Strongly Correlated Fermi Systems in Two-Dimensional Triangular & Honeycomb Lattices

Kenneth O'Hara
PENNSYLVANIA STATE UNIVERSITY

04/27/2020
Final Report

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ RTB1
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
16-07-2020

2. REPORT TYPE
Final Performance

3. DATES COVERED *(From - To)*
01 Jul 2015 to 30 Jun 2019

4. TITLE AND SUBTITLE
Strongly Correlated Fermi Systems in Two-Dimensional Triangular & Honeycomb Lattices

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-15-1-0239

5c. PROGRAM ELEMENT NUMBER
61102F

6. AUTHOR(S)
Kenneth O'Hara

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
PENNSYLVANIA STATE UNIVERSITY
201 OLD MAIN
UNIVERSITY PARK, PA 16802-1505 US

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AF Office of Scientific Research
875 N. Randolph St. Room 3112
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/AFOSR RTB1

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-AFOSR-VA-TR-2020-0097

12. DISTRIBUTION/AVAILABILITY STATEMENT
A DISTRIBUTION UNLIMITED: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This research project aimed to study strongly correlated Fermi gases which result from confinement of the gases in a 2D lattice. The presence of the lattice partitions the gas into an ensemble of one-dimensional Fermi gases which, due to Fermi surface nesting in 1D, are predicted to become highly correlated even for weak interactions which gives rise to spin-charge separation at zero temperature. Attempts to observe spin-charge separation were compromised by the finite temperature of the gas. However, new discoveries were made regarding the suppression of inelastic collisions in 1D near p-wave Feshbach resonances. This may permit the study of p-wave superfluidity in a dilute 1D gas of neutral atoms.

15. SUBJECT TERMS
ultracold fermions, honeycomb lattice

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			METCALFE, GRACE
Unclassified	Unclassified	Unclassified	UU		**19b. TELEPHONE NUMBER** *(Include area code)* 703-696-9740

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Final Performance Report
Award No.: FA9550-15-1-0239

Strongly Correlated Fermi Systems in Two-Dimensional Triangular and Honeycomb Lattices

Principle Investigator: Kenneth M. O'Hara

The Pennsylvania State University

Office of Sponsored Programs

110 Technology Center

University Park, PA 16802-2150

A. Objectives

This research program aimed to study strongly correlated phases of matter that can arise when fermionic particles are confined to (1) move only in one dimension (1D) or (2) to move in two dimensional (2D) planes when in the presence of an underlying 2D honeycomb lattice potential. Both avenues of research were to be explored on a single experimental platform based on neutral fermionic lithium atoms confined in a 2D triangular/honeycomb optical lattice potential. To study strongly correlated matter in 1D, the triangular/honeycomb 2D lattice provides an ensemble of highly-elongated potentials at each lattice site. In this case, atoms at each site are so tightly confined by the lattice potential in two dimensions that kinematic motion is only allowed in the weakly confined direction perpendicular to the lattice plane. Alternatively, by adding a lattice potential perpendicular to the 2D lattice and operating the 2D lattice at a reduced depth, atoms can be constrained to move in planes formed by the new lattice where they experience a 2D triangular/honeycomb potential. In this case, a number of strongly correlated phases of matter can arise especially if atoms occupy the lowest p-orbital band of a 2D honeycomb lattice potential.

In the case of 1D confinement, Fermi gases are highly susceptible to forming a correlated gas even when interactions are weak due to the phenomenon of perfect Fermi-surface nesting that occurs in one dimension. For this reason, 1D Fermi gases do not conform to Fermi liquid theory but are rather described as Luttinger liquids for which the low-energy excitations are collective motions of spin- and charge-density waves which move at different velocities. A primary goal of this research program was to unambiguously observe signatures of strongly correlated 1D Fermi systems such as the phenomenon of spin-charge separation. Further, for attractive interactions in a partially polarized spin-1/2 Fermi gas in 1D, magnetic ordering and superfluidity are predicted to co-exist in the Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) phase. Direct observation of Cooper pairing with a non-zero center-of-mass momentum, a hallmark of the FFLO phase, was another goal of this research program. Finally, for fermions confined to move in 2D in the presence of a honeycomb lattice potential, strongly correlated phases of matter can arise if the Fermi surface lies in the lowest p-orbital band. This is due to the fact that the band structure for the lowest p-orbital band is predicted to be flat. Thus, since the kinetic energy is quenched, weak interactions can give rise to correlated phases of matter (e.g. ferromagnetism and Wigner crystalization). Observation of these phases are long-term goals of this research effort.

This experimental platform also allowed for the experimental investigation of new exciting theoretical predictions put forth during the course of this research program regarding the suppression of inelastic collisions near p-wave resonances when Fermi gases are confined to move in reduced dimensions. Such suppression, if observed, could permit the realization and study of low-dimensional p-wave superfluid phases. P-wave superfluids in reduced dimensions are of significant interest as they are predicted to feature low-energy excitations obeying non-Abelian statistics which would be useful for topologically protected quantum computing.

