Light-matter engineering of topology in quantum materials


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QDev Summer School
Copenhagen, July 7-8, 2022

Funded through DFG Emmy Noether programme (SE 2558/2)

Notes for these lectures: cf. https://lab.sentef.org/teaching/
Before I start …

Welcome

Virtual Science Forum is a volunteer-run open platform aiming to host academic events. Additionally, we develop best practices and provide recom

What we do

We offer beginning-to-end support for organizing an academic event:

- We provide a minimal effort platform for making an event possible
- We announce the events to our mailing list of currently around 672 subscribers
- We provide advice, technical support, and a collection of best practices

Check out the organizer guide to see what it takes. We have host stories from organizers, biweekly tips, and technical support. We promise allowing a more welcoming, equitable online environment for all across the spectrum of identities and lived experiences. We encourage participation, either as speakers, organizers or audience, of all members of the scientific community.
Outline of lectures

1 - Intro
   Pump-probe spectroscopy
   Floquet theory in a nutshell
   Dirac fermion with circularly polarized laser
   Floquet topology across platforms
   Floquet sidebands in time-resolved photoemission
   Light-induced anomalous Hall effect

   Exercise 1— Gap opening in circularly driven Dirac fermions I: Discrete time evolution

2 - Floquet concepts

   Exercise 2— Gap opening in circularly driven Dirac fermions II: Floquet

3 - From Floquet to cavity
Can we employ light-matter interactions to change materials properties?

\[ \alpha = \frac{1}{4\pi\varepsilon_0} \frac{e^2}{\hbar c} = \frac{\mu_0}{4\pi} \frac{e^2 c}{\hbar} = \frac{\kappa c e^2}{\hbar c} = \frac{e^2}{2\varepsilon_0 c h} = \frac{c\mu_0}{2\Re} = \frac{e^2 Z_0}{2\hbar} = \frac{e^2 Z_0}{4\pi\hbar} \]

- vacuum: \( g = \alpha \)
- strong laser driving
- nonthermal quantum materials
- Floquet engineering
- cavity quantum materials
- light-matter strong coupling
- many-body groundstates
- light-matter coupling strength
Stroboscopic investigations of dynamic phenomena

employ time-resolved pump-probe spectroscopy to investigate dynamic phenomena on their intrinsic time and energy scales
Stroboscopic investigations of dynamic phenomena

employ time-resolved pump-probe spectroscopy to investigate dynamic phenomena on their intrinsic time and energy scales

Image source: FHI Berlin
Can one engineer the Haldane model dynamically?

Graphene + circularly polarized light (breaks trs)

Haldane model (PRL 61, 2015 (1988))

Local flux $\phi$
Staggered field $m$
Fictitious fields!
Kapitza pendulum: dynamical stabilization of metastable state
Floquet theory in a nutshell (more details later)

time periodic system

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

= discrete Fourier trans.

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

Floquet Hamiltonian (static eigenvalue problem)

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

\( \varepsilon_\alpha \): Floquet quasi-energy

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

comes from the \( i\partial_t \) term

\[ H_m = \mathcal{H}^{m0} \]

\~ absorption of \( m \) “photons”
Dirac fermion with circularly polarized laser

**Coupling to AC field**

\[ \mathbf{k} \rightarrow \mathbf{k} + \mathbf{A}(t) \]

\[ \mathbf{k} = k_x + i k_y \]

\[ \mathbf{A}(t) = \begin{pmatrix} F/\Omega \cos \Omega t, & F/\Omega \sin \Omega t \end{pmatrix} \]

\[ A = F/\Omega \]

**Time dependent Schrödinger equation**

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

**Floquet theory**

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

**Floquet Hamiltonian**

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

truncated at m=0, +1, -1 for display
Dirac fermion with circularly polarized laser

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

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

Dirac fermion with circularly polarized laser

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

sign of mass term determined by chirality of light

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

Haldane, PRL 61, 2015 (1988)


Oka and Aoki, PRB 79, 081406 (2009)
Floquet topology across platforms

Photonic Floquet topological insulators
M. Rechtsman et al., Nature 496, 196 (2013)

Haldane model with ultracold fermions

review:
Floquet sidebands in materials

Prediction for graphene …
Floquet sidebands in materials

... observation in 3D topological insulator surface 2D Dirac fermions

What about observing Floquet states in time-resolved photoemission of graphene?

Ongoing challenge to overcome decoherence and dissipation

e.g., Aeschlimann et al., Nano Lett. 21, 5028 (2021)
Light-induced anomalous Hall effect


T. Oka & H. Aoki, PRB (2009)
Femtosecond science on-chip
Light-induced anomalous Hall effect

(a) $I_{\gamma}[C_{\gamma}-C]$ (µA)
-15
-10
-5
0
5
10
15

Time (ps)
-20
0
20
40
60

$V_y = +0.6 \text{ V}$

$V_y = -0.6 \text{ V}$

(b) $I_{\gamma}[C_{\gamma}-C]$ (µA)
-90
-60
-30
0
30
60
90

Time (ps)
-20
0
20
Light-induced anomalous Hall effect

Light-induced anomalous Hall effect

- a light-induced Hall effect without applying magnetic field
- has the right symmetries (changing from right-handed to left-handed light changes the sign)
- Hall conductance at strong laser fluence approaches a value consistent with $2e^2/h$
- shows peaks and dips reminiscent of Floquet-induced gaps as a function of chemical potential
- … are these really Floquet topology effects?

Theory: yes but there are also population imbalance contributions
Summary part I

- Floquet theory as a basis to understand dynamics in periodically driven systems
- Floquet topological insulator: induce the nontrivial Haldane mass term with circularly polarized light
- Time-resolved photoemission spectroscopy and ultrafast (femtosecond) transport as efficient experimental probes of light-induced states of matter
II Floquet concepts

[whiteboard]
III From Floquet to cavity