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Single-atom microscopy of dipolar Fermi gases

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14. ABSTRACT

This final report summarizes our accomplishments over the four years of support under this grant. The first area of research focuses on the realization of Rydberg dressed Fermi gases in optical lattices. These are itinerant many-body quantum systems with strong long-range interactions that can be used as quantum simulators for a wide range of Hamiltonians that lead to interesting equilibrium phases and novel quantum dynamics. The second area of research relates to the implementation of an imaging technique based on Raman sideband cooling in an optical lattice that enables high-fidelity detection of single atoms on individual sites of the lattice. Using quantum gas microscopy, we characterized the interaction potentials of Rydberg dressed atoms using many-body Ramsey interferometry, explored the lifetime of mesoscopic samples of Rydberg dressed atoms and studied the quench dynamics in this platform revealing the interplay between motional and interaction effects.

15. SUBJECT TERMS

Rydberg dressing; ultracold gases; degenerate Fermi gases; long-range interactions; quantum simulation.

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Final Report for
Grant FA9550-16-1-0269

SINGLE-ATOM MICROSCOPY OF DIPOLAR FERMI GASES

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October 13, 2020

I. Summary: Objectives and Status of Effort

In this report we summarize our accomplishments under Grant FA9550-16-1-0269. This project had two interrelated goals. The first was to develop a new platform for the quantum simulation of strongly correlated electronic systems with long-range interactions based on Rydberg-dressed atomic Fermi gases. The second was to improve the performance of a lithium quantum gas microscope that we had constructed prior to the start of the performance period and to use it for high resolution probing and manipulation of Rydberg-dressed Fermi gases.

We have accomplished both of these goals. In particular, we achieved the following: a) Developed a technique for imaging single atoms in an optical lattice based on Raman cooling in a new regime that improved the detection fidelity beyond the previously used technique based on electromagnetically induced transparency, b) Demonstrated the single-photon excitation of atoms in a lithium-6 Fermi gas to Rydberg states using a deep UV laser system to achieve Rabi couplings on the order of 10 MHz, c) Revealed antiferromagnetic spin correlations in a resonantly excited spin-polarized band insulator of fermions. The system realized a 2D quantum Ising spin model in which we studied the quench dynamics of the antiferromagnetic correlations providing benchmark experimental data that was used to test state of the art numerical techniques for simulating the dynamics of quantum systems, d) Realized a Rydberg dressed Fermi gas, characterized interactions in the gas through many-body Ramsey interferometry and studied the collective lifetime of the system in the presence of tunneling. The system was used to realize a coupled-chain t-V model in which we probed the interplay of tunneling and non-local interactions by exploring the quench dynamics of charge-density waves, e) Used the upgraded quantum gas microscope for a variety of other experiments including studying canted antiferromagnetism in spin-imbalanced Fermi-Hubbard models, charge-density waves in attractive Hubbard systems, strange metallicity in doped Mott insulators, angle-resolved photoemission in Hubbard systems and sub-diffusive charge transport in tilted Hubbard systems.

In summary, we have used Rydberg dressing to realize the first degenerate quantum gas of itinerant particles with strong, long-range interactions. This has been a long-sought goal for the ultracold gas community. With further improvements to the coherence time, this new platform may be used to explore a wide range of equilibrium and non-equilibrium many-body quantum phenomena. The insights gleaned from such experiments are important for the development of technological materials with novel properties that further the mission of the Air Force and the DoD more broadly.

II. Accomplishments

In this section we briefly describe our research under this grant. We only provide a short summary of each accomplishment and refer the reader to the publications listed at the end of this report for more details.

2.1 Quantum gas microscopy of lithium atoms with Raman sideband cooling in a new regime

Prior to the start of this grant, the Bakr group had constructed a lithium-6 quantum gas microscopy apparatus for probing single atoms of a degenerate Fermi gas in an optical lattice. At the time, we were using electromagnetically induced transparency as the cooling technique during imaging. The main deficiency of this technique was that the atom hopping rate during the imaging was rather high, making it necessary to use low exposure times which led to a low single atom detection fidelity. During the first year of the performance period, we switched to a cooling technique based on Raman cooling in an optical potential consisting of a 2D optical lattice and a light sheet to confine the gas to a single plane. While the tight confinement of the 2D lattice enabled sideband cooling in the Lamb-Dicke regime in two dimensions, the third direction was far from that regime. Nevertheless, the cooling was observed to be efficient and enabled atom detection fidelities on the order of 98% in a lattice with a 750 nm spacing. The success of this approach greatly simplifies the technical requirements for quantum gas microscopy.

