Quantum simulation in optical superlattice

Yu-Ao Chen

Center for Quantum Engineering
Shanghai Division of Quantum Physics and Quantum Information,
National Lab for Physical Sciences at the Microscale,
University of Science and Technology of China
National Laboratory for Physical Sciences at Microscale

Information
- Quantum communication & quantum computation

Energy
- Engineering at Microscale, for efficient energy exchange coherently

Material
- Understanding physics for complex system

Life Sci.
- Quantum biology
- Life process & quantum entanglement
Division of Quantum Physics & Quantum Information

- Fundamental test of quantum mechanics
- Quantum computation
- Quantum communication
- Quantum simulation

Quantum Physics & Quantum Information
Postdoc positions available
The Boson Experiment in Munich

- $^{87}$Rb (bosons)
- $N_{BEC} \sim 10^5$
- $T \sim 10\text{nK}$
- 3D optical lattice
  - $\lambda_z = 843\text{nm}$
  - $\lambda_{xs,ys} = 767\text{nm}$
- 1D Superlattice
  - $+ \lambda_{xl} = 1534\text{nm}$
- Another Superlattice
  - $+ \lambda_{yl} = 1534\text{nm}$

Bare chamber (no magnetic coils, no optics, etc.)
And a lot of optics and electronics!
The Bichromatic Superlattice
The Bichromatic Superlattice

$V_{\text{long}}$

1534 nm lattice
The Bichromatic Superlattice

$V_{\text{long}}$ $V_{\text{short}}$

1534 nm lattice + 767 nm lattice
The Bichromatic Superlattice

1534 nm lattice + 767 nm lattice

Now: Dito, but increase blue wavelength
The Bichromatic Superlattice

\[ V(x) = V_l \cos(2k_l x) + V_s \cos(4k_l x + \varphi) \]

Now: Dito, but increase blue wavelength

1534 nm lattice + 767 nm lattice
The Bichromatic Superlattice

1534 nm lattice + 767 nm lattice

Now: Dito, but increase blue wavelength

Full (independent) dynamical control over:
- $V_{\text{long}}, V_{\text{short}}$
- Relative phase $\varphi$
- Transverse lattices

$$V(x) = V_l \cos(2k_l x) + V_s \cos(4k_l x + \varphi)$$
The Bichromatic Superlattice

- Adjusting $\varphi$ by fine-tuning $\lambda_I$
- Offset-locking frequency-doubled fiber-laser to Ti:Sa-laser

- Offset-frequency $\Delta\nu = 1 - 2$ GHz
  - Tuning range $\varphi = 0 \ldots 2\pi$
The Bichromatic Superlattice

- Novel *state preparation* techniques, e.g. *patterned loading*
The Bichromatic Superlattice

- Novel state preparation techniques, e.g. patterned loading

- Novel read-out methods, e.g. sub-lattice resolved detection

(Alternative: Raman-spectroscopy)
The Bichromatic Superlattice

- Novel *state read out* techniques, e.g. Stern-Gerlach
Preparing Spin Singlets

- Atom pairs in long-lattice wells $|F = -1, m_F = 0\rangle$

- Initialize in $|F = 1, m_F = 0\rangle$

- Microwave-dressed spin-changing collisions
  $\rightarrow$ **Spin-pairs** in $|F = 1, m_F = \pm 1\rangle$

A. Widera et al., PRL 95 (2005), F. Gerbier et al., PRA 73 (2006)
Preparing Entangled Spin Singlets

- **Spin pairs** in $|F = 1, m_F = \pm 1\rangle \equiv |\uparrow\rangle, |\downarrow\rangle$
- Barrier raised *slowly* to split
  $\rightarrow$ Crossing a miniature Mott-transition: $n_{\text{Left}} = n_{\text{Right}}$

J. Sebby-Strabley et al., PRL 98 (2007)

- **Bosons**: Symmetric wavefunction $\rightarrow$ Triplet $|t_0\rangle$
  (Fermions: Antisymmetric wavefunction $\rightarrow$ Singlet $|s_0\rangle$)

Details on the loading of the Spin-pairs:
2D Superlattice Geometries (2 SL)

Coupled Plaquette Systems
see B. Paredes & I. Bloch, PRA 77, 23603 (2008)
S. Trebst et al., PRL 96, 250402 (2006)

Higher Lattice Orbital Physics
see V. Liu, A. Ho, C. Wu and others work
exp: related to A. Hemmerich’s exp.
Experiments in the Superlattice

