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TOWARDS QUANTUM SIMULATION OF THE 2D FERMI HUBBARD MODEL - DEVELOPMENT OF A LOCAL PROBE OF DENSITY AND SPIN ORDERING

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UNIV OF TORONTO

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Final Report

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14. ABSTRACT
We report on the results obtained across the three-year AFOSR-supported project, whose purpose was to study ultracold lattice fermions. We built a ultrahigh vacuum system with exceptional optical access, used both to create an optical lattice and to imagine atoms in situ. We used 405-nm light to laser cool potassium-40, the fermionic isotope of interest. Our data provides an upper bound on the ionization cross section, which is sufficiently low that high-resolution imaging using this optical transition should be feasible. With ultracold rubidium-87, we observe a quantum phase transition between a lattice superfluid and a Mott insulator. We are also able to create a degenerate Fermi gas of potassium-40, and load it into the lowest band of an optical lattice.

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Contents

1 Cumulative list of people involved in the research effort

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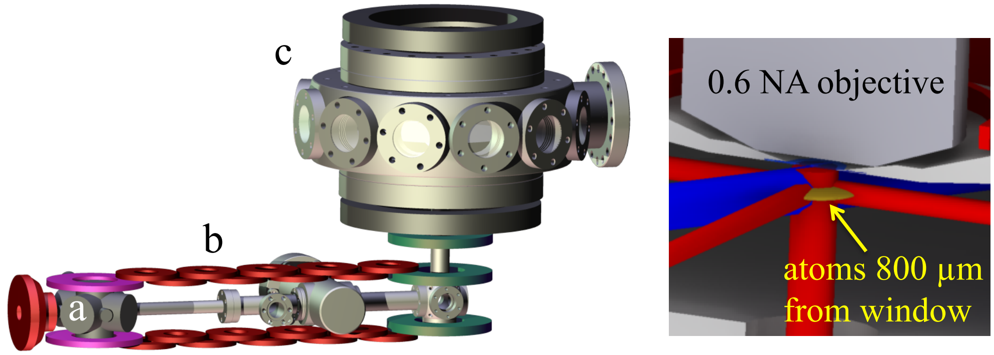

Figure 1: Vacuum system enabling extreme optical access to cold atoms. Atomic sources produce a vapor in a glass MOT (magneto-optical trap) chamber (labeled **a**), which is laser cooled and trapped. A magnetic transport system (labeled **b**) moves the atoms a distance of 0.5 m to the lattice chamber (labeled **c**). Since the second chamber is displaced horizontally and vertically, it is unconstrained by the optics and coils of the MOT chamber. There are twelve windows in the horizontal plane of the lattice chamber, as well as a recessed flange for microscopy, shown in in the **inset**.

2 Student theses

Hai-Jun Cho, "High-Resolution Imaging for an Optical Lattice Experiment", M.Sc. report (September 2010)

David C. McKay, "Quantum Simulation in Strongly Correlated Optical Lattices," Ph.D. thesis (July 2012)

Carolyn Kierans, "Testing of a microscope for site-resolved imaging of atoms in an optical lattice," M.Sc. report (August 2012)

Dan Fine, "Frequency offset locking for imaging of 40K in high magnetic fields," M.Sc. report (January 2013)

3 Results

3.1 Extreme optical access

We have built a vacuum system with unprecedented optical access to trapped atoms. Figure 1 shows how atoms are transported from the MOT (magneto-optical trap) chamber to the lattice chamber, freeing optical axis in a new plane, as well as enabling a microscope port.