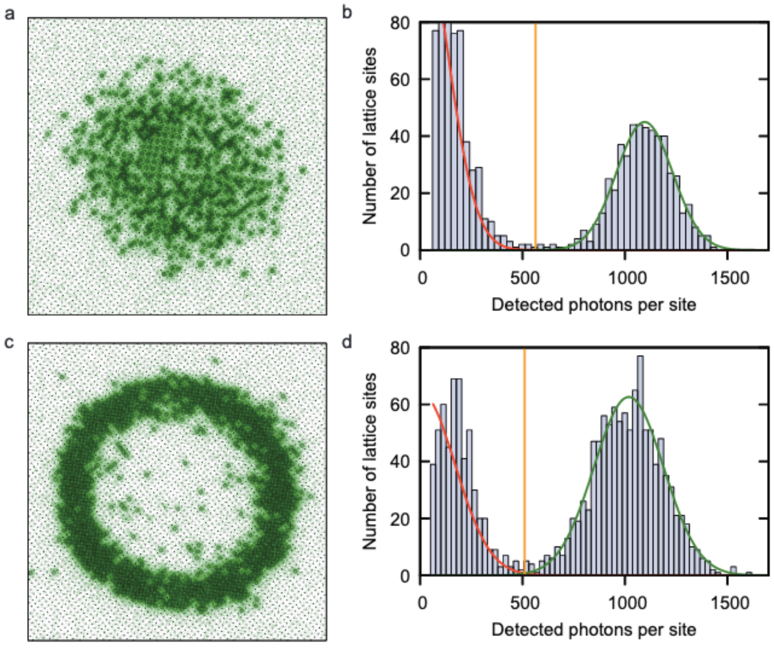

Fig. 1. Fluorescence images of a cloud exhibiting (a) antiferromagnetic correlations and (c) and a cloud showing Mott and band insulators taken with the Raman-cooling-based imaging technique. As seen from the distribution of photon count histograms (b,d), sites with zero atoms and one atom are clearly distinguishable leading to a high detection fidelity.

2.2 Single photon excitation of atoms in a lithium-6 Fermi gas to Rydberg states

Previous Rydberg experiments had focused on rubidium and cesium. For the research pursued in this grant, we worked with lithium-6 for two reasons. First, it is one of only two alkali fermionic species. Second, its light mass makes it particularly suitable for dressing experiments where fast tunneling in the optical lattice is desirable since one has to compete with loss mechanisms associated with decay from the Rydberg admixture. To achieve a lifetime corresponding to many interaction times, it is necessary to achieve a large coupling strength to the Rydberg state of interest. Consequently, we identified single-photon excitation as the most promising approach to reach the desired coupling strength. Single-photon excitation of lithium-6 requires operating at a challenging wavelength of 231 nm (deep in the UV). To obtain light at this wavelength, we set up an amplified diode laser system followed by two second harmonic generation cavities. We achieved powers of up to 60 mW in the UV and were able to couple ground state atoms to the 28P Rydberg state with a Rabi frequency of 10 MHz.

2.3 Probing the quench dynamics of antiferromagnetic correlations in a 2D quantum Ising spin system

Our first experiment involved resonant excitation of atoms to a low-lying Rydberg state. Previous experiments in optical lattices had studied the resonant excitation of atoms in a Mott insulator to Rydberg states with principal quantum numbers greater than 40 where the Rydberg blockade radius is typically on the order of 10 sites. This led to the observation of Rydberg crystals of a few atoms. In this work, we prepared atoms in a spin-polarized fermionic band insulator. This allowed us to create systems of about 200 atoms with near-unit occupancy of the lattice sites. We excited the atoms resonantly to the 23P Rydberg state which had a blockade radius on the order of one lattice site. Encoding a pseudospin-1/2 in the ground/Rydberg states, this allowed us to realize a 2D quantum Ising model with transverse and longitudinal fields, where the fields are controlled by the coupling strength and the detuning from resonance respectively. The small blockade radius leads to the generation of antiferromagnetic correlations in the dynamics, which we were able to observe directly using site-resolved microscopy. We studied the dynamics of the antiferromagnetic correlations for sudden quenches from a paramagnetic state. We also prepared many-body states with longer range antiferromagnetic correlations by implementing a near-adiabatic ramp of the longitudinal field and studied the build-up of the correlations as we varied the rate with which we changed the field.