- Isolated double-wells:
  - Correlated tunneling

\[
U \uparrow \quad \text{resonant} \quad \propto \frac{J^2}{U} \\
\text{detuned} \quad \propto \sqrt{J^2 + U^2}
\]
Experiments in the Superlattice

• Isolated double-wells:
  - Correlated tunneling, Superexchange interactions
Experiments in the Superlattice

- Isolated double-wells:
  - Correlated tunneling, Superexchange interactions
  - Counting atoms via interaction blockade
Experiments in the Superlattice

- Isolated double-wells:
  - Correlated tunneling, Superexchange interactions
  - Counting atoms via interaction blockade
Experiments in the Superlattice

- Isolated double-wells:
  - Correlated tunneling, Superexchange interactions
  - Counting atoms via interaction blockade
  - Control of n.n. spin correlations
Experiments in the Superlattice

- **Isolated double-wells:**
  - Correlated tunneling, Superexchange interactions
  - Counting atoms via interaction blockade
  - Control of n.n. spin correlations
Experiments in the Superlattice

• Isolated double-wells:
  - Correlated tunneling, Superexchange interactions
  - Counting atoms via interaction blockade
  - Control of n.n. spin correlations
Experiments in the Superlattice

- Isolated double-wells:
  - Correlated tunneling, Superexchange interactions
  - Counting atoms via interaction blockade
  - Control of n.n. spin correlations

→ Triplet:

→ Singlet:
Experiments in the Superlattice

- Isolated double-wells:
  - Correlated tunneling, Superexchange interactions
  - Counting atoms via interaction blockade
  - Control of n.n. spin correlations

→ Triplet:

→ Singlet:
Experiments in the Superlattice

- **Isolated double-wells:**
  - Correlated tunneling, Superexchange interactions
  - Counting atoms via interaction blockade
  - Control of n.n. spin correlations

- **Non-equilibrium & adiabatic dynamics:**
  - Decay of patterned states (spin, density) after quantum quenches
Experiments in the Superlattice

• Isolated double-wells:
  - Correlated tunneling, Superexchange interactions
  - Counting atoms via interaction blockade
  - Control of n.n. spin correlations

…

• Non-equilibrium & adiabatic dynamics:
  - Decay of patterned states (spin, density) after quantum quenches
  - Landau-Zener sweeps w. 1D gases
Experiments in the Superlattice

- **Isolated double-wells:**
  - Correlated tunneling, Superexchange interactions
  - Counting atoms via interaction blockade
  - Control of n.n. spin correlations
  ...

- **Non-equilibrium & adiabatic dynamics:**
  - Decay of patterned states (spin, density) after quantum quenches
  - Landau-Zener sweeps w. 1D gases
  ...

- **Isolated plaquettes:**
  - Resonating Valence Bond State
Experiments in the Superlattice

- Isolated double-wells:
  - Correlated tunneling, Superexchange interactions
  - Counting atoms via interaction blockade
  - Control of n.n. spin correlations
- Non-equilibrium & adiabatic dynamics:
  - Decay of patterned states (spin, density) after quantum quenches
  - Landau-Zener sweeps w. 1D gases

- Isolated plaquettes:
  - Resonating Valence Bond State
Experiments in the Superlattice

- **Isolated double-wells:**
  - Correlated tunneling, Superexchange interactions
  - Counting atoms via interaction blockade
  - Control of n.n. spin correlations
  ...

- **Non-equilibrium & adiabatic dynamics:**
  - Decay of patterned states (spin, density) after quantum quenches
  - Landau-Zener sweeps w. 1D gases
  ...

- **Isolated plaquettes:**
  - Resonating Valence Bond State
  - **Artificial Gauge Field**
  - Zak Phase in Topological Bloch Bands
  ...

- **Many-body phases in the superlattice**
CREATION OF STRONG EFFECTIVE MAGNETIC FIELDS

M. Aidelsburger et al.,
PRL 107, 255301 (2011)
Quantum Hall effect in 2D electron gases

- Integer quantum Hall effect

\[ \sigma_{xy} = \nu \frac{e^2}{h}, \quad \nu \text{ integer} \]

\[ \hbar \omega_c \]

- Fractional quantum Hall effect

Laughlin state at \( \nu = 1/3 \)
The Coriolis force $F_C = 2m \mathbf{v} \times \Omega_{\text{rot}}$ is analogous to
the Lorentz force $F_L = q \mathbf{v} \times \mathbf{B}$

Issue: typically $\gamma > 1000$


Spatially dependent optical couplings lead to a Berry
phase analogous to the Aharonov-Bohm phase.

Issues: small $B$ fields, heating from Raman lasers.