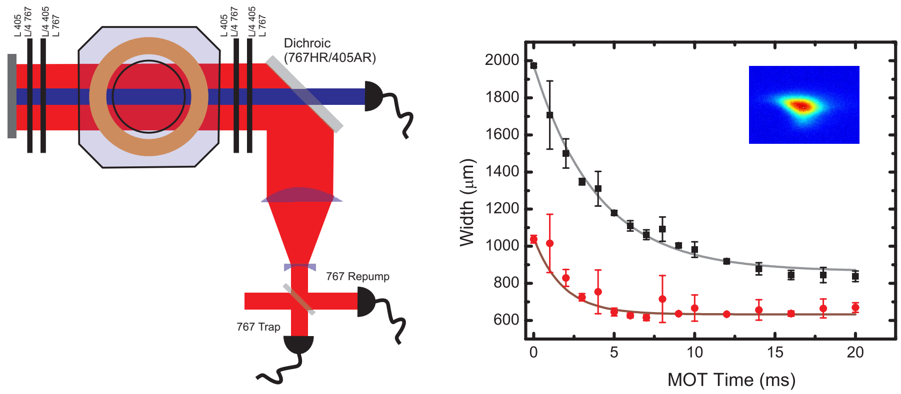

Figure 2: Cooling after transfer into a 405 nm MOT. **Left:** The optical configuration includes 767 nm trapping and repump beams (both shown in red) and a 405 nm trapping beam (shown in solid blue). The two colors are mixed on a dichroic mirror, manipulated with dichroic quarter-wave plates, and retro-reflected off a broad-band mirror. Each DWP has a quarter-wave retardation at one wavelength, and no retardation at the other wavelength. Only one MOT direction has been shown for clarity, but there is an identical beam path in three orthogonal directions. The magnetic quadrupole coils typically apply 10 G/cm along their strong axis. **Right:** Cooling dynamics are observed at various hold times in a violet MOT, here with $\Delta = -2\,\mathrm{MHz}$ and $I \approx 50\,\mathrm{mW/cm}^2$. The rms width is shown for both the vertical (open red circles) and horizontal (black squares) directions. Simple exponential fits are shown as solid lines, with a $1/e$ time of 1.8 ms for the vertical width and 4 ms for the horizontal width.

3.2 Violet laser cooling of potassium

Laser-cooled fermionic potassium is limited to roughly 200 microKelvin when cooling at 767 nm, on the 4S-4P "D2" transition (see level diagram in the Appendix). We developed a laser system that uses the 4S-5P "violet" transition, near 405 nm, finding that cooling was possible, and that the steady-state temperature was lower. The setup used is shown in Fig. 2. Atoms are first captured using the standard D2 transition. That light is extinguished, and the violet light is turned on. Fig. 2 shows that the cloud size is reduced within 5–10 ms after the violet light is turned on.

There are two reasons the cloud size decreases. First, the temperature decreases by roughly a factor of five. Temperature in this case is set by the line width of the transition, which is 6 MHz for the D2 transition and 1.2 MHz for the violet transition. In neither case is the "Doppler limit" $k_B T = \hbar\Gamma/2$ reached, since the cooling mechanism is competitive with heating. Second, atoms are pumped to dark states more strongly. Third, the same trapping strength is a achieved with a scattering rate that is roughly six times smaller, which reduces repulsive forces.

Figure 3 shows that we have cooled both fermionic and bosonic isotopes of potassium. In related work, a group at Rice University showed that the analogous transition could be used in lithium. There is no reason this technique could not be extended to other alkali atoms. Our work shows that the open nature of the transition is not an impediment to laser cooling, and even comes with the benefit of a reduced re-scattering cross section.

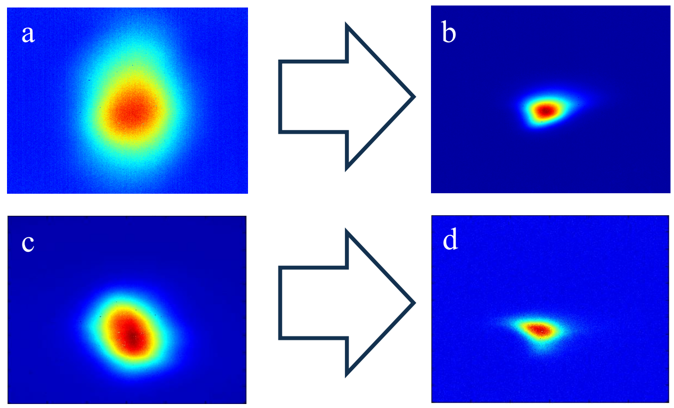

Figure 3: Typical absorption images of **(left column)** a 767 nm MOT with detuning $\Delta = -35$ MHz and intensity $I \approx 16$ mW/cm^2; and **(right column)** a 405 nm MOT, for $\Delta = -1$ MHz, $I \approx 90$ mW/cm^2. In all images, pixel color denotes optical density. Images were taken shortly (1.5 ms) after release from the trap, such that clouds are little changed from their in situ distributions. The top row shows bosonic ^{39}K, and the bottom row shows fermionic ^{40}K.