Simulating the out-of-equilibrium dynamics of quantum many-body systems poses a major theoretical challenge, especially in more than one dimension. The 2D dynamics experiments we performed in this work provided valuable data for benchmarking numerical algorithms that are being developed to simulate the dynamics of strongly correlated materials (e.g. photo-induced superconductivity). In particular, in this work, we compared our experimental data against a recently developed numerical technique known as the dynamical numerical linked cluster expansion. We found good agreement with the experiment for the short evolution times that the classical simulation was able to study. However, the experiment also explored longer evolution times which remain out of reach for current numerics.

An additional interesting aspect that this experiment shed light on was the interplay between motion and spin in such experiments. Interacting Rydberg atoms experience strong forces that lead to motion in the lattice. The light mass of the atom used in these experiments, lithium-6, makes this effect particularly important compared to heavier species. In this experiment, the motion acts a decoherence mechanism since it is not included within the spin Hamiltonian. However, spin-motion couplings are a coherent effect that may be exploited in future work.

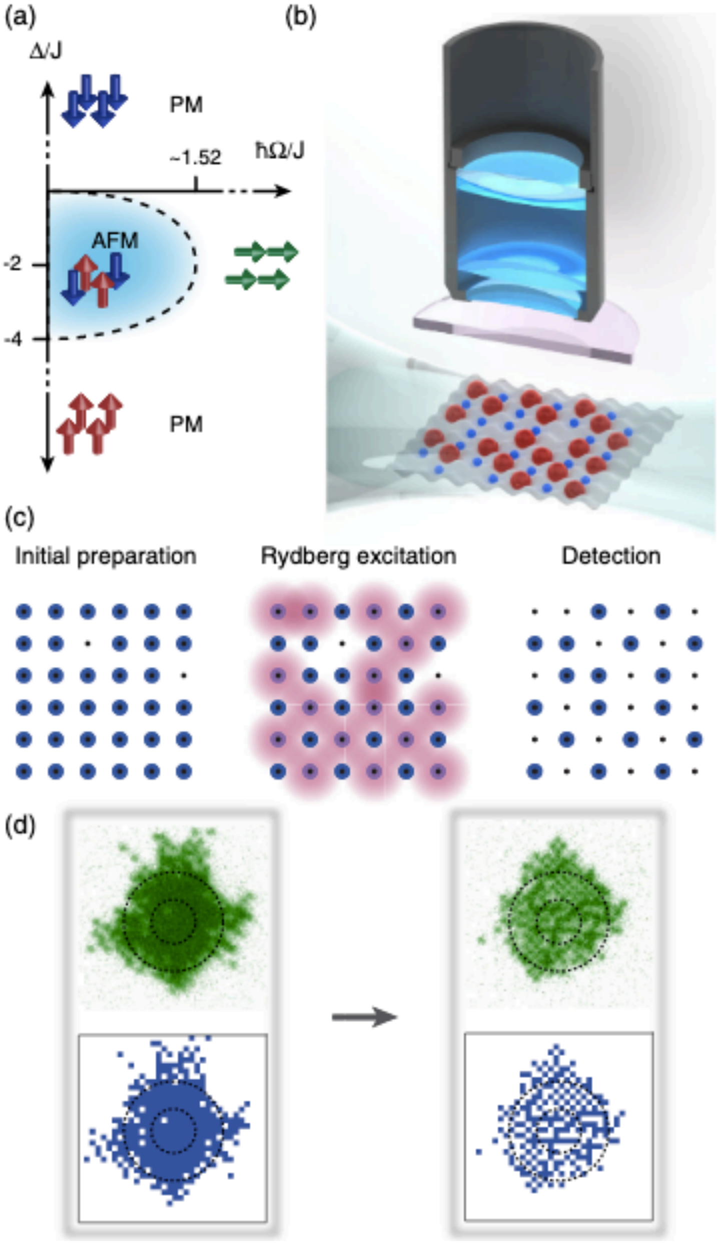

Fig. 2. (a) Phase diagram of the quantum Ising model explored in this experiment, shown in the space of the transverse and longitudinal fields. (b) Schematic of the experiment with UV light exciting atoms in a 2D spin-polarized band insulator to a low-lying Rydberg state and the resulting configuration imaged with single-site resolution. (c) Experimental protocol: a spin-polarized band insulator is prepared, the atoms are coupled resonantly to a Rydberg state and the ground state atoms are subsequently imaged after the Rydberg atoms are ejected. (d) Fluorescence and binarized images of atoms in the band insulator and a time-evolved state with strong antiferromagnetic correlations.