Artificial B fields with ultracold atoms in OLs

Controlling atom tunneling along $x$ with Raman lasers leads to effective tunnel couplings with spatially-dependent Peierls phases $\phi(R)$

$$\hat{H} = -\sum_{R} \left( Ke^{i\phi(R)} \hat{a}^\dagger_{R} \hat{a}_{R+d_x} + J \hat{a}^\dagger_{R} \hat{a}_{R+d_y} \right) + \text{h.c.}$$

Magnetic flux through a plaquette

$$\phi = \int B \, dS = \varphi_1 - \varphi_2$$

F. Gerbier & J. Dalibard, NJP 12, 033007 (2010)
A. Kolovsky, Europhys. Lett. 93, 20003 (2011)
Harper Hamiltonian and Hofstadter butterfly

Harper Hamiltonian: $J=K$ and $\phi$ uniform.
Harper Hamiltonian and Hofstadter butterfly

Harper Hamiltonian: $J=K$ and $\phi$ uniform.

- Lowest band is topologically equivalent to lowest Landau level
- $\nu=1/2 +$ repulsive interactions $\rightarrow$ Laughlin state for Bosons.
Staggered flux lattice with Rb atoms

Consider a 2D optical lattice, where tunneling is inhibited along the $x$ direction by a superlattice potential.

F. Gerbier & J. Dalibard, NJP 12, 033007 (2010)
A. Kolovsky, Europhys. Lett. 93, 20003 (2011)
**Staggered flux lattice with Rb atoms**

Tunneling along this direction can be restored using Raman beams.

---

Staggered flux lattice with Rb atoms

\[ \Delta \Omega \]

F. Gerbier & J. Dalibard, NJP 12, 033007 (2010)
A. Kolovsky, Europhys. Lett. 93, 20003 (2011)
Staggered flux lattice with Rb atoms

\[ \delta \mathbf{k} = \mathbf{k}_1 - \mathbf{k}_2 \]

\[
K_{|\bullet\rangle \rightarrow |\circ\rangle}(\mathbf{R}) = \int d\mathbf{r} \ w^*_\bullet(\mathbf{r} - \mathbf{R}) w_\circ(\mathbf{r} - \mathbf{R} - \mathbf{d}_x) \Omega(\mathbf{r}) \\
= K e^{i\delta \mathbf{k} \cdot \mathbf{R}} \quad \text{for} \quad \Omega(\mathbf{r}) = V_K e^{i\delta \mathbf{k} \cdot \mathbf{r}} \\
K_{|\circ\rangle \rightarrow |\bullet\rangle}(\mathbf{R}') = K e^{-i\delta \mathbf{k} \cdot \mathbf{R}'}
\]

F. Gerbier & J. Dalibard, NP 12, 033007 (2010)
A. Kolovsky, Europhys. Lett. 93, 20003 (2011)
Staggered flux lattice with Rb atoms

→ Staggered flux $\phi$
with zero mean

→ Tunable flux value,
$\delta \mathbf{k} = \mathbf{k}_1 - \mathbf{k}_2$
(our setup: $\phi = \pi/2$)

$$K_{\bullet \rightarrow \circ}(\mathbf{R}) = \int d\mathbf{r} \, w^*_{\bullet}(\mathbf{r} - \mathbf{R})w_{\circ}(\mathbf{r} - \mathbf{R} - \mathbf{d}_x)\Omega(\mathbf{r})$$
$$= K \, e^{i\delta \mathbf{k} \cdot \mathbf{R}} \quad \text{for} \quad \Omega(\mathbf{r}) = V_K \, e^{i\delta \mathbf{k} \cdot \mathbf{r}}$$

$$K_{\circ \rightarrow \bullet}(\mathbf{R}') = K \, e^{-i\delta \mathbf{k} \cdot \mathbf{R}'}$$

F. Gerbier & J. Dalibard, NJP 12, 033007 (2010)
A. Kolovsky, Europhys. Lett. 93, 20003 (2011)
Staggered flux lattice with Rb atoms

Methods to rectify the flux:
- Linear potential gradient
- State-dependent lattices

\[
K_{\left| \Lambda \right> \rightarrow \left| \Lambda \right>}(R) = K e^{i\delta k \cdot R}, \quad K_{\left| \Lambda \right> \rightarrow \left| \Lambda \right>}(R') = K e^{-i\delta k \cdot R'}
\]

\[\delta k = k_1 - k_2\]
(our setup: \(\phi = \pi/2\))

\[\rightarrow\] Staggered flux \(\phi\)
with zero mean

\[\rightarrow\] Tunable flux value,

F. Gerbier & J. Dalibard, NJP 12, 033007 (2010)
A. Kolovsky, Europhys. Lett. 93, 20003 (2011)
In the limit of $V_K \ll \Delta$ the amplitude of the Raman-assisted tunneling is given by:

$$K \approx \frac{1}{2\sqrt{2}} \frac{V_K J}{\Delta}$$
We load a \(^{87}\text{Rb}\) condensate into a 2D-optical lattice.

