Light-induced new states of matter in solids: Prospects, concepts, and challenges

Michael A. Sentef
MPSD Theory Department
Driven is different

Kapitza pendulum

dynamical stabilization of a metastable state
Driven is different

\[
H(t)
\]

\[
H_{\text{eff}}
\]

dynamical stabilization of metastable states?
or even completely „new states“?
Outline

Prospects
Concepts
Floquet engineering in a nutshell
Link to time-resolved spectroscopy

Challenges

from model concepts to ab initio simulations

• Hannes Hübener
• Umberto de Giovannini
Propects of laser control

Exposing hidden states

Transmitent new states?

Possible light-induced superconductivity in K$_3$C$_{60}$ at high temperature

... and many more.

challenges. requires concepts. modeling + ab initio
Floquet engineering – buzz or useful?

Photonic Floquet topological insulators

Mikael C. Rechtsman, Julia M. Zeuner, Yonatan Plotnik, Yaakov Lumer, Daniel Podolsky, Felix Dreisow, Stefan Nolte, Mordechai Segev & Alexander Szameit

Affiliations | Contributions | Corresponding authors

Nature 496, 196–200 (11 April 2013) | doi:10.1038/nature12056
Received 17 December 2012 | Accepted 12 March 2013 | Published online 10 April 2013

Experimental realization of the topological Haldane model with ultracold fermions

Gregor Jotzu, Michael Messer, Rémi Desbuquois, Martin Lebrat, Thomas Uehlinger, Daniel Greif & Tilman Esslinger

Affiliations | Contributions | Corresponding author

Nature 515, 237–240 (13 November 2014) | doi:10.1038/nature13915
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Condensed Matter > Quantum Gases

Experimental reconstruction of the Berry curvature in a topological Bloch band


Featured in Physics | Editors’ Suggestion

Experimental Floquet Engineering of Correlated Tunneling in the Bose-Hubbard Model with Ultracold Atoms

F. Melnert, M. J. Mark, K. Lauber, A. J. Daley, and H.-C. Nägerl

See Synopsis: No Vacancy for Tunneling
Floquet engineering in a nutshell

time periodic system

\[ i \partial_t \psi = H(t) \psi \quad H(t) = H(t + T) \quad \Omega = 2\pi / T \]

“Floquet mapping”
= Bloch state in time

\[ \Psi(t) = e^{-i\varepsilon t} \sum_m \phi^m e^{-im\Omega t} \]

Floquet Hamiltonian (static eigenvalue problem)

\[ \sum_{m = -\infty}^{\infty} \mathcal{H}^{mn} \phi^m_{\alpha} = \varepsilon_{\alpha} \phi^n_{\alpha} \]

\( \varepsilon \): Floquet quasi-energy

\[ (\mathcal{H})^{mn} = \frac{1}{T} \int_0^T dt H(t) e^{i(m-n)\Omega t} + m\delta_{mn} \Omega I \]

\(~ absorption of \( m \) “photons”~)
Floquet spectrum: Dirac model + circularly polarized laser

Coupling to AC field

\[ k \rightarrow k + A(t) \]

\[ k = k_x + i k_y \]

\[ A(t) = \left( \frac{F}{\Omega} \cos \Omega t, \frac{F}{\Omega} \sin \Omega t \right) \]

\[ A = \frac{F}{\Omega} \]

time dependent Schrödinger equation

\[ i \partial_t \psi_k = \begin{pmatrix} 0 & k + A e^{i \Omega t} \\ \bar{k} + A e^{-i \Omega t} & 0 \end{pmatrix} \psi_k \]

\[ (\mathcal{H})^{mn} = \frac{1}{T} \int_0^T dt H(t) e^{i(m-n)\Omega t} + m \delta_{mn} \Omega I \]

\[ H^{\text{Floquet}} = \begin{pmatrix} \Omega & k & 0 & A & 0 & 0 \\ \bar{k} & \Omega & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & k & 0 & A \\ A & 0 & \bar{k} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\Omega & k \\ 0 & 0 & A & 0 & \bar{k} - \Omega \end{pmatrix} \]

truncated at m=0, +1, -1 for display
Floquet spectrum: Dirac model + circularly polarized laser

\[ H^{\text{Floquet}} = \begin{pmatrix}
\Omega & k & 0 & A & 0 & 0 \\
\bar{k} & \Omega & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & k & 0 & A \\
A & 0 & \bar{k} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -\Omega & k \\
0 & 0 & A & 0 & \bar{k} & -\Omega \\
\end{pmatrix} \]

0-photon absorbed state

0-photon absorbed state
Floquet spectrum: Dirac model + circularly polarized laser

\[ H^{\text{Floquet}} = \begin{pmatrix}
  \Omega & k & 0 & A & 0 & 0 \\
  \bar{k} & \Omega & 0 & 0 & 0 & 0 \\
  0 & 0 & 0 & k & 0 & A \\
  A & 0 & \bar{k} & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 & -\Omega & k \\
  0 & 0 & A & 0 & \bar{k} & -\Omega \\
\end{pmatrix} \]

1-photon absorbed state

0-photon absorbed state

1-photon absorbed state

0-photon absorbed state
Floquet spectrum: Dirac model + circularly polarized laser

$H^{\text{Floquet}} = \begin{pmatrix}
\Omega & \bar{k} & 0 & A & 0 & 0 \\
\bar{k} & \Omega & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \bar{k} & 0 & A \\
A & 0 & \bar{k} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -\Omega & k \\
0 & 0 & A & 0 & k & -\Omega \\
\end{pmatrix}$