2.4 Single-atom imaging of a Rydberg-dressed Fermi gas and study of quench dynamics in this system

In the next experiment, we switched from resonant coupling to the Rydberg state to off-resonant coupling, realizing a Rydberg-dressed gas of lattice fermions. This system realizes a degenerate quantum gas with strong long-range interactions, a long-standing goal for the community. Ultracold gases of atoms in the ground state interact with weak van der Waals potentials with a typical range of a few nanometers. Since the de Broglie wavelength of ultracold atoms are on the order of one micron, this means the interactions of ground state atoms can be considered to be effectively contact interactions. In a lattice setting, this means only atoms on the same site are interacting. While this has allowed the study of rich physics in Hubbard systems with on-site interactions, there has been much activity in recent years trying to realize systems with strong long-range interactions on the order of lattice separations. This would enable simulating new Hamiltonians which can be used to study exotic phases such as supersolids or fractional Mott insulators or to study novel dynamics such as the breakdown of thermalization in systems with long-range interactions. Two leading candidates in this direction of research are magnetic atoms and polar molecules. However, magnetic atoms typically have very weak interactions of only tens of Hz at typical lattice spacings while polar molecules have suffered from short lifetimes due to poorly understood loss mechanisms. These limitations have hindered the realization of many-body quantum systems with strong off-site interactions. In this work, we demonstrated a new approach to engineering such systems with Rydberg dressing.

Atoms in Rydberg states interact through strong van der Waals interactions. Such states are have lifetimes on the order of tens of microseconds, which is short compared to millisecond motional scales for atoms in an optical lattice. Furthermore, the interactions between Rydberg atoms are orders of magnitude stronger than the kinetic energy of a degenerate gas. This hinders the study of the interplay between interactions and the kinetic energy. Rydberg dressing solves both of these problems by using off-resonant coupling of a ground state to a Rydberg state to create a superposition of a ground state atom with a small Rydberg admixture. For a small admixture, the lifetime of the dressed state can be orders of magnitude larger than that of the bare Rydberg state. On the other hand, the interactions between Rydberg dressed atoms are at the kHz scale, matching the kinetic energy scale. The strength and range of the interactions is tunable in real time since they are controlled by the coupling strength, the detuning and the principal quantum number of the Rydberg state.

In this work, we studied Rydberg dressing of a Fermi gas of lithium-6. The light mass of this atom is crucial since it leads to fast tunneling in the lattice and makes the study of motional effects in the Rydberg-dressed sample easier. The first measurement we did involved using many-body Ramsey interferometry to measure the off-site interactions in the gas. For these measurements, we prepared a spin-polarized band insulator in the optical lattice. We then used a radiofrequency pulse to put the atoms in a superposition of two spin states and then turned on the Rydberg dressing light. The components of the superposition acquired a differential phase during the evolution due to Stark shifts from the dressing light and the interactions between the dressed atoms. The Stark shift contribution was cancelled using a spin-echo sequence. Since the Stark shifts are almost two orders of magnitude larger than the Rydberg-dressed interactions, this step needed very good intensity stability of the dressing light, which we accomplished by adding an EOM-based noise-eater to the system. The soft-core dressing interaction potential was mapped by measuring the spin correlations in the gas. We were able to achieve nearest-neighbor interactions on the order of 5 kHz and an interaction range on the order of one site.