B. Accomplishments/New Findings

Experiments for Observing Spin-Charge Separation

Over the course of this research program, our group has been investigating one-dimensional Fermi gases prepared by loading an ultracold Fermi gas of atoms into a two-dimensional (2D) optical lattice which partitions the gas into an array of isolated 1D tubes. While we had initially studied a 2D triangular lattice formed by intersecting three lasers, we have in our most recent experiments used a configuration of two retro-reflected laser beams to form a 2D square lattice (see Fig. 1).

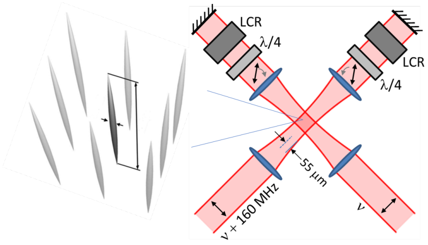

Figure 1: Experimental implentation of a square 2D lattice.

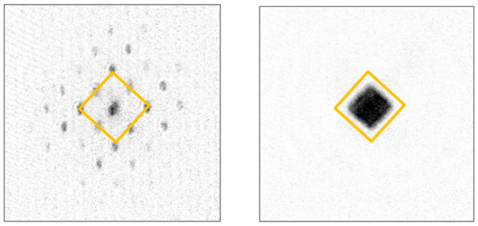

Figure 2: (left) Diffraction of a mBEC. (right) Band mapping of a Fermi gas.

In order to confirm that atoms, once loaded into the 2D lattice, only occupy the lowest band of the lattice, we performed the technique of band mapping where the lattice is lowered on a timescale adiabatic with respect to band excitation just prior to time-of-flight expansion. Absorption imaging of the expanded cloud then reveals the quasi-momentum occupation number. For atoms occupying only the lowest band, the quasi-momentum occupation should be limited to be contained within the first Brillouin zone. For calibration, we determine the size of the first Brillouin zone by performing matter-wave diffraction of a molecular Bose-Einstein condensate (mBEC). Here, a mBEC is produced and the lattice is pulsed on for $1\,\mu\mathrm{s}$ prior to the same time-of-flight expansion time to be used for the band mapping procedure. An example of the corresponding matter wave diffraction pattern that we observe is shown in Fig. 2 where the square depicts the first Brillouin zone for atoms if the same time-of-flight were to be used. Fig. 2 shows the quasi-momentum distribution obtained by band mapping using the same time-of-flight as that shown in Fig. 2. Here, a degenerate Fermi gas has been loaded into the 2D lattice prior to implementing the band-mapping technique. The fact that the quasi-momentum distribution is contained within the first Brillouin zone indicates that only the ground band of the 2D lattice is occupied.

A primary thrust of our research on 1D Fermi gases has been to directly observe the phenomena of spin-charge separation – a hallmark feature of Luttinger liquids – in a 1D gas of spin-1/2 fermions interacting via s-wave collisions. In the first year of the research program we demonstrated a novel technique for exciting spin- and density-waves in our trapped two-component mixture. In the experiments which excite spin-dipole and charge-dipole oscillations, we begin with a two-component Fermi gas confined in 1D where the axis of the 1D harmonic potential is aligned vertically and the atoms are suspended against the force of gravity by a magnetic field gradient. We then transfer atoms in one of the two spin state (hyperfine states in the ^{6}Li ground state manifold) to a different hyperfine state having a magnetic dipole moment anti-parallel to that of the original state. (The transfer is accomplished by a two-photon Raman transition.) The atoms in the two-component mixture that have been transferred now experience an acceleration in the direction parallel to gravity. After having been accelerated for a time, these atoms are transferred back to their original state and subsequently oscillate in the 1D harmonic potential. This produces both a spin-density dipole and a charge-density dipole oscillation (see Fig. 3 for example of spin- and charge-dipole oscillations in a non-interacting gas).

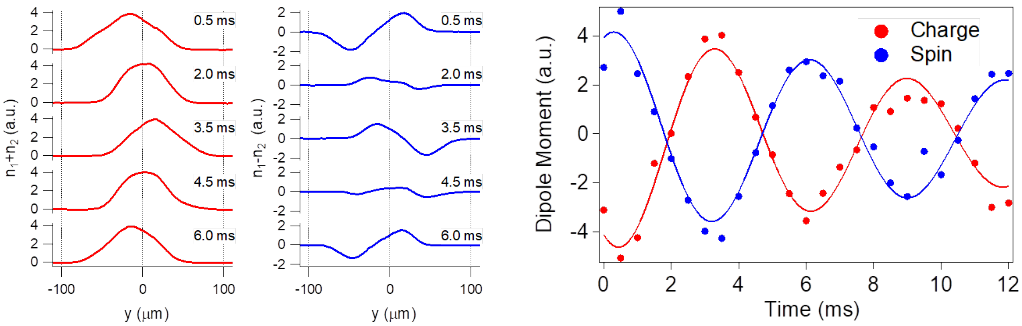

Figure 3: Spin-density and charge-density dipole oscillations for non-interacting 1D Fermi gas. (left) Charge-density and spin-density along 1D axis for various times after start of oscillations. (right) Charge-dipole and spin-dipole moment as a function of time for non-interacting gas.

