Single-atom resolved imaging and manipulation in an atomic Mott insulator


newspin2
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Motivation

Condensed matter

~ 0.5 nm

Ultracold atoms

~ 0.5 µm
Single-atom imaging

Single-site detection in the strongly-correlated regime

Garching 2010

Harvard 2010

Sherson et al., Nature 467, 68 (2010)

Bakr et al., Science 329, 547 (2010)
Outline

Single-atom imaging
- Atomic Mott insulators

Single-spin manipulation
- Coherent tunneling dynamics

Coherent light scattering
- "AFM" detection
1. Single-atom imaging
Single-atom imaging

Single 2D degenerate gas
1000 Rb atoms (Bosons)
700 nm resolution
Fluorescence detection

Depth ~ 10 Er
- Freeze density distribution
- Lose phase coherence

Depth ~ 4000 Er
- 300 µK

- Fluorescence rate/atom: 60 kHz
- ~ 5000 photons/atom collected in 900ms
We detect the parity of the occupation number

\[ n_{\text{meas}} = \text{mod}_2 n \]
Reconstruction of site occupation

2 µm

original image

Reconstruction algorithm

digitized image convoluted with point-spread function

noise-free digitized image

2 µm
Bose-Hubbard Hamiltonian

\[ H = -J \sum_{\langle i, j \rangle} \hat{a}_i^\dagger \hat{a}_j + \sum_i \varepsilon_i \hat{n}_i + \frac{1}{2} U \sum_i \hat{n}_i (\hat{n}_i - 1) \]

\( \hat{a}_i^\dagger, \hat{a}_i \) : creation and annihilation operator for Boson on \( i \)-th lattice site

\( \hat{n}_i \) : number operator

Mott insulators

**Superfluid**
(tunneling dominant, $J >> U$)

- Poissonian atom number distribution
- Long range phase coherence

**Mott insulator**
(interactions dominant, $U >> J$)

- Number squeezing
- No phase coherence

Filling the Lattice with Atoms

Creation of Mott-shells

Occupation number

\[ n=1 \quad n=2 \quad n=1 \]

Mott-Insulator state

U: Interaction energy
Images of Mott insulators

Theoretical model: zero-tunneling approximation

occupation probability: $P_r(n) = e^{\beta [\mu_{loc}(r)n - E_n]} / Z(r)$

interaction energy: $E_n = U \frac{n(n-1)}{2}$

fit parameters: $T/U; \mu/U; U/\omega^2$

Entropy per particle $S/N = 0.32(2)\ k_B$

„Outlook“: single-atom imaging

• Detect parity-parity correlations in 1D and 2D Mott insulators: particle-hole pairs and string order across transition.

• Out-of equilibrium dynamics: Light-cone-like spreading of correlations after quenching


2. Single-spin addressing
Coherent addressing of atoms

Time sequence:
- freeze density distribution
- switch on addressing beam
- sweep microwave
- switch off addressing beam
- move addressing beam
- …
- (cycle duration 50 ms)

"magic" wavelength 787.55 nm (σ-pol)
between \( F = 1, m_F = -1 \) and \( F = 2, m_F = -2 \)

Related proposals:
D. Weiss et al., PRA 70, 040302 (2004)
C. Zhang et al., PRA 74, 042316 (2006)
Single site addressing

C. Weitenberg et al., Nature 471, 319 (2011)
Precise Positioning

Lattice position

Addressing beam position

Lattice drifts

<0.04 sites/repetition (25 sec cycle time)

Positioning with an error of 50 nm (0.1 of lattice spacing)

C. Weitenberg et al., Nature 471, 319 (2011)
Spin-flip fidelity

Fidelity = 0.95(2)

FWHM = 330(10) nm

Edge sharpness = 50(10) nm

fidelity = 95%
edge sharpness = 50 nm

C. Weitenberg et al., Nature 471, 319 (2011)
Single-particle tunneling dynamics

1D tunneling along $x$: $V_x = 5 \, E_r$, $V_{y,z} \sim 25 \, E_r$

C. Weitenberg et al., Nature 471, 319 (2011)
Single-particle tunneling dynamics

1D tunneling along x: \( V_x = 5 \, E_r \), \( V_{y,z} \sim 25 \, E_r \)

\[ n(x) = \frac{\langle x | e^{-iH_0 t/\hbar} | x = 0 \rangle^2}{\sum_{x=-5}^{5} \langle x | e^{-iH_0 t/\hbar} | x = 0 \rangle^2} \]

\[ H_0 = J_0 \sum_{(i,j)} a_i^+ a_j + \frac{m \omega^2}{2} (x + x_{off})^2 \]

\( J_0 / \hbar = 940(20) \, \text{Hz}, \, x_{off} = -6.3 \, \text{lattice sites} \)

C. Weitenberg et al., Nature 471, 319 (2011)
Single-particle tunneling dynamics

\[ \langle n(x) \rangle = f_0 \left| \langle x | e^{-iH_0 t/\hbar} | 0 \rangle \right|^2 + f_1 \left| \langle x | e^{-iH_1 t/\hbar} | 0 \rangle \right|^2 \]

\[ H_{0,1} = J_{0,1} \sum_{\langle i,j \rangle} a_i^+ a_j + \frac{m \omega^2}{2} (x + x_{\text{off}})^2 \]

85% of the atoms remain in the lowest band.