The most exciting application of this transition is to high-resolution imaging. The shorter wavelength (405 nm vs 767 nm) reduces the diffraction limit for comparable numerical aperture. However, since two 405-nm photons have sufficient energy to ionize that atom, ionization will eventually limit the number of photons that can be scattered from an atom, and thus the fidelity of imaging. Using an objective with 0.6 numerical aperture, collection efficiency would be 10% and resolution would be 0.4 μm. In such a configuration, our results (ionization cross-section of $\sigma < 8 \times 10^{18}$cm^2) suggest that fluorescence imaging at $I_{sat}/4$ could collect 10^4 blue photons with a 1% upper bound on the probability of ionization. Lowering the imaging beam intensity would lower the ionization probability for the same number of collected photons, but would require longer imaging times.

3.3 Isotopically enriched sources

Our primary technical impediment during the first 18 months of this project was the weakness of commercially available atomic sources. The sources were sufficient to investigate new methods of laser cooling, and during this time we developed the violet cooling method described in this report. However the intensity of these initial sources was not sufficient to produce a quantum degenerate cloud of fermions. The maximum ^{40}K number was below 10^9, and provided insufficient collision rates in the magnetic trap after transport to the lattice chamber.

To resolve these issues, we developed our own isotopically enriched sources, and a hybrid glass cell that included replaceable copper-sealed flanges. These innovations came online in the winter of 2011 (see §4), and resolved all source issues.

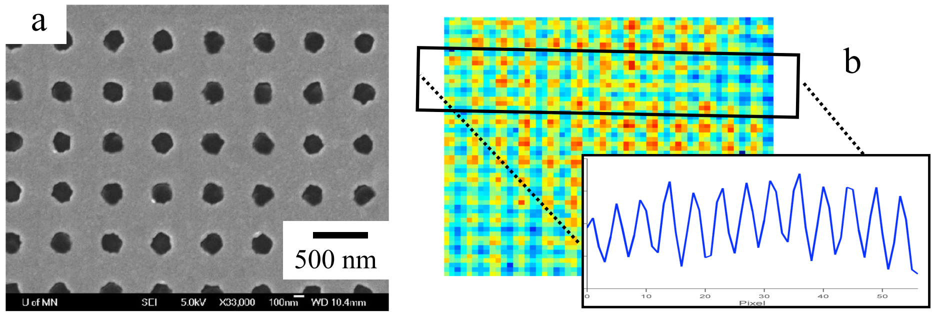

Figure 4: **(a)** Scanning electron microscope image of the nano hold array, provided by the group of Sang-Hyun Oh. The darker areas are optically transparent; the lighter grey areas have a thickness of 100 nm and 200 nm in two different targets provided. **(b)** Optical image of 405-nm light transmitted through the array, and imaged using our microscope objective. The inset shows the transmitted intensity versus position for several adjacent pixels rows.

3.4 Quantum degenerate atoms

We demonstrated the ability to produce optically trapped, quantum degenerate gases of both ^{87}Rb and ^{40}K in the apparatus described in §3.1.

In March 2012, we observed our first Bose Einstein condensate (BEC) of rubidium in the apparatus. This was achieved using forced evaporative cooling in the magnetic quadrupole trap in the lattice chamber. Fermions are sympathetically cooled in our apparatus. In the spring of 2012, we used cold rubidium to bring potassium to Fermi degeneracy in the magnetic trap.

Sympathetic cooling of ^{40}K with ^{87}Rb is a natural choice because their resonant wavelengths are only 13 nm apart, so the same optics, fibres, wave plates, and even amplifiers can be used for both elements. However, the collisional properties of these atoms are not ideal. The inter-species triplet scattering length is large and negative, leading to losses at high density. In order to minimize these losses, we use the absolute ground state of ^{87}Rb, which is not magnetically trappable. This requires finishing the sympathetic cooling in an optical trap.

We implemented an crossed optical dipole trap (CDT) in the spring of 2012, created a BEC in the CDT in September 2012, and sympathetically cooled potassium in the CDT in October of 2012. The final temperature was $0.3E_F/k_B$, where E_F is the Fermi energy and k_B is the Boltzmann constant. The final ^{40}K atom number was fifty thousand.

