Quantum gas microscopy of the Fermi-Hubbard model in new regimes

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The Fermi-Hubbard model

- Two species of fermions in a 2D lattice.
- Nearest neighbor tunneling $t$.
- Onsite interactions $U$.

\[
\mathcal{H} = -t \sum_{\langle ij \rangle, \sigma} \left( c_{i,\sigma}^\dagger c_{j,\sigma} + c_{j,\sigma}^\dagger c_{i,\sigma} \right) + U \sum_i n_{i,\uparrow} n_{i,\downarrow}
\]

- Realized naturally with cold atoms in optical lattices with fully tunable parameters.

Jaksch, PRL 81, 3108 (1998)
The parameter space

- **Interactions**
  - Attractive
  - Repulsive

- **Temperature**
  - \( U \)
  - \( t^2/U \)

- **Doping**

- **Spin-imbalance**

- **Antiferromagnet**
  - ETH, Rice, Harvard, MIT, Munich, Bonn

- **Mott insulator**
  - Munich, ETH

- **d-wave SF?**
Quantum gas microscopy

- Boson microscopes
  - Harvard
  - MPQ
  - Kyoto
  - Tokyo

- Fermion microscopes
  - Harvard
  - MPQ
  - Strathclyde
  - MIT
  - Toronto
  - Princeton
Antiferromagnetic correlations

Esslinger group
Science 340, 1307 (2013)

Greiner group
T/t = 0.45 (2D)
Science 353, 1253 (2016)

Hulet group
Nature 519, 211 (2015)

Bloch/Gross group
1D
Science 353, 1257 (2016)

Köhl group (2D)
PRL 118, 170401 (2017)

Zwierlein group
T/t = 0.89 (2D)
Science 353, 1260 (2016)
A simplified Fermi gas microscope

- Single beam optical lattice @ 1064 nm simplifies microscopy:
  4-fold interference enhances depth + larger lattice spacing.

Lithium allows for large lattice spacing:
- Light
- "good" Feshbach resonances
- NA = 0.5 is sufficient for single-site

Vertical polarization: 752 nm
Horizontal polarization: 532 nm
Repulsive Hubbard model: Mott insulators and band insulators

Detect 1000 photons/atom in 1.2s via Raman sideband cooling
Hopping: 0.4%, loss: 1.6%

Brown et. al., Science 357, 1385 (2017)
Outline

1. Spin-imbalance in repulsive Hubbard model

2. Attractive Hubbard model
1. Spin-imbalance in a 2D Fermi-Hubbard system

Brown et. al., Science 357, 1385 (2017)
Spin imbalance

Condensed matter system:
Spin imbalance by applied magnetic field (Zeeman effect)

Cold atoms:
Spin-imbalance prepared before loading to lattice by evaporation in spin-dependent potential.
No spin-relaxation.

Zeeman field
Spin-polarization
Spin canting – classical model

Classical antiferromagnetic Heisenberg model

\[ H = J \sum_{\langle i,j \rangle} S_i \cdot S_j + h \sum_i S_i^z \]

Increasing magnetic field \( h \)

Polarization:

\[ P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} = 2S_z \]

\[ C_j^{x,z} = \langle S_i^{x,z} S_{i+j}^{x,z} \rangle - \langle S_i^{x,z} \rangle \langle S_{i+j}^{x,z} \rangle \]

\( \rightarrow \) Main signature: Asymmetry in \( S_z^2 \) vs \( S_x^2 \) correlation
Spin Canting: 2D Hubbard Phase Diagram at half-filling

- Superexchange energy scale $J = 4t^2/U$, BKT phase transition
- Field breaks SU(2) symmetry
- AFM correlations build up preferably in XY plane

Isotropic AF with QGM:
Science 353, 1253 (2016)
Science 353, 1257 (2016)
Science 353, 1260 (2016)

Phase Diagram:
PRB 69, 184501 (2004)
PRA 81, 023628 (2010)
Spin-imbalanced Mott insulators

Mott physics is not affected by imbalance
Polarization is constant in Mott insulator region

\[ p^s = \frac{n^s_{\uparrow} - n^s_{\downarrow}}{n^s_{\uparrow} + n^s_{\downarrow}} \]

\[ U/t = 8 \]
Interesting interesting behavior in density at larger interaction ($U/t = 15$)

\[ n_s^\uparrow, n_s^\downarrow, n_\downarrow, p \]

\[ p = \frac{n_\uparrow - n_\downarrow}{n_\uparrow + n_\downarrow} \]

\[ h = 0.2t, \quad \chi = \frac{p}{2h} \]
Spin-Susceptibility

non-degenerate gas    Metallic region    AF region

\[ \chi_m \propto \frac{1}{t} \quad \chi_{AF} \propto \frac{1}{J} = \frac{U}{4t^2} \]

\[ \chi = \frac{1}{n} \frac{\partial \langle S^z \rangle}{\partial \mu} \bigg|_{\mu} = \frac{p}{2h} \quad \text{(linear regime)} \]

Hubbard reproduces peak in cuprate susceptibility at about 20% doping.

