled a study of the transition between quasi-2D and 2D behavior. These experiments resolved a

previous controversy: Atom pairing spectra in 2D and quasi-2D systems were observed to be different. Chingyun showed that in true 2D, atom pairs behave as simple bound dimers, as predicted by BCS theory in two dimensions. However, for a quasi-2D system, she found that polaron behavior dominates. Here, loosely bound dimers are larger than the interparticle spacing, and each spin-up or spin-down atom is surrounded by a cloud of particle-hole pairs of the opposite spin. She observed that the radio frequency pair-breaking spectra of the true 2D and quasi-2D systems are quite different, and were explained by our 2D polaron model.

3) Atom Pairing in Optical Lattices

- Jayampathi Kangara (Kan) completed his Ph. D. thesis on the measurement of atom pairing spectra in a bichromatic superlattice (publication 5 above). These experiments superposed 1064 nm and 532 nm standing waves with a controllable relative position to create a one dimensional lattice of symmetric or asymmetric double-well potentials. The 532 nm beam was generated by frequency doubling of the 1064 nm beam, to assure a perfect 2:1 frequency ratio, enabling stable control of the double-well asymmetry. Kan precisely measured radio frequency atom pairing spectra, which exhibited a rich structure. This structure was successfully explained using a 9-band lattice model that included harmonic radial confinement from a CO₂ laser trap. The model showed that the center of mass and relative coordinates are *entangled*. Further, the data and the model revealed that *two types of atom pairs* co-exist in each double well, with two different symmetries.

4) Spin-Energy Correlation in Weakly Interacting Fermi Gases

Our experiments on weakly interacting Fermi gases evolved out of the first observation of anomalous spin segregation in a weakly interacting Fermi gas by our group in 2008, supported by ARO.

- Saeed Pegahan completed the first part of his Ph. D. thesis (publication 8 above) by precisely measuring and explaining spin-energy correlation in a weakly interacting Fermi gas, which is revealed as a complex spin-wave structure in the spatial profile of the spin density. Recently, this work led to our first experiments on the study of *information scrambling* in weakly interacting Fermi gases with effective long-range interactions, which comprised the second part of Saeed's thesis.

In these experiments, we exploit the fact that harmonically-trapped, weakly interacting atoms do not change their energy states on experimental time scales. With

an s-wave scattering length of just a few Bohr, the collision rate is of order 10^{-3} per second. The atoms therefore remain in their respective harmonic oscillator states, creating an “energy-space lattice,” where the harmonic oscillator quantum numbers n_x, n_y, n_z define the “location” in the lattice. However, the wavefunctions of the atoms do overlap, producing forward scattering and a non-vanishing mean field. Spin-energy correlation and spin-waves arise from combined energy-dependent Zeeman and mean-field-induced spin rotations.

Saeed began the first measurements of out-of-time-order correlation (OTOC) functions in an “energy-space lattice,” to study information scrambling. The OTOC experiments employ phase-controlled radio-frequency (rf) pulses and reversal of the many-body Hamiltonian, which is achieved using a small bias magnetic field to reverse the sign of the scattering length and a π pulse.

Additional work acknowledging ARO support

1) Optical control of interactions in ultra-cold gases (AFOSR primary).

Recently, we showed that two optical fields can be used to control magnetic Feshbach resonances in ${}^6\text{Li}$, while suppressing spontaneous scattering compared to single-field methods.

- Graduate students Arun Jaganathan and his wife Nithya (publications 3, 6, 7 above) completed both of their Ph. D. thesis in my laboratory on the optical control of magnetic Feshbach resonances. They developed the original two-field optical control apparatus. This required a three diode laser system, one master laser locked to an iodine resonance and two slave lasers locked to a common optical cavity. With a relative frequency jitter of just 10’s of kHz, they were able to demonstrate suppression of optical scattering near the broad Feshbach resonance, increasing the lifetime from 0.5 ms with single laser optical tuning to 0.4 sec with the two-field EIT method. Their work verified a new theoretical model of two-field optical control, using a Fano basis. Arun’s thesis showed that tuning the frequency of one of the EIT lasers near the zero loss, two-photon resonance greatly improves the trade-off between loss and tunability compared to single field methods (publication 3 above).

- Nithya’s thesis demonstrated broad tuning of the scattering length near the narrow resonance in ${}^6\text{Li}$ and probed the momentum dependence of the scattering amplitude (publication 4 above). Further, she demonstrated spatial control, by creating an “interaction sandwich,” comprising a non-interacting cloud, with a strongly interacting slice in the center (publication 5 above).

2) Hydrodynamic Linear Response of a Unitary Fermi Gas. (NSF primary)

Lorin Baird completed his Ph. D. thesis (publication 9 above) on a resonantly interacting (unitary) Fermi gas, trapped in a box potential. The box comprises 6 sheets of repulsive, blue-detuned light, which are projected using two digital micromirror devices (DMDs). One DMD also projects a spatially periodic optical potential, which is translated through the trapped cloud at speeds ranging from subsonic to supersonic. The resulting spatial profiles of the trapped cloud were analyzed using a linearized hydrodynamics model, which showed that the response is sensitive to both the shear viscosity and the thermal conductivity, enabling the first measurement of the latter. The use of DMD arrays enables dynamical control of the box potential and its perturbations, opening up a new arena for hydrodynamic transport measurements in quantum gases.