Sub-lattice Control in a State-dependent Double-well Lattice

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Apr. 26 2007
Research Directions

• Quantum information processing w/ neutral atoms

• Correlated many-body physics w/ neutral atoms

• Engineering new optical trapping and control techniques
This Talk

• Realizing a dynamic double-well lattice
  - Demonstration of tools
  - Using state-dependence
  - Combining tools: toward a swap gate

• Future
  potential applications to lattice simulation
Basic Tool: Light Shifts

Intensity and state dependent light shift

Flexibility to tune scalar vs. vector component

Optical standing wave

Red detuning → attractive
Blue detuning → repulsive

$|e\rangle \rightarrow |g\rangle$

$\Omega^2 \sim I$

$\Delta$

$\delta U$

$e \rightarrow h v$

Pure scalar, intensity lattice

Intensity + polarization

Effective field, with -scale spatial structure

$g \rightarrow 2 - I$
Basic Tool: Light Shifts

Example: lin  lin

\[ \vec{\mathbf{B}}_{\text{eff}} \]  
Position dependent effective magnetic field

\[ \vec{\mathbf{E}} = \hat{x} \]
no ellipticity, intensity modulation

\[ \vec{\mathbf{E}} = \hat{x} \]
Example: lin  lin

\[ \vec{\mathbf{E}} = \hat{x} \]
no intensity modulation, alternating circular polarization

\[ \vec{\mathbf{E}} = \hat{y} \]
Motivation for the double-well lattice:
Isolate pairs of atoms in controllable potential, to test
- addressing ideas
- controlled interactions, at 2-atom level
etc.

Provide new possibilities for cold atom lattice physics
• **Realizing a dynamic double-well lattice**
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• **Future**
  potential applications to lattice simulation
Phase Stable 2D Double Well

Basic idea:
Combine two different period lattices with adjustable
- intensities
- positions
Mott insulator $\rightarrow$ single atom/site

\[ \lambda \] + \[ \lambda/2 \] =
\[ \hat{\mathbf{r}} = \hat{\mathbf{y}} \]

\[ \hat{\mathbf{r}} = \hat{\mathbf{z}} \]

Folded retro-reflection is phase stable

\[ 16E^2 \sin^4 \left( \frac{kx}{2} \right) \]

\[ 4E^2 \left( \cos^2 \left( kx + \phi \right) + 1 \right) \]

Sebby-Strabley et al., PRA 73 033605 (2006)
Polarization Controlled 2-period Lattice

Add an independent, deep vertical lattice

Provides an independent array of 2D systems
We use the quadratic Zeeman shift to isolate a pseudo spin-1/2

\[ F = 1, m_F = 0 \]

\[ F = 1, m_F = 1 \]

\[ F = 1, m_F = -1 \]

\[ \text{~34 MHz} \]

\[ \text{~34.3 MHz} \]

\[ \text{~50 gauss} \]

For the demonstrations shown here, we use these 2 states in $^{87}\text{Rb}$
X-Y directions coupled
- Checkerboard topology
- Not sinusoidal (in all directions)

\[
\cos^2(x + y)\cos^2(x - y) \rightarrow \cos^4(x)
\]

E.g., leads to very different tunneling

- Spin-dependence in sub-lattice
Reciprocal Lattices and Brillouin Zones

'λ' lattice

Band-adiabatic load in 500 μs, snap off

'λ/2' lattice

Brillouin Zone mapping

500 μs
20 μs
300 ms
500 μs
phase incoherent
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2D Mott-insulator

Spielman, Phillips, TP

PRL 98, 080404 (2007)
2D Mott-insulator

Momentum distribution

Quite good comparison to a homogeneous theory
(no free parameters)

Sengupta and Dupuis, PRA 71, 033629
Information in the Noise?

Signal and width

*Some* information available...
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Dynamic Lattice Manipulation

Use double well split/combine control to, e.g.

• characterize particular number distribution
• construct particular number distributions
• adiabatically populate vibrational levels
• distinguish left/right populations
Double Slit Diffraction

Slowly load mostly-λ lattice, snap off

- Load in ~300 ms
- Phase scrambled

Coherently split single well

- Split in ~200 μs
- Coherent split
Time dependence of diffraction

In 3D lattice, see: Greiner et al. Nature, 419 (2002)

Time dependence confirms single-atom loading
Constructing $n=2$ Shell

Normally available $n=2$ and $n=1$ shells

Adiabatically purify $n=2$ shell
Number Distribution Dependence

For $n=2$, collapse and revival shows revivals at half the original period.

May provide hole populations (dominant infidelity)

Indications:
Fermionized but not necessarily Mott

Sebbey-Strabley et al., PRL in press
(quant-ph/0701110)
Probe: Selective Removal of Sites

Load right well → expel left

Load left well → expel left

Starting ‘$\lambda/2$’ 30 $E_R$
“Expelling” as a left/right probe

\[ \Delta \theta \]

dump left

\[ \Delta \theta \]

dump left

\[ \Delta \theta \]

dump left
"Expelling" as a left/right probe

Scan the relative phase between lattices
Atoms can be put on the same site, (but different vibrational level), allowed to interact, and then separated adiabatically.
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State Dependent Potential

$|F = 1, m_F = 0\rangle$

$|F = 1, m_F = -1\rangle$

34 MHz Zeeman

~150 kHz Lattice
Start with atoms in $m=-1$

Apply RF to spin flip to $m=0$

“Evaporate” $m=0$ atoms

Measure $m=-1$ occupation in the left or right well.

