Simulating Topological and Disordered Systems with Resonantly Driven Atomic Matter Waves

Fangzhao Alex An
Eric J. Meier

Bryce Gadway
University of Illinois at Urbana-Champaign

publish.illinois.edu/gadwaylab/
The Gadway Group

Rb/K quantum gases project (8/2014-)
- resonant Hamiltonian engineering
- topological matter

Er/Rb quantum gases project (1/2016-)
- Emergent behavior in quantum spin systems
- Nonequilibrium spin transport

Eric J. Meier
Fangzhao Alex An

Local theory friends: Smitha Vishveshwara, Taylor Hughes

Jackson Ang’ong’a
A short and biased history of cold atom simulation

Let the atoms (or molecules) act naturally
- superfluid behavior of atomic Bose-Einstein condensates
- BEC/BCS crossover physics of atomic Fermi gases
- atoms in standard optical lattices – Hubbard models w/ on-site interactions & emergent magnetism ($t^2/U$)
- long-range interactions with dipolar atoms/molecules, Rydberg atoms, ions, and cavity-mediated interactions of atoms

Ketterle group, 2001
Greiner, Mandel, Esslinger, Hansch & Bloch, 2002
Hulet group, 2015
Esslinger group, 2015
Jin & Ye groups, 2013
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Still natural behavior, but added complexity
- additional potentials for new physics
  - disordered Hubbard models
  - optical superlattices, etc.
- spin-dependent potentials
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Mostly non-native behavior
- Lorentz forces (classical gauge fields), spin-orbit coupling
- “Gauss’ Law” in dynamical gauge field simulations

Top-down Hamiltonian engineering
Bottom-up approaches to Hamiltonian design

Create a large set of available modes & connect them in a controlled fashion

- arbitrary spatial variations
- well-defined system boundaries

cf. also Zilberberg, Silberberg, Christodoulides, Simon, White, etc.
Bottom-up approaches to Hamiltonian design

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Regal group (cf. also Jochim, Greiner, etc.)

Browaeys group (cf. also Saffman, Bloch, etc.)
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- arbitrary spatial variations
- well-defined system boundaries

Field-driven transitions between the modes – “driven tunneling”

- spectroscopic control over system parameters
- tunneling phase control
- arbitrary time-dependence

In the spirit of employing “synthetic dimensions”

Celi, et al. PRL 112 043001 (2014)
Mancini, et al. Science 349 1510 (2015);
Outline

Bottom-up Hamiltonian design with resonant control
- realization with lattice-driven matter waves
- long-range interactions, higher dimensions, non-Abelian gauge fields

First studies: dynamics, disorder, and topological defect states

Near-term prospects: higher dimensions, coupled topological wires, and quantum chaotic dynamics
Atom-optics simulator of tight-binding lattice models

atomic diffraction, Chin group, Chicago

laser diffraction, dragonlasers.com

modes = plane-wave momentum states of a BEC

\[ p_n = 2n\hbar k_L \]

\[ E_n = n^2 E_1 = 4n^2 E_R \]
Atom-optics simulator of tight-binding lattice models

momentum states are coupled through global Bragg laser fields, and this coupling is energy-selective, and thus state-selective

- Detunings determine potential landscape
- Fields strengths control tunneling amplitude
- Laser phase directly controls tunneling phase
- (Rabi freq. << 8E_R/h to address individual links)

potential landscape tunneling amplitudes and phases

\[ H = \sum_n \varepsilon_n c_n^{\dagger} c_n + \sum_n t_n \left( e^{i\varphi_n} c_n^{\dagger} c_{n+1} + h.c. \right) \]

BG. PRA 92 043606 (2015)
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Atom-optics simulator of tight-binding lattice models

Completely out-of-equilibrium

Initial temperature scales are irrelevant
Atom-optics simulator of tight-binding lattice models

$\sim 42 \, \mu K$

Image mode populations in time-of-flight

Natural decoherence mechanism - atoms fly off from "near field" region

Continuous-time random walk
Why pursue this matter-wave approach?

Local, arbitrary, and time-dependent control of parameters
(also, multi-range hopping through higher-order Bragg)

Easily extendable to higher dimensions
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Non-Abelian gauge fields

\[ H_{\text{eff}}^I \approx \sum_n t_n \left( \hat{c}^\dagger_{n+1} \hat{U}_n \hat{c}_n + \text{h.c.} \right) \]
Why pursue this matter-wave approach?

