Probe of Band Structure Singularities with a Lattice-Trapped Quantum Gas

Charles D. Brown II
Department of Physics
University of California, Berkeley

Physics Club
Yale University
10/18/2021

Experiment
Shao-Wen Chang
Malte Schwarz
Tsz-Him Leung
Dan Stamper-Kurn

Theory
Alexander Avdoshkin
Vladyslav Kozii
Joel Moore
Quantum Simulation

mimicking quantum systems for the purpose of understanding their states, phases, and dynamics

\[ \hat{H}(r) = \sum_i \hat{T}(r_i) + \sum_i \hat{V}(r_i) + \sum_{i \neq j} \hat{I}(r_i, r_j) \]

Digital Simulation

Requires quantum computer device

1. Initialize a state
2. Perform quantum algorithm (implement series of gates or transformations on qubits)
3. Perform measurement to get result

Analog Simulation

Cold atoms in lattices
- Rydberg tweezers

Trapped Ion Chains

Photonics
Problem-types that quantum simulators have addressed

time-dependent
- equilibration and thermalization
  - Groups
    - Bloch
    - Köhl
    - Bakr
    - Greiner
    - Zweirlein
  - DeMarco
  - Schneider
  - Monroe
- dynamical phase transitions, (slow) quenches
  - Groups
    - Weld
    - Esslinger
    - Bloch
    - Spielman
    - Aidelsburger
    - Chin

ground states
- quantum magnetism
  - Groups
    - Bloch
    - Bakr
    - Browaeys
    - Schauss
- quantum spin liquid
  - Groups
    - Lukin
    - Vuletic
    - Greiner
    - Stamper-Kurn
- superconductivity
  - Groups
    - Hulet

Oct. 18, 2021
Charles D. Brown II
Quantum simulation is not just for condensed matter

Quantum simulation experiments may provide insight on problems in particle physics.

HEP tells us that gauge fields are ubiquitous in nature:
- Photons: electromagnetism
- Gluons: strong force
- W and Z particles: weak force

How to achieve artificial gauge fields in a lattice:
- Lattice shaking
- Laser-assisted tunneling (Spielman Group)

Time-dependent artificial gauge fields → dynamical

EXCITING!

Monika Aidelsburger Thesis 2015
Why do we want to simulate solid-state systems?

Many exciting questions on exotic superconductivity and magnetism, quantum Hall effects, topological matter...

An ultracold quantum simulator offers several advantages:
- Controllable defects
- Long-lived quantum coherence
- The ability to prepare many identical copies
- The ability to study out-of-equilibrium physics

We can provide great insight into the behavior of solid materials with crystalline lattice structure.
Crystalline Lattice

A periodic set of points that has some set of symmetries
A solid’s band structure describes the allowable energy levels for electrons in a crystal lattice.

**Band structure explains material properties**

Electrical Resistivity

Optical Absorption

\[ \psi_n(q) = u_n(\vec{r})e^{iq \cdot \vec{r}} \]

\[ u_n(\vec{r}) = u_n(\vec{r} + \vec{R}) \]

![Energy Bands of Particles in a Lattice](image)
Energy Bands of Particles in a Lattice

A solid’s band structure describes the allowable energy levels for electrons in a crystal lattice.

Band structure explains material properties:
- Electrical Resistivity
- Optical Absorption
- Quantum Hall Effects
- Orbital Magnetism
- Topological Insulators

Bloch wavefunctions: \( \psi_n(q) = u_n(\vec{r})e^{i\vec{q}\cdot\vec{r}} \)

Berry Connection: \( A_{mn}(q) = \langle \psi_m(q) | \nabla_q | \psi_n(q) \rangle \)

\[ V_{\text{lat}} = 0 \quad V_{\text{lat}} \neq 0 \]
We use the bosonic isotope $^{87}$Rb to make a Bose-Einstein Condensate.
An exotic state of matter: Bose-Einstein condensate