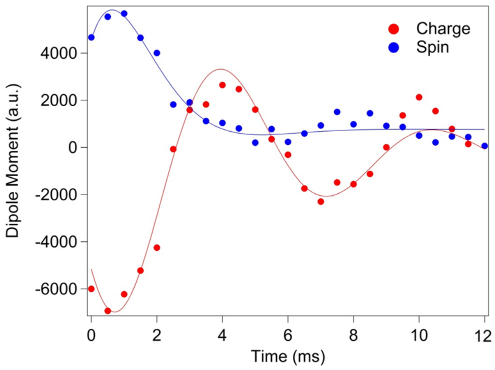

Figure 4: Charge-dipole and spin-dipole moment as a function of time for an interacting 1D Fermi gas.

We used this technique to study the dynamics of spin-dipole and density-dipole oscillations in our system. Our expectations were that the density-dipole mode would oscillate at the harmonic oscillator frequency for the axial direction of the 1D tubes while the spin-dipole mode would exhibit an oscillation frequency which decreased significantly as the inter-particle interaction strength was increased. While spin-dipole and charge-dipole oscillations were readily observed for a non-interacting gas (see Fig. 3), the oscillations were damped when interactions were increased with the spin-dipole oscillations being very strongly damped. An example of the strongly damped oscillations which result for an interacting 1D gas are shown in Fig. 4. The damping may result from one of several possibilities. First, in order to give a sizeable signal-to-noise for extracting the dipole moments, we imparted a substantial energy to the sample relative to the size of the Fermi energy. Second, to excite the dipole oscillations using the technique described above, the atoms were momentarily transferred to a non-interacting mixture from an interacting one and then transferred back again. This sudden quench of interactions may disrupt correlations that existed in the Luttinger liquid. Finally, even prior to exciting the oscillations, the 1D Fermi gas was not at zero temperature. Lower initial temperatures may be required to observe Luttinger liquid behavior as it is a zero temperature theory.

To address some of these issues, we developed, during the third grant period, a complimentary approach to investigate the phenomenon of spin-charge separation by creating spin- and charge-density wavepackets in our system. To excite the wavepackets, we selectively removed one of the spin states in the two-component mixture in a localized region of space. Selective removal was accomplished by a pair of co-propagating focussed Raman beams which transferred atoms in one of the spin states to a different hyperfine state, which, by two-body exothermic inelastic collisions, were expelled from the trap. In this manner, by selectively removing atoms in one spin state for a localized spatial region, spin-density and charge-density wavepackets were created. Fig. shows the removal of one spin state in the two component mixture which results in a spin-density and charge-density wavepacket to be created immediately after the excitation.

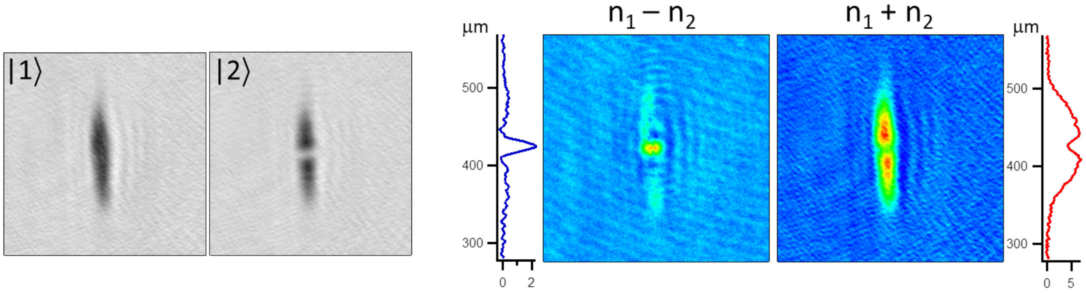

Figure 5: Exciting spin- and charge-density wavepackets. (left) Spatially selective removal of one of the two spin states from a two-component mixture. (right) Spatially selective removal of one of the spin states creates spin- and charge-density wavepackets.

Once excited, the spin- and charge-density wavepackets should propagate with different velocities as a function of interaction strength. Unfortunately, we observed that once excited, the spin- and charge-density wavepackets did not propagate in our 1D systems. At present, we believe that for both experiments the temperature we achieve in 1D is too high to observe the predicted phenomena of spin-charge separation which is based on a zero-temperature model. We are exploring approaches to reduce the temperature further.