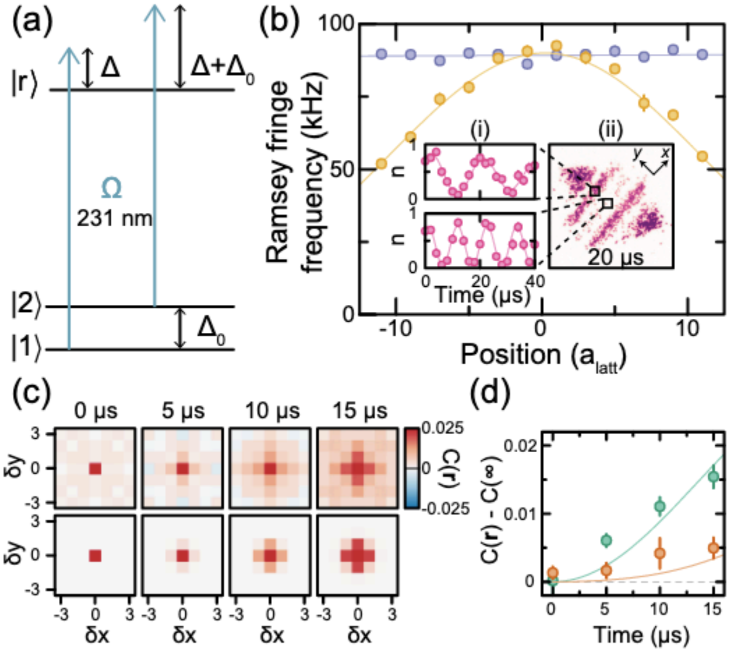

Fig. 3. (a) Level diagram for many-body Ramsey interferometry. Two hyperfine ground states were coupled to th 28P Rydberg state, with the lower ground state being much more strongly dressed. (b) At large detunings of the dressing laser, the interactions are negligible and the Ramsey fringes measure the differential Stark shift due to the dressing light. From these measurements, we were able to measure the coupling strength to the Rydberg state, on the order of 10 MHz. (c,d) Time evolution of spin correlations measured after a spin-echo Ramsey sequence, which allow us to map the soft-core Rydberg dressing potential.

Next, we studied the lifetime of the Rydberg dressed samples. Previous experiments on Rydberg dressing were limited by very short lifetimes. An isolated Rydberg dressed atom is expected to have a lifetime enhanced relative to a bare Rydberg atom by a factor of the inverse of the square of the admixture strength. However, the collective lifetimes observed in large clouds were much shorter. This was attributed to an avalanche loss mechanism in which the Rydberg admixture of one of the dressed atoms undergoes a blackbody induced transition to a Rydberg state of opposite parity. This contaminant broadens the line through resonant state interactions with the other dressed atoms, leading to an avalanche of resonantly excited Rydberg atoms that are rapidly lost from the system. In our experiments, we worked with much smaller atom numbers (typically 30-60 atoms) in a 2D gas. We observed significant suppression of avalanche losses and were able to reach lifetimes in the gas on the order of 30% of the expected single-particle lifetime even for a dense lattice (n=0.5). Furthermore, while we observed a strong dependence of the lifetime on the density in the lattice, we observed that in contrast to the predictions of the avalanche theory, the lifetime did not depend on the atom number at fixed density. Finally, we studied the lifetime of the gas outside of the frozen regime and observed that introducing tunneling does not reduce the lifetime of the dressed gas, in contrast to some theoretical predictions. By combining our Ramsey and lifetime measurements, we established that we could prepare Rydberg-dressed systems with lifetimes on the order of 20-30 interaction times.

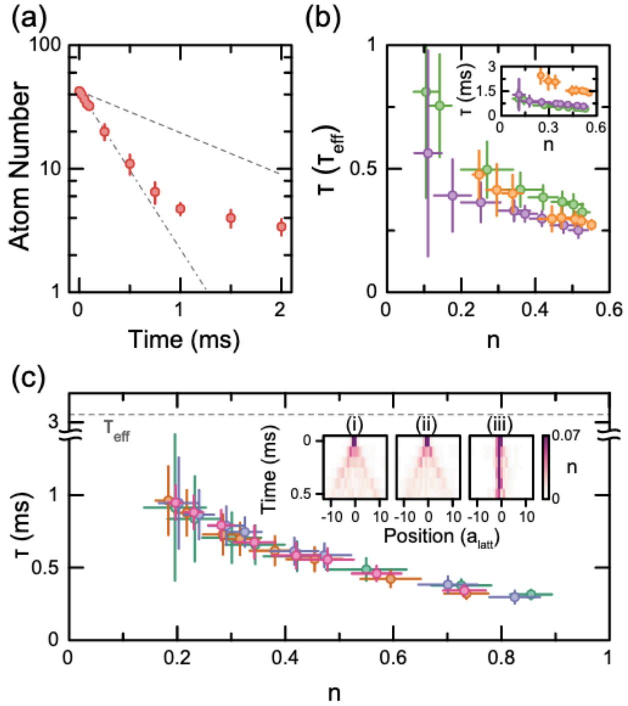

Fig. 4. (a) Atom number decay in a Rydberg dressed sample. The non-exponential decay indicates a density dependent lifetime. (b) We studied the density-dependent collective lifetime at various detunings finding that for certain detunings, the collective lifetime could reach 30% of the single-particle lifetime in a half-filled system. (c) We also studied the lifetime vs. the tunneling rate and found that atomic motion does not enhance loss.