**Sub-Lattice Addressing**

Sub-Lattice Addressing by light shift gradient
Start with atoms in $m=-1$

Apply RF to spin flip to $m=0$

“Evaporate” $m=0$ atoms

Measure $m=-1$ occupation in the left or right well.

Lee et al., quant-ph/0702039
Example: Addressable One-qubit gates

Atoms at sub-$\lambda$ spacing
-focused beam sees
several sites
Example: Addressable One-qubit gates

Atoms at sub-\(\lambda\) spacing
- focused beam sees several sites
- state dependent shifts effective field gradients
Example: Addressable One-qubit gates

Atoms at sub-\(\lambda\) spacing
-focused beam sees several sites
-state dependent shifts effective field gradients

RF, \(\mu\)wave or Raman
Example: Addressable One-qubit gates

Atoms at sub-\(\lambda\) spacing
- focused beam sees several sites
  - state dependent shifts effective field gradients
  - frequency addressing
State selective motion/splitting

Start with either $m=-1$ or $m=0$
Selectively split sites

Similar to Mandel et al., PRL 91 (2003)
but confined to a double-well

$m=0$ on left
$m=-1$ on right
State selective motion/splitting

Start with either $m=-1$ or $m=0$
Selectively split sites

Tilt dependence

Fraction of atoms in $R$ vs. Relative position ($\delta x/\lambda$)
Coherent State-Dependent “Splitting”

\( \pi/2 \) pulse

Double-slit diffraction

Site specific RF excitation

(Actually, folded into a spin-echo sequence)

Lee et al., quant-ph/0702039
State dependent detection

- via Stern-Gerlach
- via state-dependent motion

Stern-Gerlach

$\mathbf{m}_F = 0$ on left
$\mathbf{m}_F = -1$ on right

State dependent motion

$m=0$ on left  $m=-1$ on right
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Putting it all together: a $\sqrt{\text{swap}}$ gate

Step 1: load single atoms into sites

Step 2: spin flip atoms on right

Step 3: combine wells into same site

Step 4: wait for time $T$

Step 5: measure state occupation (vibrational + internal)
**Exchange Gate:** $\sqrt{\text{swap}}$

- **|1,0⟩**: Projection
- **|1,1⟩** (triplet)
  - **|0,1⟩ + |1,0⟩**
  - **|00⟩** (exchange split by energy $U$)
- **|0,1⟩ − |1,0⟩** (singlet)
Exchange Gate: $\sqrt{\text{swap}}$

|1,0⟩  

projection  

|1,1⟩  
|0,1⟩  
|0,0⟩  
|1,0⟩  

projection  

|1,1⟩  

|0,1⟩ + |1,0⟩  

|00⟩  

|0,1⟩ – |1,0⟩  

exchange split by energy $U$

|1,1⟩  
|0,1⟩ + $i$|1,0⟩  
|0,0⟩  
|0,1⟩ – $i$|1,0⟩  

triplet  

singlet
Controlled Exchange Interactions

Qubit basis: $|0\rangle$, $m_r = 0$; $|1\rangle$, $m_r = -1$

$T_1 = |↑↑\rangle$

$T_0 = |↑↓\rangle + |↓↑\rangle$

$S = |↑↓\rangle - |↓↑\rangle$

$T_{-1} = |↓↓\rangle$
Basis Measurements

All axes are momentum $[\hbar k_R / \sqrt{2}]$
Swap Oscillations

Onsite exchange -> fast 140μs swap time

~700μs total manipulation time

Population coherence preserved for >10 ms. (despite 150 - T2*)
Coherent Evolution

First $\pi/2$

Second $\pi/2$

b) control case

c) first $\pi/2$ only

d) $\pi/2 - \pi - \pi/2$

Population in state $e$

Time [ms]

$|0\rangle$

$|1\rangle$

$m_z = 0$

$m_z = -1$

$-1$

Time [ms]

Time [ms]
Current (Improvable) Limitations

- Initial Mott state preparation
  (30% holes $\rightarrow$ 50% bad pairs)

- Imperfect vibrational motion $\sim$ 85%

- Imperfect projection onto $T_0$, $S$ $\sim$ 95%

- Sub-lattice spin control $>95$

- Field stability
  move to clock states
  (state-dependent control through intermediate states)
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Tools for lattice systems

State preparation, e.g.
- ‘filter’ cooling
- constructing anti-ferromagnetic state.

Diagnostics, e.g.
- number distributions (including holes)
- neighboring spin correlations

Realizing lattice Hamiltonians, e.g.
- band structure engineering
- ‘stroboscopic’ techniques
- coupled 1D-lattice “ladder” systems
- RVB physics
Wannier function control

Two band Hubbard model
state-dependent control of:
\( t/U, \Delta/U, \) position of \( \lambda \)-lattice

Ian Spielman
Characterizing Holes

In a fixed period lattice, difficult to measure “holes”

*Isolated holes in $\lambda/2$*

Combine holes with neighbors
Coupling spin and motion

\[ |m_F = 1\rangle \]
\[ |m_F = 0\rangle \]
\[ |m_F = -1\rangle \]

Purely vector part of line perpendicular to line with no coupling (large Zeeman splitting)

Can be coupled with perpendicular DC or RF fields

couples spin to Bloch state motion
Coupling spin and motion

local effective field

alternating plaquettes
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The End