Experiments for Observing Suppression of Inelastic Loss Near a P-Wave Resonance

S-wave Feshbach resonances have been used with great success to study the smooth BEC to BCS crossover in dilute Fermi gases. A promising approach to realize unconventional superfluidity in dilute ultracold atomic gases is to investigate pairing in a spin-polarized Fermi gas near a p-wave Feshbach resonance. In contrast to conventional BCS superfluids with condensates comprised of spin-singlet Cooper pairs with isotropic (s-wave) pair wavefunctions, unconventional superfluids feature non-trivial anisotropic pairing with correspondingly rich phase diagrams and exotic quasiparticle excitations. In 3D, such a system is predicted to exhibit an array of phases separated by classical, quantum, and topological phase transitions. In reduced dimensions, p-wave superfluids have remarkable properties of current intense interest. For example, in 2D a topological $p_x + ip_y$ superfluid characterized by a Pfaffian ground state with non-Abelian excitations is expected. In 1D, a spin-polarized Fermi gas with p-wave pairing may provide a realization of Kitaev's chain which can feature unpaired Majorana fermions localized at the ends of the chain.

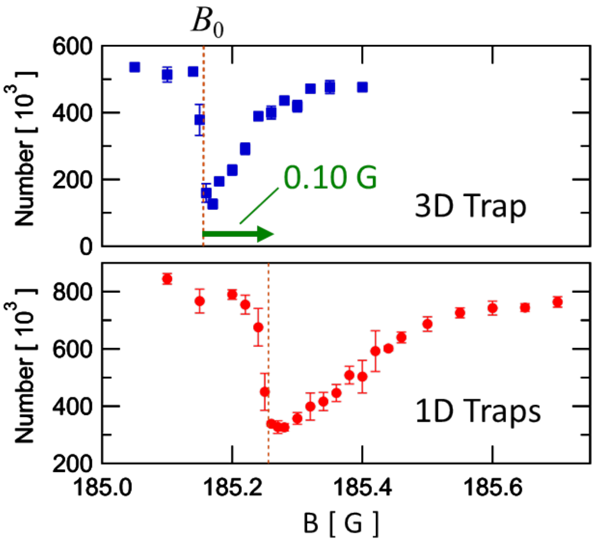

Figure 6: Confinement induced resonance shift in 1D for a p-wave resonance. (top) Position of p-wave resonance in a three-dimensional trap. (bottom)Position of p-wave resonance when confined in one dimension.

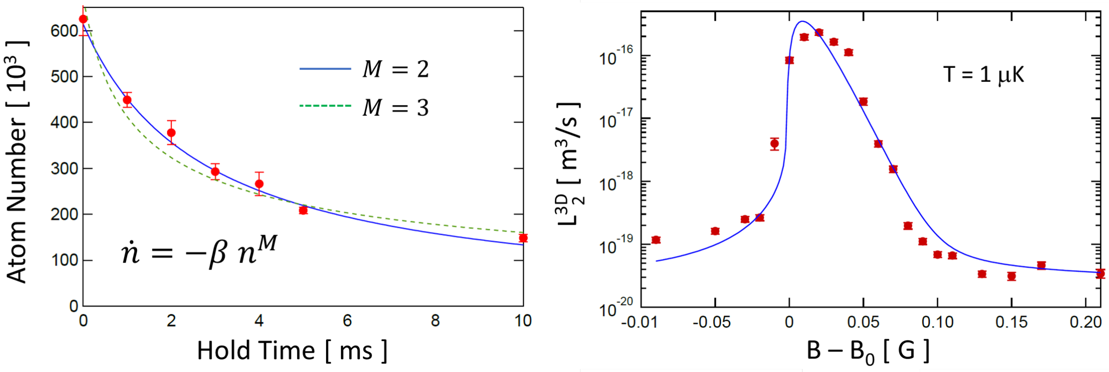

Figure 7: Two-body loss near a p-wave Feshbach resonance in a 3D trap. (left) Example of the time-dependent decay that occurs in the vicinity of the p-wave resonance which is well-described by two-body decay. (right) Measured two-body recombination rate constant as a function of magnetic field.

Unfortunately, inelastic loss near p-wave Feshbach resonances has compromised attempts to observe p-wave superfluidity in 3D. Spin-polarized Fermi gases that are not in their lowest energy hyperfine state suffer from strong two-body dipolar relaxation. While such loss can be avoided for fermions in their absolute ground state, three-body recombination rates are still large enough to prohibit evaporation to degeneracy at equilibrium. Only out-of-equilibrium studies of the p-wave contacts have been possible. While three-body recombination has proven insurmountable in 3D, it has been predicted to be suppressed for atoms confined to 1D [1, 2, 3].

While we have found that lower temperatures are required to observe spin-charge separation in a 1D Fermi gas, we realized that this system provided an opportunity to investigate recent exciting theoretical predictions regarding inelastic p-wave collisions in low dimensions. Recent theoretical predictions have suggested that inelastic loss near a p-wave scattering resonance is strongly suppressed in reduced dimensions. Such a suppression, if observed, could permit the realization of p-wave paired superfluid phases in dilute atomic gases which have thus far eluded observation due to strong inelastic loss. Two mechanisms lead to strong loss: two-body relaxation and three-body recombination. Our group made two significant observations within the last 1.5 years of the total grant period. These observations respectively concern the suppression of 2-body relaxation and 3-body recombination near a p-wave resonance in a 1D Fermi gas.