Our Rydberg dressed system approximately realizes a t-V model. This is the simplest lattice model of spin-polarized fermions with off-site interactions. The large Stark shifts due to the Rydberg dressing light inhibit tunneling along the waist direction while the fermions tunnel freely along the Rayleigh range direction which has a very slow spatial variation of the Stark shift. Consequently, we realize a coupled chain t-V model where the tunneling is along one direction only while we have isotropic off-site interactions with range of order one site.

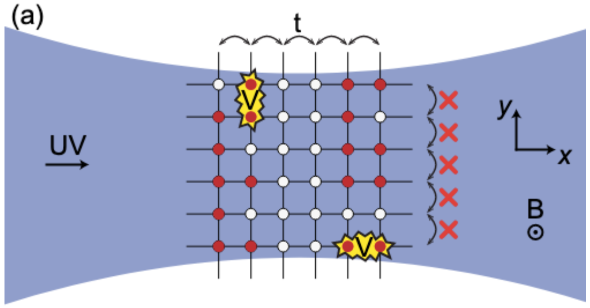

Fig. 5. Schematic of the mixed dimension t-V model realized with the Rydberg dressed fermions. The fermions tunnel along one direction only while the interactions are isotropic.

To probe the interplay of long-range interactions with tunneling in this model, we prepared charge density wave states using a spatial light modulator and studied their relaxation. We found that the relaxation slowed down for strong interactions due to a conservation of bonds between occupied sites in the strong interaction limit. In that limit, the system exhibits Hilbert space fragmentation, a novel mechanism for breaking ergodicity that has been studied in recent theoretical works but had not been realized experimentally yet. Systems exhibiting such Hilbert space fragmentation are promising systems for realizing quantum memories.

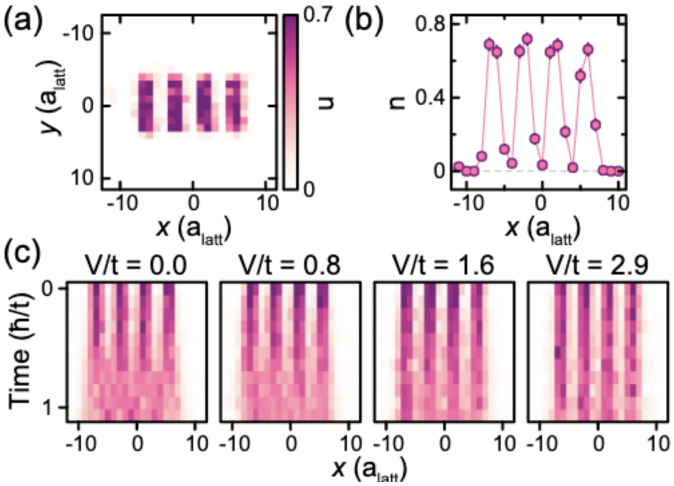

Fig. 6. (a,b) Initial charge density wave pattern prepared in the 2D system. (c) Evolution of this pattern in the Rydberg dressed system which may be approximately described by a mixed dimension t-V model. For increasing interactions V/t, the relaxation of the wave slows down due to a conservation of bonds in the system.

This work was the first time in which Rydberg dressing was demonstrated outside what is known as the frozen gas regime. There are several avenues for improving the coherence of the system in future work. The coupling strength to the Rydberg state may be enhanced by a factor of 10 to 20 using a build-up cavity, and the lifetime to interaction time ratio is linear in this enhancement for fixed Rydberg admixture. Increasing the coupling strength allows using larger detunings for the dressing, which shrinks the facilitation radii involved in avalanche loss leading to further improvements of the lifetime. Alternatively, a cryogenic environment may be used to suppress the avalanche loss completely. Another promising avenue that has been proposed is dressing to Rydberg molecular states. Finally, Rydberg dressing to longer-lived states with higher principal quantum number is possible in larger spacing lattices.

