Engineering Dirac points with ultracold fermions in optical lattices

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Band structures with topological defects

Topological defects: Dirac points

Quantum gases in lattices with topological defects

Excited bands:
- 1D « Dirac point » (Weitz group, Bonn)
- Quadratic avoided band crossing (Hemmerich group, Hamburg)

Honeycomb lattice: Dirac points in the lowest band!
- BEC in a honeycomb lattice (Sengstock group, Hamburg, Stamper-Kurn group, Berkeley)
Outline

An optical lattice of tunable geometry

Probing Dirac points by interband transitions

Adjusting, moving and merging Dirac points
An optical lattice of tunable geometry

Setup

Optical potential

\[ V(x, y) = V_{X} \cos^2(kx + \theta / 2) + V_{X} \cos^2(kx) + V_{Y} \cos^2(ky) + 2\alpha \sqrt{V_{X}V_{Y}} \cos(kx)\cos(ky) \]

\[ \lambda = 1064\text{nm} \]
An optical lattice of tunable geometry

\[ V_Y = 2 \ E_R, \ \theta = \pi \]

- chequerboard
- triangular
- dimer
- honeycomb
- 1D chains

\[ V_X \ [E_R] \]
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An optical lattice of tunable geometry

Chequerboard

Dimer

1D zig-zag chains

\[ V_X [E_R] \]

\[ V_X = 0 \]

Triangular

Honeycomb

Square
Honeycomb lattice

Real space

Reciprocal space

2 sublattices → 2 sub-bands

2 Dirac points inside the Brillouin zone:
- Conical energy spectrum
- Spinor wavefunctions
- Dirac fermions

Topologically equivalent to regular hexagonal lattice
Probing the Dirac points

**Challenges:**
- vanishing density of states
- small energy scales

Probe energy splitting of the bands *dynamically*


**Bloch oscillations + interband transitions**

- Passing away from Dirac point: stay in lowest band
- Passing through Dirac point: transfer to 2\textsuperscript{nd} band

Pot. Gradient $\triangle$ Force

**Observable:** quasi-momentum distribution
**Interband transitions: experiment**

Starting point: \( t=0 \)

\[ q_x \]
\[ q_y \]

\(~60.000\) spin-polarized \(^{40}\text{K}\) atoms

Non-interacting gas

Lowest band of a honeycomb lattice

\[ V_{X,X,Y} = (4.1, 0.28, 1.8)E_R \]

After a Bloch cycle: \( t=T_B \)

Transfer to 2\(^{\text{nd}}\) band at the position of the Dirac points

Energy resolution:

\[ \frac{E_{\text{res}}}{h} \sim 88 \text{ Hz} \]

\[ \frac{E_{\text{gap}}}{h} \sim 500 \text{ Hz} \]
Tuning the Dirac points

Dirac points with ultracold atoms

Tunability

- Mass
- Dirac point position
- Cone asymmetry

Breaking inversion symmetry

Control of sublattice energy offset

Experiment

Relative positioning $\theta$ of $X$ and $\bar{X}$ (detuning $\delta$)
Breaking inversion symmetry

\[ \xi = \frac{N(\square)}{N(\blacklozenge) + N(\blacklozenge)} \]

Higher band fraction

Tuning the mass of Dirac fermions

\[ \Delta/h = 390 \text{ Hz} \]
Position and anisotropy of Dirac cones

Adjusting the laser intensities $(V_X, V_\bar{X})$

- isotropic Dirac points
- fixed position
- anisotropic Dirac points
- different positions

Moving Dirac points

$V_X = 3.4 E_R$

$V_X = 4.0 E_R$

$V_X = 5.5 E_R$

$tune\ tunneling$

$V_{X,Y} = [0.28, 1.8] E_R$

Distance to B.Z. corner [$q_B$]

3.0 3.5 4.0 4.5 5.0 5.5

$V_X [E_R]$
Merging Dirac points

Dirac points → Topological Transition → No Dirac points

Lifshitz transition, Sov. Phys. JETP 11, 1130 (1960)
The topological transition

$V_Y = 1.8 \, E_R$

Transferred fraction $\xi$

0.0 0.1 0.2 0.3


Force along $x$

T.  D.  H.c.  1D c.
The topological transition

$V_Y = 1.8 \, E_R$

Transferred fraction $\xi$

Force along $y$
The topological transition

**Conclusion**

**Summary**

Optical lattice of tunable geometry
Probing Dirac points *via* interband transitions
Adjusting, moving and merging Dirac points
Mapping out the topological transition


**Outlook**

Detection of the Berry phase
Topologically ordered states
Combination of complex lattice geometries with interactions
The group

L. T.                Gregor Jotzu
Thomas Uehlinger    Daniel Greif
Tilman Esslinger
Cold atoms in Bordeaux

with Philippe Bouyer, Giorgio Santarelli, Baptiste Battelier

http://www.lp2n.institutoptique.fr/

PhD and post-doc positions open!