3.5 Sub-micron resolution

A new class of experiment, the "quantum gas microscope", was pioneered by M. Greiner and collaborators at Harvard, and by S. Kuhr and collaborators at the MPQ in Garching. The distinguishing feature of these microscopes is that they are able to resolve single atoms in an optical lattice, while still using a sub-micron period to allow for tunneling transport. Both of these pioneering experiments used bosonic ^{87}Rb. Our experiment is built to be a quantum gas microscope for fermionic ^{40}K.

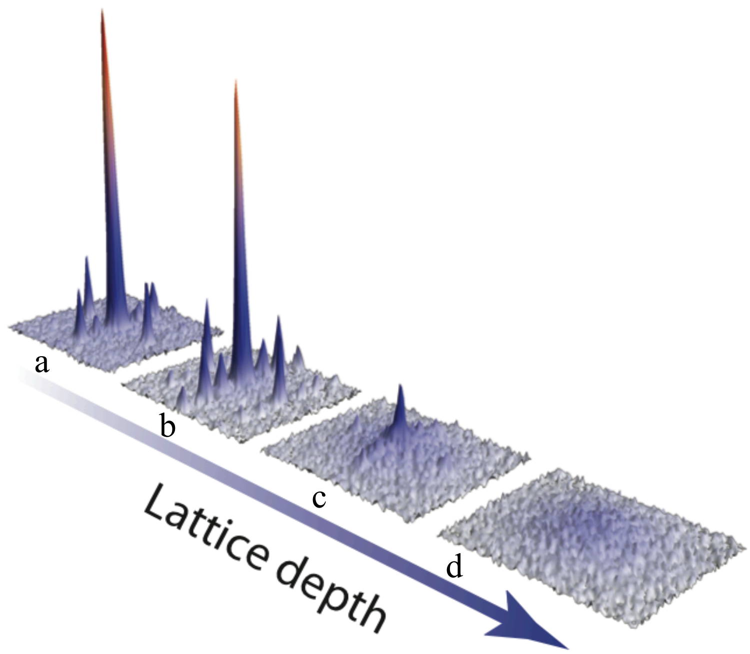

Figure 5: **Loss of phase coherence.** Bosonic ^{87}Rb atoms are loaded into a three-dimensional optical lattice, and released at various lattice depths: **(a)** 12 E_R **(b)** 14 E_R, **(c)** 18 E_R, and **(d)** 20 E_R, where E_R is the single-photon recoil energy of ^{87}Rb at 1054 nm. The progressive loss of contrast in the diffraction pattern indicates that phase coherence is lost across the matter wave source, which shows loss of superfluidity. Instead, atoms are localized to particular lattice sites, in an insulating phase. This superfluid-insulator phase is called a quantum phase transition since a hamiltonian parameter (here tunneling strength) is changed, instead of temperature.

Our optical microscope was tested by imaging a silver nano-hole array (provided by the group of Sang-Hyun Oh at the University of Minnesota). Figure 4 shows both a scanning electron microscope image of the holes and our optical image of the holes, using light at 405 nm. We observe a contrast of approximately 15%. Once implemented, this system will be the highest resolution quantum gas microscope yet.

3.6 Quantum phase transition: Atoms in optical lattices

In the final six months of the project, we have worked with atoms in optical lattices. In January 2013, we saw diffraction of ^{87}Rb from one and two lattice directions. Holding atoms in these lattices revealed technical heating issues, and electronics were improved. In March 2013, we were able to see a quantum phase transition with ^{87}Rb in the lattice.

Fermionic potassium was loaded into the lattice in April 2013. By ramping down the lattice slowly compared to the single-particle band gap, the filling of the first Bloch band was confirmed.

4 Project Chronology & Milestones

2010.06.15 - Project start 2010.Fall - Magneto-optical trap (MOT#3)
2011.Summer - 405nm MOT for 40K
2011.10 to 11 - Spectroscopy of 39,40,41 potassium isotopes
2011.Winter - Resolution of source issues (MOT#4)
2012.03.12 - Bose-Einstein condensate (BEC) in magnetic quadrupole trap
2012.Spring - Sympathetic cooling of ^{40}K in magnetic trap
2012.04 to 05 - Evaporation at microscopy window
2012.07 to 08 - Working in crossed dipole trap (CDT)
2012.09.27 - BEC of ^{87}Rb in CDT
2012.10.18 - DFG of ^{40}K in CDT
2012.12.19 - Absorption image through microscope
2013.01.07 - Fluorescence through microscope
2013.01 - Vertical lattice
2013.01.24 - 2D Diffraction
2013.03 - 3D diffraction, insulator-to-superfluid transition
2013.04 - Band-mapping of ^{40}K in optical lattice
2013.06.14 - Project end