\[ J = 2\pi \times 60(3) \text{ Hz} \]
Experimental sequence

- We load a $^{87}$Rb condensate into a 2D-optical lattice.

\[
J = 2\pi \times 60(3) \text{ Hz}
\]

- We inhibit tunneling along $x$ with a superlattice.

\[
\Delta = 2\pi \times 4.4(1) \text{ kHz}
\]
Experimental sequence

❖ We load a $^{87}$Rb condensate into a 2D-optical lattice.

\[ J = 2\pi \times 60(3) \text{ Hz} \]

❖ We inhibit tunneling along $x$ with a superlattice.

\[ \Delta = 2\pi \times 4.4(1) \text{ kHz} \]

❖ We switch on Raman lasers on resonance to induce tunneling.

\[ K = 2\pi \times 59(2) \text{ Hz} \]
Experimental sequence

❖ We load a $^{87}$Rb condensate into a 2D-optical lattice.

$$J = 2\pi \times 60(3) \text{ Hz}$$

❖ We inhibit tunneling along $x$ with a superlattice.

$$\Delta = 2\pi \times 4.4(1) \text{ kHz}$$

❖ We switch on Raman lasers on resonance to induce tunneling.

$$K = 2\pi \times 59(2) \text{ Hz}$$

❖ After 10 ms hold time, TOF images.
Momentum distribution ($J/K=1$): observations

Reference: cubic lattice
(no Raman drive)

$J/K=1.0(1)$

Due to the frustration introduced by the phase factors in $K(R)$, the condensation occurs for non-zero momenta.
"Band structure

• ‘Magnetic’ Brillouin zone"
**Band structure**

- ‘Magnetic’ Brillouin zone

\[ \phi, -\phi, \phi \]

- Single-particle spectrum in the tight-binding approximation

From the magnetic translation symmetries:

\[
\psi_{|k_x,k_y\rangle}(\mathbf{R} = m \mathbf{d}_x + n \mathbf{d}_y) = e^{i(m \cdot k_x d_x + n \cdot k_y d_y)} \times \begin{cases} 
\psi_e & m \text{ even} \\
\psi_o e^{i \frac{\pi}{2} (m+n)} & m \text{ odd}
\end{cases}
\]
Band structure

- ‘Magnetic’ Brillouin zone

- Single-particle spectrum in the tight-binding approximation
  From the magnetic translation symmetries:

$$\psi_{|k_x,k_y\rangle}(R = m \mathbf{d_x} + n \mathbf{d_y}) = e^{i(m \cdot k_x d_x + n \cdot k_y d_y)} \times \begin{cases} \psi_e & m \text{ even} \\ \psi_o e^{i\frac{\pi}{2} (m+n)} & m \text{ odd} \end{cases}$$

An eigenstate $|k_x, k_y\rangle$ has two momentum components at

$(k_x, k_y)$ and $(k_x, k_y) + (k_s/2, k_s/2)$
Momentum distribution (J/K=1): comparison with theory

experiment

theory

OD (a.u.)
The diffraction peaks are splitted $\longrightarrow$ two-fold ground state degeneracy
Momentum distribution (J/K=2.5)

The diffraction peaks are splitted $\rightarrow$ two-fold ground state degeneracy
Momenta of the two degenerate ground states

G. Moeller, N. Cooper, PRA 82, 1 (2010)
J. Struck et al., Science 333, 996 (2011)
Momenta of the two degenerate ground states

In the case of ground state degeneracy, we observe an equal population of both states.