PRB 40, 8872 (1989)
PRL 62, 957 (1989)
PRB 40, 2254 (1989)

Probing spin-imbalanced lattice gases

- 1-3 mixture of lithium
- Evaporate in gradient
- Load into lattice at $U/t = 8$

\[ S^z \]

\[ S^x \]

Vary: \[ p^s = \frac{(n^s_\uparrow - n^s_\downarrow)}{(n^s_\uparrow + n^s_\downarrow)} \]

Spin Canting

- \( p^s = \frac{n^s_{\uparrow} - n^s_{\downarrow}}{n^s_{\uparrow} + n^s_{\downarrow}} \)
- Good agreement with NLCE & DQMC
- \( T/t \) increases from 0.40 to 0.57

DQMC by Thereza Paiva and Nandini Trivedi
NLCE by Ehsan Khatami

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Why negative NNN?

Unpolarized gas: isotropic spin correlations [SU(2) symmetry]
Polarized gas: AFM correlations preferred in the plane
2. Quantum gas microscopy of an attractive Fermi-Hubbard system

Mitra et. al, Nature Physics, 10.1038/nphys4297 (2017)
Spin-balanced attractive Hubbard model

Preformed pairs: $U$
Superfluidity: $4t^2/U$  
Mitra et. al, Nat. Phys., 10.1038/nphys4297 (2017)
Site-resolved doublon detection

\[ |3\rangle \rightarrow \text{attractive pair} \rightarrow |3\rangle \rightarrow \text{repulsive pair} \rightarrow \text{single atom} \]

\[ |1\rangle \rightarrow \text{RF transfer + change interaction} \rightarrow |2\rangle \rightarrow \text{remove} \]

90% fidelity

Band insulator

Mitra et al, Nat. Phys., 10.1038/nphys4297 (2017)
Density profile of attractive lattice gas

Experimental data with DQMC fit
T/t = 0.45
U/t = -5.7

Expect s-wave pairing correlations near n = 1
Density in doublons
Singles fraction suppressed at large |U|/t due to fermion pairing

Reasonably large region of cloud near half filling
At trap frequency $\omega = 2\pi 200$ Hz

Mitra et. al, Nat. Phys., 10.1038/nphys4297 (2017)
Thermometry in attractive Hubbard system

$C^d(a) = 4\left(\langle n^d_r n^d_{r+a}\rangle - \langle n^d_r \rangle \langle n^d_{r+a}\rangle\right)$

$n^d = n_\uparrow n_\downarrow$

- Singles fraction increases as gas heats up during hold time
- Singles fraction for thermometry only for $T/t > 1$
- Correlation thermometry at $T/t < 1$

Mitra et. al, Nat. Phys., 10.1038/nphys4297 (2017)
Doublon-doublon correlators

$U/t = -5.7$

The graph shows the behavior of nearest neighbor and diagonal neighbor correlators as a function of density. At a density of $d = 2$, the diagonal correlator goes negative, a phenomenon that has been observed before. The question arises: Haven’t we heard this story before?
Mapping between the models

Repulsive $U > 0$

- Mott insulator
- Antiferromagnet

Attractive $U < 0$

- Preformed pairs
- Charge density wave

$c_{i\downarrow} \leftrightarrow (-1)^{i_x+i_y} c_{i\downarrow}^\dagger$

1. $U \leftrightarrow -U$
2. $\mu \leftrightarrow h$

Correlator symmetry

Attractive Hubbard

Repulsive Hubbard
Correlator symmetry

Attractive Hubbard

Repulsive Hubbard

Doublon-doublon correlations are lower bound for s-wave pairing correlations

\[ C^\Delta(a) = \langle \Delta_r^x \Delta_{r+a}^x \rangle_c \]

\[ \Delta_r^x = c_{r,\downarrow}^\dagger c_{r,\uparrow}^\dagger + c_{r,\uparrow} c_{r,\downarrow} \]
Conclusions and outlook

• Observation of canted antiferromagnetic correlations in spin-imbalanced repulsive gases.

• Observation of charge density wave correlations in attractive lattice gases.

• Outlook:
  – Lower temperatures (e.g. entropy redistribution)
  – Beyond single band Hubbard on attractive branch
  – Spin-imbalanced attractive gases in 1D-2D crossover (FFLO)
  – Dynamics
  – LDOS measurements on topological defects
  – Dipolar interactions through Rydberg dressing
Lithium Rydberg excitation

Quench dynamics in an antiferromagnetic 2D Ising Hamiltonian

- Direct excitation at 230nm
- Detection via loss
- Rabi frequency: up to 6 MHz
- Towards Rydberg dressing of Fermions

Outlook: Hubbard dynamics

Strange metal phase is within reach of current Fermi-Hubbard experiments.

Defined by “strange” transport behavior (dynamics)

Ongoing: charge hydrodynamics (sound, diffusion in doped Hubbard model.)
Outlook: Hubbard dynamics

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