We’re using matter waves – interactions!

short-ranged (almost zero-ranged) in real space & long-ranged (almost infinite-ranged) in momentum-space

\[ \sigma(k_{rel}) = \frac{8\pi a^2}{1 + (k_{rel}a)^2} \]

For our lattice
\[ \lambda = 1064 \text{ nm} \]
\[ k_{rel} = 4\pi\Delta n/\lambda \]

For our \(^{87}\text{Rb}\) atoms
\[ a \approx 5.3 \text{ nm} \]
\[ k_{rel}a \approx 0.063\Delta n \]

Nearly “all-to-all” for current parameters – no clear influence yet

Future studies of interacting topological fluids & influence of interactions on localization physics
First demonstrations of new control technique

Continuous-time quantum walks on finite-sized lattices
- ballistic spreading and reflection from boundaries

\[ H = \sum_{n} \varepsilon_n c_n^\dagger c_n + \sum_{n} t_n \left( e^{i\varphi_n} c_n^\dagger c_{n+1} + h.c. \right) \]

Eric J. Meier, F. Alex An, and BG. PRA(R) forthcoming
First demonstrations of new control technique

Continuous-time quantum walks on tilted lattices
- Bloch oscillations

\[ \Delta \varepsilon / t = 1 \]

\[ H = \sum_n \varepsilon_n c_n^\dagger c_n + \sum_n t_n \left( e^{i\phi_n} c_n^\dagger c_{n+1} + h.c. \right) \]

Eric J. Meier, F. Alex An, and BG. PRA(R) forthcoming
First demonstrations of new control technique

Global tunneling phase inversion (band inversion)
- rotary echo

\[ H = \sum_{n} \varepsilon_n c_n^\dagger c_n + \sum_{n} t_n \left( e^{i\varphi_n} c_n^\dagger c_{n+1} + h.c. \right) \]

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Prospects for simulating disordered systems

- Arbitrary potential landscapes
  - Varying disorder correlation lengths
  - Comparing different disorder distributions
  - Random dimer models, $n$-mer models
  - quasidisorder and quasicrystal lattices

- Off-diagonal disorder and/or diagonal disorder

- Disordered topological systems

- Time-fluctuating disorder – annealed vs. quenched disorder

- Disorder in higher dimensions
  - Random flux lattices
  - Bond percolation networks
Nonequilibrium disordered quantum walks

Quantum walks in a pseudo-disordered potential

\[ H = \Delta \sum_{n} \cos(b \pi n + \phi) c_n^\dagger c_n + t \sum_{n} (c_n^\dagger c_{n+1} + h.c.) \]

Aubry-André model

\[ b = (1 + \sqrt{5}) / 2 \]

golden ratio

Inguscio
Rolston
Schneble
Bloch
etc.
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Quantum annealing into disorder

Slowly modify Hamiltonian to increase $\frac{t}{\Delta}$

$$H = \Delta \sum_n \cos(b \pi n + \phi) c_n^\dagger c_n + t \sum_n (c_n^\dagger c_{n+1} + h.c.)$$

$\Delta$

$t$

$time \quad 1.5 \text{ ms}$

Aubry André: Populations after 1ms
Quantum annealing into disorder

Slowly modify Hamiltonian to increase $t / \Delta$

$$H = \Delta \sum_n \cos(b \pi n + \phi) c_n^\dagger c_n + t \sum_n \left( c_n^\dagger c_{n+1} + h.c. \right)$$

- $H$: Hamiltonian
- $\Delta$: Disorder
- $\Delta \sum_n$:
- $\cos(b \pi n + \phi)$:
- $c_n^\dagger c_n$:
- $t \sum_n$:
- $c_n^\dagger c_{n+1}$:
- $h.c.$: Hermitian conjugate

Diagram:
- $\Delta$ and $t$ axes
- Time: 1.5 ms

Aubry André: Populations after 1ms

Graph:
- $\Delta/t$ vs $n/2\pi$
- Color represents probability
Quantum annealing into disorder

Slowly modify Hamiltonian to increase $\frac{t}{\Delta}$

$$H = \Delta \sum_n \cos(b \pi n + \phi) c_n^\dagger c_n + t \sum (c_n^\dagger c_{n+1} + h.c.)$$