Theoretical model:

lowest band: \( J_0/\hbar = 940(20) \text{ Hz} \)

first excited band: \( J_1/\hbar = 6.22(6) \text{ kHz} \)

\( C. \) Weitenberg et al., Nature 471, 319 (2011)
Outlook: single-spin addressing

- Out-of-equilibrium dynamics:
  spin-charge separation...
  Kleine et al. PRA 77, 13607 (2008)

- Novel cooling schemes:
  local removal of regions with high entropy
  Bernier et al. PRA 79, 061601(R) (2009)

- Tunneling dynamics:
  in 2D, across barriers, with interactions,...
  Micheli et al. PRL 93, 140408 (2004)

- Quantum information processing:
  One-way QC, Rydberg gates in a lattice,...
  Wilk et al. PRL 104, 010502 (2010)
3. Coherent light scattering
Focussed and defocussed images

100 µm travel

40 µm

focussed

defocussed

5 µm
Coherent light scattering

C. Weitenberg et al., PRL 106, 215301 (2011)
Coherent light scattering

Model
- Spherical wave emitted from each atom
- Detection in farfield \((r > d)\)

Scattering cross section:

\[
\frac{d\sigma}{d\theta}(\theta) \propto \frac{\sin^2 [k a_{\text{lat}} (\sin \theta - 1) N_x / 2]}{\sin^2 [k a_{\text{lat}} (\sin \theta - 1) / 2]}
\]

Diffraction maxima:

\[
\sin \theta_n = 1 + n \frac{\lambda}{a_{\text{lat}}}
\]

- \(n = 0\): forward scattered light (independent of \(\lambda, a_{\text{lat}}\))
- \(n = 1\): maximum at \(\theta_{-1} = -27.8^\circ\) \((a_{\text{lat}} = 532 \text{ nm})\)
Near field vs. far field

Experimental Data

2D Simulation

- Data: Single realization of experiment
- Simulation: Uses real atom distribution, only coherently scattered light

C. Weitenberg et al., PRL 106, 215301 (2011)
Quantitative analysis

Measured:
$\theta_{-1} = -27.4(6)^\circ$

Theory:
$\theta_{-1} = -27.8^\circ$

$$
\frac{d\sigma}{d\theta}(\theta) \propto \frac{\sin^2[k a_{lat}(\sin \theta - 1) N_x/2]}{\sin^2[k a_{lat}(\sin \theta - 1)/2]}
$$

Peak height
$A \sim N^2$

Peak width
$w \sim 1/\sqrt{N}$

C. Weitenberg et al., arXiv:1102.3859v1 (PRL, in press)
Coherent vs. incoherent scattering

**Effect** | **Reduction factor**
--- | ---
Forward scattering not detected | 20%
Debye-Waller factor $\beta^2$ | 75%
Density fluctuations | 70%
Coherence of scattering | 99%
Inelasticity (change vibrational level) | 98%
Inelasticity (change $m_F$ level) | 33%
Expected power in detected peaks | 3%
Measured power in detected peaks | 3%
Detecting Spin correlations?

Interference maxima:

\[
\sin \theta_n = 1 + n \frac{\lambda}{a_{\text{lat}}}
\]

\[a_{\text{lat}} = 532 \text{ nm} \rightarrow \theta_{-1} = -27.8^\circ\]

1D AFM as density wave:

\[a_{\text{lat}} = 2 \times 532 \text{ nm} \rightarrow \theta_{-2} = -27.8^\circ\]

\[\theta_{-1} = 15.5^\circ\]

related work
H. Miyake et al., PRL 107, 175302 (2011)
T. A. Corcovilos et al., PRA 81, 013415 (2010)
Scattering from a 1D AFM

Prepare AFM as density wave along one dimension by single-site addressing:

Measured:
\(|\theta_{-1}| = 14.5(6)^\circ\)
\(|\theta_{-2}| = 27.4(6)^\circ\)

Theory:
\(|\theta_{-1}| = 15.5^\circ\)
\(|\theta_{-2}| = -27.8^\circ\)

C. Weitenberg et al., PRL 106, 215301 (2011)
Summary
**Summary**

**Single-atom imaging**
- Single-atom resolved images of Mott insulators
- In-situ temperature measurements

**Single-spin manipulation**
- Addressing laser beam + microwave
- Sub-diffraction limited resolution
- Coherent tunneling dynamics

**Coherent light scattering**
- Far-field diffraction patterns
- „AFM“ detection