First, to demonstrate that we are observing a p-wave resonance in one dimension, we have measured the confinement induced resonance shift for the p-wave resonance. Prior to this measurement, the lattice depth is first calibrated by performing parametric resonance spectroscopy where the lattice depth is modulated at different frequencies and the number and temperature of the gas is monitored. Parametric resonance, indicated by a loss of atoms and increase in temperature, occurs when the driving frequency is twice the harmonic oscillator frequency for individual lattice sites. Using this technique, we determine the lattice depth is $V_0 = 22\, E_R$ where E_R is the recoil energy for a lattice photon. Given this lattice depth, the predicted confinement induced resonance shift is $110\,\mathrm{mG}$. To observe this shift, we first determine the location of the p-wave resonance in a 3D trap by measuring the number of atoms remaining in the trap after a short hold time as a function of magnetic field. This measurement is shown at the top of Fig. 6. The location of the p-wave resonance, where the molecular state associated with the resonance crosses threshold, is indicated by the sharp drop in number of atoms remaining. An equivalent

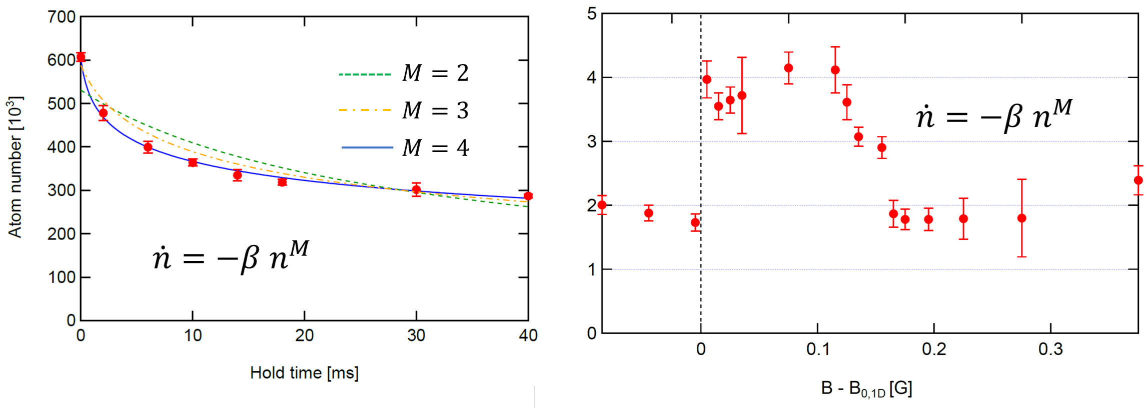

Figure 8: Development of correlations in a 1D Fermi gas near a p-wave resonance which features two-body loss in 3D. (left) For magnetic fields in close proximity to the peak of the resonance, the time-dependent loss of atoms from the trap is well-described by an apparent "four"-body loss due to the development of correlations in the gas. (right) The apparent "N"-body loss for different magnetic fields accross the p-wave resonance.

experiment is then performed for atoms confined in the ensemble of 1D traps provided by the 2D lattice. The confinement induced resonance shift, which is the shift in magnetic field between the onset of loss observed in 1D and in 3D, is observed to be $100\,\mathrm{G}$ which is in good agreement of the prediction of $100\,\mathrm{mG}$ for our measured lattice depth.

We first studied two-body relaxation near a p-wave resonance in a 3D trap by studying a mixture with stored internal state energy. Our observations were in good agreement with previous observations [4]. Namely, we observed that the time-dependent decay of the gas was well-described by a theory which assumed the gas decayed by two-body loss. Further, we measured the two-body recombination rate constant as a function of magnetic field and found it to be in good agreement with a theorretical model prediction [2] and earlier observations [4]. These results are shown in Fig. 7.

We then studied the same two-component mixture near the same p-wave resonance in 1D where the resonance was shifted by the confinement induced resonance shift mentioned earlier. With the gas confined in 1D, we observed remarkable behavior for magnetic fields in close proximity to the peak of the resonance. Instead of a decay well-described by two-body relaxation, we found that an apparent "four"-body decay provided a much better description of the time-dependent loss data. An example can be seen on the left in Fig. 8. We interpret the apparent "four"-body loss as the development of correlations in the 1D gas. The apparent "four"-body loss we observe would occur if the two-particle correlation function is proportional to the square of

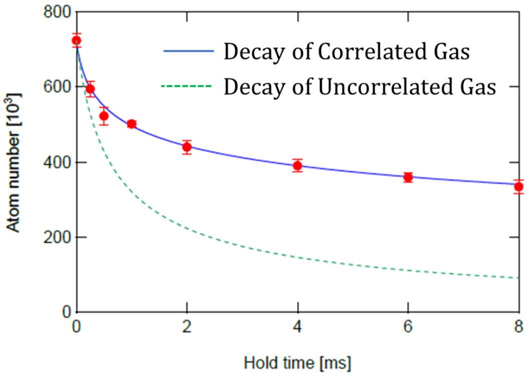

Figure 9: Decay of correlated gas compared to decay for uncorrelated gas with the same initial loss rate.