2.5 Other experiments that have been enabled by the microscope upgrades during the performance period

The upgrades performed on the lithium-6 quantum gas microscope enabled an array of other experiments with this setup during the performance period. These include:

a) The study of spin-imbalanced fermionic Mott insulators. This led to the observation of canted antiferromagnetic correlations in such systems.
b) Observation of charge density wave correlations in attractive Hubbard systems.
c) Discovery of strange metallicity in doped Mott insulators. The linear-in-temperature resistivity observed in this system in an intermediate temperature regime has inspired

several theoretical studies of the underlying mechanism and has allowed us to test various theoretical techniques for calculating transport coefficients including the finite temperature Lanczos method and dynamical mean field theory.

d) Development of angle-resolved photoemission spectroscopy for Fermi-Hubbard systems and benchmarking the technique using attractive Hubbard systems against state of the art quantum Monte Carlo numerics.

e) Development of artificial intelligence based algorithms for detecting antiferromagnetic and strange metallic correlations in quantum gas microscope images.

f) Study of tilted Fermi-Hubbard systems and discovery of sub-diffusive charge transport in these systems and a slow thermalization mechanism attributed to an interplay of heat and charge transport.

III. Personnel

The following is a list of personnel who have worked on research supported in whole or in part by the Air Force Office of Scientific Research under Grant FA9550-16-1-0269.

Prof. Waseem Bakr, principal investigator.
Dr. Stanimir Kondov, post-doc.
Dr. Peter Schauss, post-doc.
Dr. Peter Brown, graduate student (PhD completed)
Dr. Debayan Mitra, graduate student (PhD completed)
Mr. Elmer Guardado-Sanchez (PhD in progress)
Mr. Benjamin Spar (PhD in progress)

IV. Publications

The publications listed below represent papers, preprints and theses supported in whole or in part by the Air Force Office of Scientific Research under Grant FA9550-16-1-0269.

1. Guardado-Sanchez, E., Spar, B., Schauss, P., Belyansky, R., Young, J. T., Bienias, P., Gorshkov, A. V., Iadecola T. & Bakr, W., "Quench dynamics of a Fermi gas with strong long-range interactions," *arxiv*:2010.05871 (2020).

2. Guardado-Sanchez, E., Morningstar, A., Spar, B., Brown, P., Huse, D. & Bakr, W., "Subdiffusion and heat transport in a tilted 2D Fermi-Hubbard system," *Phys. Rev. X* 10, 011042 (2020).

3. Brown, P., Guardado-Sanchez, E., Spar, B., Huang, E., Devereaux, T. & Bakr, W., "Angle-resolved photoemission spectroscopy of a Fermi-Hubbard system," *Nature Physics* 16, 26–31 (2020).

4. Khatami, E., Guardado-Sanchez, E., Spar, B., Carrasquilla, J., Bakr, W., & Scalettar, R., "Visualizing strange metallic correlations in the two-dimensional Fermi-Hubbard model with artificial intelligence," *Phys. Rev. A* (2020).

5. Brown, P., Mitra, D., Guardado-Sanchez, E., Nourafkan, R., Reymbaut, A., Hebert, C.-D., Bergeron, S., Tremblay, A. -M., Kokalj, J., Huse, D., Schauss, P. & Bakr, W., "Bad metallic transport in a cold atom Fermi-Hubbard system," *Science* 363, 379 (2019).

6. Brown, P., "Probing dynamical quantities in the 2D Fermi-Hubbard model with quantum gas microscopy", *Princeton PhD thesis* (2019).

7. Guardado-Sanchez, E., Brown, P., Mitra, D., Devakul, T., Huse, D. Schauss, P. & Bakr, W., "Probing the Quench Dynamics of Antiferromagnetic Correlations in a 2D Quantum Ising Spin System," *Phys. Rev. X* 8, 021069 (2018).

8. Mitra, D., "Exploring attractively interacting fermions in 2D using a quantum gas microscope," *Princeton PhD thesis* (2018).

9. Mitra, D., Brown, P., Guardado-Sanchez, E., Kondov, S., Devakul, T., Huse, D. Schauss, P. & Bakr, W., "Quantum gas microscopy of an attractive Fermi-Hubbard system," *Nature Physics* 14, 173-177 (2017).