5 Appendix: Atomic data

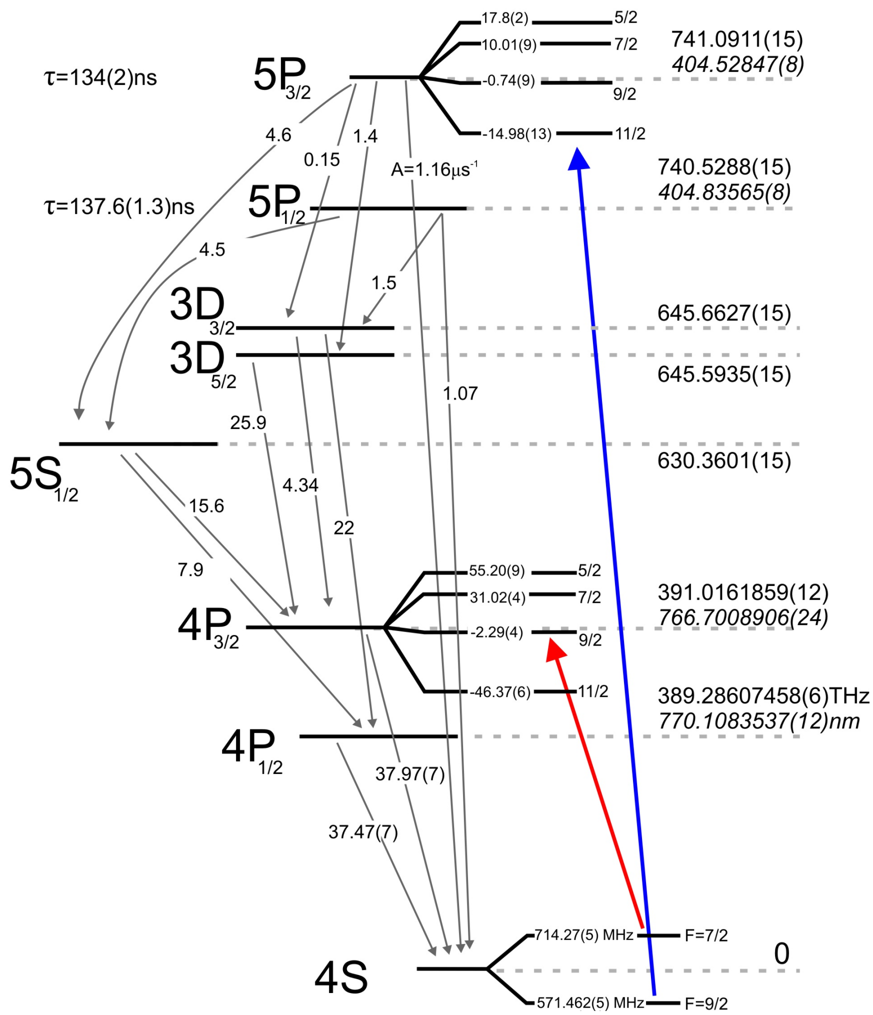

Figure 6: **Level diagram** including all the possible decay channels of the 4S → 5P transition in ^{40}K. Transition probabilities are listed as $A = 1/\tau$ in units of μs^{-1}. Except for 4P → 4S the uncertainties in transition probability rates are not shown explicitly. The uncertainties in the 5P → 4S rates are less than 8%, but all other rates are estimated to have uncertainties between 25% and 50%. The total measured lifetime from all decay channels is 134(2)ns for $5P_{3/2}$ and 137.6(1.3)ns for $5P_{1/2}$. Level energies E, referenced from the 4S state, are presented in both frequency units (as E/h) and wavelength units (in italics, as hc/E). Hyperfine splittings ΔE referenced to the level energies are given in frequency units (as $\Delta E/h$) The solid blue and dashed red arrows indicate the cooling and repump hyperfine transitions, respectively, used for laser cooling.