- **Delocalized**
  - theory prediction for transition in Infinite system

- **Localized**

**Graph:**
- X-axis: $\Delta/t$
- Y-axis: Normalized Population
- Points at $\Delta/t = 2$
- Title: Aubry André: Population not in $p=0, \pm 2\pi/k$
- Time: $1.5\text{ ms}$
**Dynamically fluctuating (annealed) disorder**

Mimic coupling to thermal reservoir through randomly varying system parameters

\[ H = t \sum_{n} \left( e^{i\phi_n} c_{n}^{\dagger} c_{n+1} + h.c. \right) \]

random tunneling phase jumps [with an Ohmic-like spectrum]

\[ \phi_n(T) = \sum_{i} J(\omega_i) \cos(\omega_i T + \phi_n) \quad J(\omega) \propto \omega e^{-\hbar \omega / k_B T} \]

for some effective temperature \( T \)

Observe a change from ballistic spreading to diffusive-like (\( \sqrt{\text{time}} \)) transport
Prospects for simulating topological systems

- In 2D - can directly implement arbitrary “gauge fields”
  - Uniform, spatially varying, or random fluxes

- In 1D – can control the symmetry of the Hamiltonian to access 1D topological insulator states of the chiral symmetric class (AIII and BDI)

\[
t_j = t + \Delta \left( \frac{1 + (-1)^j}{2} \right)
\]

BDI tunnelings
1D topological wires – Su-Schrieffer-Heeger model

1D chiral symmetric class BDI topological insulator

\[ H = \sum_{n \in \text{even}} (t + \Delta)(c_n^\dagger c_{n+1} + \text{h.c.}) + \sum_{n \in \text{odd}} (t - \Delta)(c_n^\dagger c_{n+1} + \text{h.c.}) \]

Electronic properties of polyacetylene (Su, Schrieffer, Heeger 1979)

Recent Thouless pumping expts. Bloch / Takahashi groups
1D topological wires – Su-Schrieffer-Heeger model

1D chiral symmetric class BDI topological insulator

\[ H = \sum_{n \text{even}} (t + \Delta)(c_n^\dagger c_{n+1} + h.c.) + \sum_{n \text{odd}} (t - \Delta)(c_n^\dagger c_{n+1} + h.c.) \]

Electronic properties of polyacetylene
Adiabatic preparation of edge & defect states

Start with zero “weak” coupling – slowly turn on weak coupling

\[ \Delta = 0.4t \]
Nonadiabatic projection onto a midgap edge state

“Inject” all atomic population directly at the system boundary

\[ \Delta = 0.2t \]

Population localized to the edge
Nonadiabatic projection onto a midgap edge state

“Inject” all atomic population directly at the system boundary

0 0.6 ms 1.2 ms

\[
\frac{p}{2\hbar k}
\]

Population localized to the edge

“Inject” population in the bulk of the system

\[
\frac{p}{2\hbar k}
\]

0 2 4 6 8 10 12
Phase-sensitive projection onto mid-gap states

In addition to their decaying amplitudes from the edge into the bulk, the BDI midgap states are characterized by a $\pi$ phase inversion every two sites.
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Try to match boundary state wavefunction through nonadiabatic transfer of population (partial transfer / $\pi$-pulse + phase shift)

$\Delta = 0.2t$

average "distance" from edge [$\hbar k$] after 760 $\mu$s evolution
Some near-term experimental prospects

Disordered topological wires

“anneal” into the edge state for no disorder

What we see when a random (box) disorder strength just exceeds $2\Delta$

Odd-even parity of edge states is destroyed

Next probe: study robustness of Thouless pumping against added diagonal disorder
Some near-term experimental prospects

Disordered topological wires

Higher dimensions (like 2)
- IQHE, Floquet Topological Insulators, coupled 1D wires, etc.
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Dynamics of Quantum Chaotic Systems
  Making kicked atoms look like “kicked tops”
Summary

Developed a new “bottom-up” approach to atomic quantum simulations

• well-suited to studying topological systems, disorder, and dynamics

Next major developments:

• extend to higher dimensions
• harness the long-ranged interaction in k-space

Thanks!
Generating multiple frequency sidebands

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Calibration of tunneling strengths

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