the 1D density. As time proceeds, the gas becomes correlated such that further two-body recombination is inhibited. This is comparable to inhibited decay of molecular condensates confined in 1D that had been observed by the group of Stephan Dürr at the Max Planck Institute [5] but now in the context of p-wave inelastic loss in a 1D Fermi gas. These experiments can be interpreted in the context of the quantum Zeno effect where the strong loss itself provides a continuous measurement of the two-particle correlations in the system. After an initial rapid loss, the gas which remains is in a state where the pair correlation function is reduced. Time evolution away from this state is arrested by the quantum Zeno effect where the rapid two-body loss itself acts as a continuous measurement of the pair correlation function. Thus, further two-body decay is suppressed as the pair correlation function remains at a reduced value. The best fit "N"-body loss that we observe as the p-wave resonance is crossed is shown on the right in Fig. 8. Away from the resonance, the decay is well-described by two-body loss whereas in close proximity to the resonance, correlations build up in the gas giving the time-dependent loss an apparent "four"-body character. While we observe that two-body loss is suppressed by the formation of a 1D correlated gas, our analysis indicates that the two-body loss rate coefficient itself is not suppressed.

In Fig. 9, we highlight the dramatic effect that the build up of correlations have on the decay of the gas in 1D. Here, we have plotted the decay of the gas in close proximity to the peak of the p-wave resonance where correlations in the gas develop in comparison to the expected decay if two-body loss alone occured in an uncorrelated gas. Both curves have the same initial rate of loss. It is evident that the correlations which develop in the gas play a significant role in arresting further decay of the gas once correlations have developed after a rapid initial loss.

In a second experiment, we studied three-body recombination in a 1D system. In this case, we could gaurantee that three-body recombination was the only loss mechanism at play by confining a spin-polarized Fermi gas in 1D where all of the atoms are in the energetically lowest hyperfine state. Thus, two-body inelastic collisions are absent and only three-body recombination (3BR) occurs near a p-wave resonance for the spin-polarized gas. In contrast to what we observed for two-body loss in 1D, the formation of a correlated gas in 1D is not observed. Rather, the time-dependent loss is always observed to be well-described by a three-body recombination loss rate equation. However, we observe that the three-body recombination rate constant itself is suppressed relative to that measured in 3D. An example of this is shown in Fig. 10 where the 3BR rate coefficient as a function of field offset from the resonance position is shown for fermionic atoms in 3D and in 1D. At the peak of the loss feature, which occurs at the resonance position, the loss rate constants observed in 1D are supressed by at least one order of magnitude relative to those observed in 3D. In 3D, the peak of the loss feature is known to be unitarity limited where the temperature dependence of the unitarity limit scales as $1/T^2$ [6]. The unitarity limit for the 3D case shown in Fig. 10 is indicated by the horizontal orange dashed line. At approximately the same temperature, the 3BR rate in 1D is observed to be at least one order of magnitude below that in 3D.

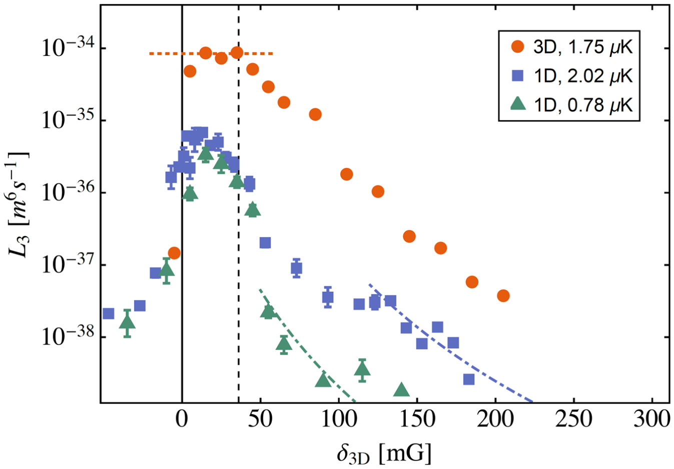

Figure 10: Comparison of three-body recombination rate constant measured in 3D to that in 1D relative to the position of the resonance in the respective dimension.

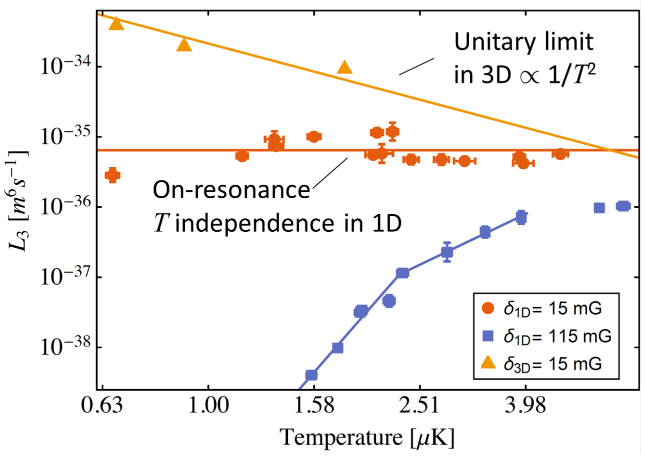

Figure 11: Temperature dependence of the three body recombination rate near the resonance peak for a 3D (orange) and a 1D (red) gas. Also shown is the temperature dependence in 1D at a magnetic field tuned away from the resonance peak (blue).