G. Moeller, N. Cooper, PRA 82, 1 (2010)
J. Struck et al., Science 333, 996 (2011)
Dispersion relation and spatial phase distribution
Dispersion relation and spatial phase distribution

\[ R_x(d_x) \]

\[ R_y(d_y) \]

Striped density pattern

\[ J = 2.5 \, \text{K} \]

\[ k_x / k_s \]

\[ k_y / k_s \]

\[ E \]

\[ 0 \quad 0 \quad 1 \]

\[ 0 \quad 1 \quad 0 \]

\[ 0 \quad 1 \quad 0 \]

\[ 0 \quad 0 \quad 2 \]

\[ 0 \quad 0 \quad 1 \]

\[ 0 \quad 0 \quad 2 \]

\[ 0 \quad 0 \quad 3 \]

\[ 0 \quad 0 \quad 4 \]

\[ 0 \quad 0 \quad 5 \]

\[ 0 \quad 0 \quad 6 \]

Quantum Physics & Quantum Information
A lattice of plaquettes
State preparation for phase imprinting

- Load single atoms into ground state of tilted plaquettes:

\[ |\psi_0\rangle = \frac{|A\rangle + |D\rangle}{\sqrt{2}} \]
State preparation for phase imprinting

- Load single atoms into ground state of tilted plaquettes:

\[ |\psi_0\rangle = \frac{|A\rangle + |D\rangle}{\sqrt{2}} \]
State preparation for phase imprinting

- Load single atoms into ground state of tilted plaquettes:

\[ |\psi_0\rangle = \frac{|A\rangle + |D\rangle}{\sqrt{2}} \]

- Switch on Raman coupling to induce atom transfer to the \(B, C\) sites

In the limit \(J \ll K\) the state is coupled to

\[ |\psi_1\rangle = \frac{|B\rangle + i|C\rangle}{\sqrt{2}} \]
Observation of phase-imprinting

\[ \text{Phase (rad)} \]

\[ T (\text{ms}) \]
Observation of phase-imprinting
Observation of phase-imprinting
Quantum `Cyclotron' Orbit

- Classical:
  Charged particle in a uniform magnetic field

\[ e^-, B \]
Quantum `Cyclotron' Orbit

- Classical:
  Charged particle in a uniform magnetic field

- Measure quantum analogue:
  Initial state:
  Single atom in ground state of tilted plaquette
Quantum `Cyclotron' Orbit

- Classical:
  Charged particle in a uniform magnetic field

- Measure quantum analogue:
  Initial state:
  Single atom in ground state of tilted plaquette

\[ |\psi_0\rangle = \frac{|A\rangle + |D\rangle}{\sqrt{2}} \]

Switch on Raman coupling to induce atom transfer

Site-resolved detection
Site-resolved detection

- Site-resolved detection in double-wells

![Diagram of site-resolved detection in double-wells with band mapping and TOF analysis.](image)
Site-resolved detection

- Site-resolved detection in double-wells

- Generalization to a lattice of plaquettes
Site-resolved detection

- Site-resolved detection in double-wells

\[ h_X^i \text{ and } h_Y^i \]

- Generalization to a lattice of plaquettes

- Evaluate mean atom positions \( \langle X \rangle \) and \( \langle Y \rangle \)
`Cyclotron' Orbit

The mean atom position during the evolution.
`Cyclotron' Orbit

The mean atom position during the evolution.
`Cyclotron' Orbit

The mean atom position during the evolution.
The mean atom position during the evolution.

From this evolution we fit the value of the phase

$$\phi = 0.73(5) \frac{\pi}{2}$$

Deviation from $\phi = \pi/2$
`Cyclotron' Orbit

The mean atom position during the evolution.

From this evolution we fit the value of the phase

$$\phi = 0.73(5) \pi/2$$

Deviation from $\phi=\pi/2$
`Cyclotron` Orbit

The mean atom position during the evolution.

From this evolution we fit the value of the phase

$$\phi = 0.73(5) \pi/2$$

Deviation from $\phi=\pi/2$
Outlook: Rectify the flux

Using a linear potential

Using a superlattice
F. Gerbier & J. Dalibard, NJP 12, 033007 (2010)
Outlook: Rectify the flux

Using a linear potential

Using a superlattice + Gradient
F. Gerbier & J. Dalibard, NJP 12, 033007 (2010)
Outlook: Rectify the flux

Ladders in a magnetic field:

- Observables
- Edge current
- Bifurcation point
- Strong interaction
- Dirac point
Outlook: Rectify the flux

Ladders in a magnetic field:

- Observables
- Edge current
- Bifurcation point
- Strong interaction
- Dirac point
Outlook: Rectify the flux

Detection of a vortex prepared in isolated 4-site plaquettes
Ongoing Project: Fermi-Fermi Mixture in OLs
Ongoing Project: Fermi-Fermi Mixture in OLs

Vacuum design——2D+MOT for K40
Ongoing Project: Fermi-Fermi Mixture in OLs

Vacuum design——Collimated Li6 atom beam

Li烤炉

差分准直管

回流炉

输出准直后的高通量Li原子束