10. Brown, P., Mitra, D., Guardado-Sanchez, E., Schauss, P., Kondov, S., Khatami, E., Paiva, T., Trivedi, N., Huse, D. & Bakr, W., "Spin-imbalance in a 2D Fermi-Hubbard system," *Science* 357, 1385 (2017).

V. Presentation at Meetings

Prof. Bakr gave the following invited talks on research supported in whole or in part by the Air Force Office of Scientific Research under Grant FA9550-16-1-0269:

1. 10/2020 ITAMP Seminar, Harvard University, Cambridge, MA
2. 04/2020 Virtual AMO Seminar
3. 03/2020 Cold Atoms and Transport at High Temperatures, Aspen, CO
4. 11/2019 Towards Dipolar Physics with Ultracold Molecules, Durham, UK
5. 11/2019 Colloquium Speaker, Stanford University, Stanford, CA
6. 10/2019 Colloquium Speaker, Penn State, State College, PA
7. 09/2019 Invited Speaker, Columbia University, New York City, NY
8. 09/2019 BEC 2019, Sant Feliu de Guixols, Spain
9. 07/2019 MPQ Colloquium, Garching, Germany
10. 05/2019 DAMOP Conference, Milwaukee, WI
11. 05/2019 Princeton Quantum Summit, Princeton University, Princeton NJ
12. 04/2019 2nd Joint Quantum Symposium, Columbia University, New York City, NY
13. 03/2019 Colloquium Speaker, City College of New York, New York City, NY
14. 03/2019 Many-body Quantum Chaos, Aspen Center for Physics, Aspen, CO
15. 01/2019 Seminar Speaker, Flatiron Institute, New York City, NY
16. 10/2018 Colloquium Speaker, MIT, Cambridge, MA
17. 10/2018 ITAMP Workshop, Harvard University, Cambridge, MA
18. 09/2018 Colloquium Speaker, Princeton University, Princeton, NJ
19. 09/2018 Packard Fellows Meeting, San Diego, CA
20. 08/2018 Condensed Matter Seminar, Univ. of Illinois at Urbana-Champaign, Urbana, IL
21. 08/2018 Quantum Gases 2018: Novel Correlations Effects, Beijing, China
22. 07/2018 International Conference on Atomic Physics (ICAP), Barcelona, Spain
23. 06/2018 Exploring Nuclear Physics with Ultracold Atoms, Trento, Italy
24. 05/2018 Quantum Science and Engineering, Ascona, Switzerland
25. 04/2018 Colloquium Speaker, Lehigh University, Bethlehem, PA
26. 04/2018 JQI Seminar, University of Maryland, College Park, MD
27. 03/2018 APS March Meeting, Los Angeles, CA
28. 01/2018 AMO Seminar Speaker, Stanford University, Stanford, CA
29. 11/2017 AMO/CM Seminar Speaker, Columbia University, New York City, NY
30. 10/2017 JFI Seminar Speaker, University of Chicago, Chicago, IL
31. 09/2017 BEC 2017, Sant Feliu de Guixols, Spain
32. 06/2017 DAMOP Conference, Sacramento, CA
33. 03/2017 Colloquium Speaker, Rutgers University, New Brunswick, NJ
34. 03/2017 Atomic Physics Seminar, Rice University, Houston, TX

In addition, graduate students and post-docs presented the research at the APS DAMOP conference in the following contributed talks and poster presentations:

1. Subdiffusion and heat transport in a tilted Fermi-Hubbard system (2020).
2. Visualizing Correlations in the 2D Fermi-Hubbard Model with AI (2020).
3. Charge and heat transport in an atomic Fermi-Hubbard system (2020).

4. Rydberg dressing of fermionic lithium (2020).
5. Probing spectral and transport properties of atomic Fermi-Hubbard systems (2019).
6. Bad Metallic Transport in a Cold Atom Fermi-Hubbard System (2018).
7. Microscopic measurements of dynamics in Fermi-Hubbard and Ising systems (2018).
8. Towards the detection of a massive collective mode of the attractive Hubbard model: the η mode (2018).
9. Observation of charge density wave correlations in the attractive Fermi-Hubbard model (2017).
10. Measuring correlations in attractive and repulsive Fermi-Hubbard systems with a lithium quantum gas microscope (2017).
11. Towards Rydberg dressing of a lithium Fermi gas (2017).