There have been several theoretical predictions which qualitatively suggest that such a suppression in 1D compared to 3D should occur [1, 2, 3]. Away from the the resonance peak, a strong energy (i.e. temperature) dependence of the suppression has been predicted [1]. On the other hand, near the resonance peak, an insenstivity to the energy (temperature) has been predicted [1]. We have measured the temperature dependence for 3BR for magnetic fields tuned to the peak of the resonance for both the 3D gas and the 1D gas. These are respectively shown as the orange and red curves in this figure. For the 3D gas, we observe the known unitarity limit for which the recombination rate scales as $1/T^2$. In contrast, the recombination rate in 1D near the peak of the resonance is observed to be insensitive to temperature. Note that as the temperature is reduced, the relative suppression of the rate constant in 1D compared to 3D grows larger. We have also measured the temperature dependence of the recombination rate constant for magnetic fields tuned away from resonance. In this case, we observe a very strong dependence on temperature. This is shown in blue in Fig. 11. We are in the process of developing a theoretical model for the temperature dependence observed away from resonance.

Finally, we have also measured the dependence of the 3BR rate constant on lattice depth. This is shown in Fig. 12. The 3BR rate constant is observed to be proportional to $1/V_L$ over a range of lattice depths from $V_L = 6E_R$ to $V_L = 20E_R$. This suggests that further suppression can be attained for deeper lattices which corresponds to tighter radial confinement within each one dimensional tube. In terms of the harmonic oscillator length scale in the radial direction, $a_\perp$, the $1/V_L$ scaling suggests that the recombination rate scales as $a_\perp^4$. Thus, by significantly reducing $a_\perp$ the suppression of the 3BR rate constant can be substantial. For example, the square lattice formed from 1064 nm laser beams used here can be replaced with a lattice formed from 532 nm laser beams. This would reduce the lattice constant by a factor of 2 which should result in a further suppression of the 3BR rate by a factor of 16 for a comparable lattice depth assuming that the scaling continues

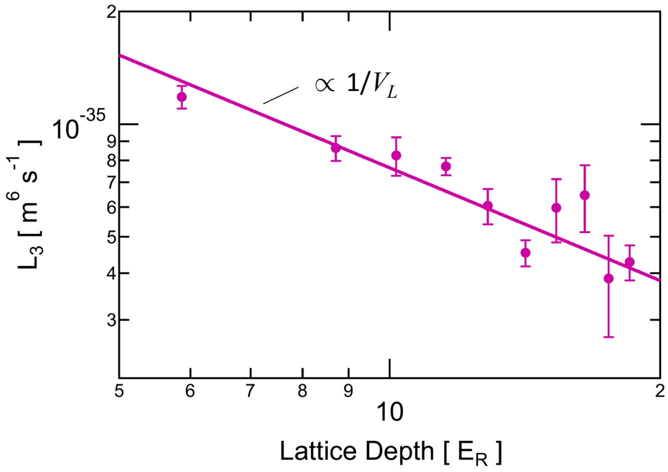

Figure 12: Dependence of the three-body recombination rate constant on lattice depth.

to hold. By increasing the lattice depth further, additional suppression of the 3BR rate constant could be realized. In this way, the confinement of Fermi gases in 1D may substantially reduce loss from three-body recombination near p-wave Feshbach resonances and allow for the realization and study of p-wave superfluidity in a one-dimensional dilute Fermi gas. A manuscript describing this work is currently in preparation.

The physical mechanism behind the suppression of three-body recombination is still not entirely understood. One possibility is that one-dimensional confinement serves to reduce the amplitude of the two-body wave function at short range [3]. Normally, in 3D, the two-body wave function for p-wave interactions can have a significant amplitude at short range due to the presence of the centrifugal barrier. The existence of a significant amplitude at short range in turn enhances three-body recombination as the molecular wave function for deeply bound molecules now has significant overlap with the scattering wave function. In the extreme case of truly one-dimensional confinement, however, where $a_\perp$ is comparable to the range of the molecular interaction potential, the centrifugal barrier would in fact be absent since orbital motion of two particles is disallowed in a strictly 1D setting. In the absence of the centrifugal barrier, the molecular wavefunction should become extended in space and the three-body recombination rate should be reduced. We have recently investigated theoretically the experimental conditions that would be required to enter this regime where the p-wave molecular state associated with the Feshbach resonance has such a character and behaves as a so-called halo-dimer where the size of the molecule is determined purely by the 1D scattering length a_{1D}. To do this, we calculate the binding energy and closed channel fraction of p-wave Feshbach molecules in quasi-1D by examining the poles of the p-wave S-matrix. We show that under the right experimental conditions, the quasi-1D p-wave molecule behaves like a halo dimer with a closed channel fraction approaching zero at resonance and a binding energy following the universal relation $E_b \propto 1/a_{\mathrm{1D}}^2$, where a_{1D} is the 1D scattering length. We calculate these experimental conditions for both ^{6}Li and ^{40}K over a range of transverse confinements. We expect that in this halo dimer regime the three body loss associated with the p-wave Feshbach resonance will be greatly suppressed, potentially allowing for a stable p-wave superfluid to be created. For an easy comparison between the 3D and quasi-1D cases, we provide the same poles analysis of the Feshbach molecules applied to the 3D p-wave resonance and show there is a qualitative difference between the two. A manuscript describing this work is currently in preparation.