The de Broglie wavelength describes the wavelike behavior of matter:

$$\lambda_{dB} = \left(\frac{2\pi \hbar^2}{mk_B T}\right)^{1/2}$$

When temperature is low enough: $$\lambda_{dB}^3 > \frac{V}{N}$$
Mathematically:

We use multiple pairs of intersecting beams to make 2D or 3D lattices.
An Optical Honeycomb Lattice

This allows us to create an ultracold atom analog of graphene
A crystal’s band structure and the geometry/topology of state space determines its properties

Graphene

- Andrew Geim, Konstantin Novoselov – 2010 Nobel prize
- Dirac singular points with Berry (geometric) phase
  - Klein tunneling
  - Half-integer quantum Hall effect
- Twisted bi-layer graphene and Moire patterns

My artificial graphene also has Dirac points with interesting topological properties

M. Katsnelson, *The Physics of Graphene*
Experimental Setup

“light preparation” table

“science” table
Ultracold Atom Analog of Graphene

2D Brillouin zone map

Tight-binding band structure

Duca et al (Schneider, Bloch), *Science* 2015
Flaschner et al (Sengstock), *Science* 2016

CDB, Joel Moore, Dan Stamper-Kurn arXiv:2109.03354


Li et al (Bloch, Schneider), *Science* 2016
Direct Probe of Dirac Singularity

\[ \vec{q} = \vec{v}_{\text{lat}} = f_{1-2} \vec{a}_{1-2} + f_{2-3} \vec{a}_{2-3} \]

Theoretical predictions:

- \( |\vec{q}| = 0 \)
- \( |\vec{q}| = 1.33|\vec{q}_K| \)

Experimental results:

Theory: \[ \text{Experiment:} \]

Oct. 18, 2021  Charles D. Brown II
Direct Probe of Dirac Singularity

- Two band model
- Population dynamics driven by:
  \[ A_{mn}(q) = \langle \psi_m(q) | \nabla_q | \psi_n(q) \rangle \]
- Measure of quantum distance:
  \[ d^2 = 1 - |\langle u_2(q') | u_1(q) \rangle|^2 \]
- Reveals the quantum metric tensor \( g \):
  \[ d^2(q, q + dq) = g_{ij}(q)dq_idq_j \]
• Band population transfer is only geometry-dependent for evolution through Dirac points

• Time-dependence returns for trajectories away from the Dirac points
  • Landau-Zener physics

• Singularity size grows with shorter acceleration times
  • Effectively increased band degeneracy
Direct Probe of QBTP

- QBTP at $\Gamma$
  - Load a running lattice, then evolve to $\Gamma$
  - Interferometric measurements can’t detect non-trivial topology of QBTP by encircling it
  - Quantum distance measurement is better for observing non-trivial topology of this singularity

- 2 windings around the QBTP instead of 1 around the Dirac point

CDB,..., Joel Moore, Dan Stamper-Kurn arXiv:2109.03354
Conclusion
• An ultracold atom quantum simulator is a powerful tool that allows for simulation of real materials or toy Hamiltonians
• Measurements of quantum distance allow the non-trivial topology of Dirac points and QBTPs to be directly revealed
• We observe quantized winding numbers
  • 1 winding around the Dirac point
  • 2 windings around the QBTP

Future Work
• Flat p-band in the honeycomb lattice
  • Where do bosons condense?
• What happens if atoms are held at singularity for various times?
Quantum Simulation of Quasicrystals

2X Nobel laureate Linus Pauling once said, “There is no such thing as quasicrystals, only quasi-scientists.”

- Dan Shechtman - 2011 Nobel prize in Chemistry for discovery
- Quasicrystals are aperiodic but ordered, with no translation symmetry
- Superconductivity discovered in a 5-fold quasicrystal in 2018
  - Unusual superconductivity?
- What sorts of other interesting and unusual states of matter might be realizable in a quasicrystal?
  - No translation symmetry means no well defined quasimomentum or Fermi surface
- A 5-fold rotation-symmetric ultracold atom quasicrystal would be very interesting
  - Quantum physics of quasicrystals
  - Wave packet diffusion
  - Phason excitations
  - Topology in quasicrystals
EXTRA
SLIDES