1-photon absorbed state
0-photon absorbed state
-1-photon absorbed state

1-photon absorbed state
0-photon absorbed state
-1-photon absorbed state

TO, Aoki 2009
Floquet spectrum: Dirac model + circularly polarized laser

\[ H^{\text{Floquet}} = \begin{pmatrix}
\Omega & k & 0 & A & 0 & 0 \\
\bar{k} & \Omega & 0 & 0 & 0 & 0 \\
0 & 0 & k & 0 & A & 0 \\
A & 0 & \bar{k} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -\Omega & k \\
0 & 0 & A & 0 & \bar{k} & -\Omega \\
\end{pmatrix} \]

1-photon absorbed state

0-photon absorbed state

-1-photon absorbed state

TO, Aoki 2009

\[ F/\Omega = 0.2 \]

1-photon absorbed state

0-photon absorbed state

-1-photon absorbed state
Floquet spectrum: Dirac model + circularly polarized laser

$$H^{\text{Floquet}} = \begin{pmatrix} \Omega & k & 0 & A & 0 & 0 \\ \bar{k} & \Omega & 0 & 0 & 0 & 0 \\ 0 & 0 & k & 0 & A & 0 \\ A & 0 & \bar{k} & 0 & 0 & 0 \\ 0 & 0 & 0 & -\Omega & k & 0 \\ 0 & 0 & A & 0 & \bar{k} - \Omega & 0 \end{pmatrix}$$

1-photon absorbed state
0-photon absorbed state
-1-photon absorbed state

near Dirac point

2\kappa

Dirac gap

$$\kappa = \frac{\sqrt{4A^2 + \Omega^2} - \Omega}{2} \sim A^2/\Omega$$

1-photon absorbed state
0-photon absorbed state
-1-photon absorbed state

TO, Aoki 2009
Dirac fermion + circularly polarized laser

Mass term = energy gap = synthetic field stemming from a real time-dependent field $A(t)$

$H_{\text{eff}} = H_0 + \frac{\sim A\sigma_- \sim A\sigma_+}{\Omega} \left[ H_{-1}, H_1 \right] + O(A^4)$

Oka and Aoki,
PRB 79, 081406 (2009)
Observation of Floquet-Bloch States on the Surface of a Topological Insulator

Y. H. Wang,* H. Steinberg, P. Jarillo-Herrero, N. Gedik†

$\text{Bi}_2\text{Se}_3$

Science 342, 453 (2013)
Floquet-Bloch states in model graphene

Time-resolved ARPES during 1.5 eV circularly polarized laser pulse

binding energy in eV

Gamma

K

M

momentum

A = 4.12179e-05
Floquet topological states in model graphene

Time-resolved ARPES during 1.5 eV laser pulse

- Circularly polarized laser induces energy gap, eventually gap closing (topological transition)
- Good agreement with Floquet band structure
- Should be measurable in principle (challenge to experiments 😊)
Another prospect

hypothetical high-Tc superconductor: solid hydrogen

can it be engineered with a (Floquet?) laser potential? how?
Summary

• Floquet states: engineering of fictitious gauge fields with real laser fields in solids
• laser control of topological states of matter
• examples: 2D Floquet model graphene (this talk), 3D Floquet Dirac semimetal (H. Hübener‘s talk), transition metal dichalcogenides (U. de Giovannini‘s talk)
Challenges (= ongoing and future work)

- Floquet theory provides a useful language in a specific limit (continuous driving). How far does it carry for real pump-probe experiments?
- Floquet states versus transient relaxation dynamics
- Realistic laser pulses: how big are the effects?
- Stabilization of light-induced states after the pulse?

from model concepts to ab initio simulations

Hannes Hübener  Umberto de Giovannini  Alexander Kemper  Angel Rubio  
(NC State)
Floquet Weyl

ab initio Floquet bandstructure: Weyl semimetal

Hannes Hübener’s talk right now
time-resolved ARPES

- td-ARPES

Umberto de Giovannini (tomorrow)
We bring together a diverse group of young researchers working in the field of strongly correlated electrons to foster the exchange of ideas and stimulate new research directions. This conference focuses on state of the art and new techniques in theoretical and experimental understanding and control of strongly correlated models and materials.

FOCUS TOPICS

- Nonequilibrium quantum dynamics in correlated systems
- Strong correlations in topological insulators and spin-orbit coupled systems
- First principles correlated electronic structure: from micro to macro world
- Strongly correlated magnetism

INVITED SPEAKERS

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- Paola di Pietro (Elettra, Trieste)
- Laura Fanfarillo (CNR-IOM, Trieste)
- Tom Fennell (PSI, Villingen)
- John Goold (ICTP, Trieste)
- Franziska Hammerath (IFW, Dresden)
- Eilif Janson (TU Wien)
- Mathieu Le Tacon (MPIPKS, Stuttgart)
- Matteo Mitrano (University of Illinois UC)
- Marco Majetti (ESRF, Grenoble)
- Yusuke Nomura (Ecole Polytechnique, Palaiseau)
- Suchitra Sebastian (Cambridge University)
- Lev Vidmar (Penn State University)
- Simon Wall (ICFO, Barcelona)
- Cedric Weber (King’s College, London)

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DATES

June 15: Abstract submission
July 1: Acceptance notification
July 15: Early bird registration
September 1: Final registration

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