C. Personnel

The research staff working on this project consists of:
Principle Investigator: Assoc. Prof. Kenneth M. O'Hara
Postdoctoral Research Associate: Dr. Chenglin Cao
Graduate Student: Francisco Fonta
Graduate Student: Andrew Marcum
Graduate Student: Arif Mawardi Bin Ismail

D. Publications

F. R. Fonta, A. S. Marcum, A. Mawardi Ismail, and K. M. O'Hara, "High-power, frequency-doubled Nd:GdVO$_4$ laser for use in lithium cold atom experiments," Optics Express **27**, 33144 (2019).

A. S. Marcum, A. Mawardi Ismail, F. R. Fonta, and K. M. O'Hara, "Suppression of Three-Body Loss Near a P-Wave Resonance Due to 1D Confinement," in preparation.

F. R. Fonta, and K. M. O'Hara, "Experimental Conditions for Obtaining Halo P-Wave Dimers in Quasi-1D," in preparation

E. Interactions/Transitions

K. M. O'Hara, "Spin-Charge Waves in 1D Fermi Gases," Aspen Center for Physics, Workshop on Ultra-Cold Quantum Matter with Atoms and Molecules, Seminar (July 17, 2015).

C. Cao, A. Marcum, A. Mawardi Ismail, F. Fonta, and K. O'Hara "Direct Observation of Spin- and Charge-Density Waves in a Luttinger Liquid," 47th Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics, Providence, RI, Contributed Talk (May 25, 2016).

A. Marcum, A. Mawardi Ismail, F. Fonta, and K. O'Hara "Observing Spin-Charge Separation in a 1D Fermi Gas," 48th Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics, Sacremento, CA, Contributed Talk (June 5, 2017).

K. M. O'Hara, "State-of-the-Art Atomic Clocks: Improving Their Accuracy by Eliminating Atomic Collision Shifts," Electro-Optics Center, The Pennsylvania State University, Freeport, PA, Seminar (April 30, 2018).

K. M. O'Hara, A. Mawardi Ismail, A. S. Marcum, and F. Fonta "Two-Body Relaxation of Fermions in 1D near a P-Wave Resonance," 49th Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics, Fort Lauderdale, FL, Contributed Talk (May 30, 2018).

F. R. Fonta, A. S. Marcum, A. Mawardi Ismail, and K. M. O'Hara, "A high power solid-state laser system for lithium atom experiments," 50th Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics, Milwaukee, WI, Poster Presentation (May 29, 2019).

A. S. Marcum, A. Mawardi Ismail, F. R. Fonta, and K. M. O'Hara, "Suppression of Inelastic Loss Near a P-Wave Resonance for Fermions in 1D," 50th Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics, Milwaukee, WI, Poster Presentation (May 30, 2019).

F. Inventions

None during this grant period.

G. Awards

None during this grant period.

References Cited

[1] N. P. Mehta, B. D. Esry, and C. H. Greene, "Three-body recombination in one dimension," *Phys. Rev. A* **76**, 022711 (2007).

[2] D. V. Kurlov, and G. V. Shlyapnikov, "Two-body relaxation of spin-polarized fermions in reduced dimensionalities near a p-wave feshbach resonance," *Phys. Rev. A* **95**, 032710 (2017).

[3] L. Zhou, and X. Cui, "Stretching p-wave molecules by transverse confinements," *Phys. Rev. A* **96**, 030701 (2017).

[4] M. Waseem, T. Saito, J. Yoshida, and T. Mukaiyama, "Two-body relaxation in a fermi gas at a p-wave feshbach resonance," *Phys. Rev. A* **96**, 062704 (2017).

[5] N. Syassen, D. M. Bauer, M. Lettner, T. Volz, D. Dietze, J. J. García-Ripoll, J. I. Cirac, G. Rempe, and S. Dürr, "Strong dissipation inhibits losses and induces correlations in cold molecular gases," *Science* **320**, 1329–1331 (2008).

[6] M. Waseem, J. Yoshida, T. Saito, and T. Mukaiyama, "Unitarity-limited behavior of three-body collisions in a p-wave interacting fermi gas," *Phys. Rev. A* **98**, 020702 (2018).