Towards a Quantum Gas Microscope for Fermions

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Ultracold Fermi Gases: a Model System

- Strongly-correlated electronic systems
- Technologically important, poorly understood

Ultracold atomic gases can simulate strongly correlated electronic physics in a controllable manner.

Atoms in Optical Lattices

Fermi-Hubbard Physics

$$\hat{H} = -J \sum_{\langle \ell, \ell' \rangle} \left( \hat{c}_{\ell \uparrow}^\dagger \hat{c}_{\ell' \downarrow} + h.c. \right) + U \sum_{\ell} \hat{n}_{\ell \uparrow} \hat{n}_{\ell \downarrow} + \sum_{\ell} \hat{n}_{\ell} \hat{\epsilon}_{\ell}$$

Direct imaging of the Mott insulating and the antiferromagnetic phases in the Fermi Hubbard model might be possible.

BIG QUESTION: Does Fermi-Hubbard predict High-Tc Superconductivity?

Ultracold Matter is made of fermionic atoms.

Synthetic Gauge Fields

A high-resolution imaging system allows detection of fermionic atoms on individual lattice sites.

Single-site Resolution
- Direct imaging of fluctuations and correlation functions
- Engineering arbitrary lattice geometries
- Single-site addressing
- New, “algorithmic” cooling schemes

Previous work at Harvard and Munich has achieved single-site detection for bosonic atoms.

Reduced Dimensionality

A quantum gas microscope provides the natural playground for studying strongly interacting fermions in a single 2D plane – thermal and quantum fluctuations play an enhanced role.

Kapitza-Dirac Calibration of our optical lattice

The microscope may allow in-situ observation of BKT phase transition: dissociation of vortex pairs above the transition temperature.

Novel Features of our Experiment Design

Top View: The 3D MOT laser beams (red) and a quadrupole magnetic trap (green) are centered around the 3D-MOT position. The center of the three-dimensional optical lattice is in the center of the imaging axis.

Rayleigh criterion for optical resolution

$$r = \frac{1.22 \lambda}{2 \sin(\theta/2)} = \frac{0.61 \lambda}{NA}$$

“Solid immersion” effect enhances NA by a factor of 1.54.

Experiment Status

Zeeman Slower and 3D MOT for $^{23}$Na

2D$^{40}$MOT and 3D MOT for $^{40}$K

Plugged Quadrupole Trap

Atoms being transported under the microscope (seen from the side)

Hybrid trap under the microscope

Sodium BEC created under the microscope via evaporation in our hybrid trap (seen from the top)

Coming up…
- Load fermions into the optical lattice
- Single-site imaging!