Light-matter engineering of topology in quantum materials



Colloquium: Nonthermal pathways to ultrafast control in quantum materials, A. de la Torre, D. M. Kennes, M. Claassen, S. Gerber, J. McIver, MAS, Rev. Mod. Phys. 93, 041002 (2021)



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Cavity Quantum Materials, F. Schlawin, D. M. Kennes, MAS, Applied Physics Reviews 9, 011312 (2022)

Michael A. Sentef

QDev Summer School Copenhagen, July 7-8, 2022

Notes for these lectures: cf. https://lab.sentef.org/teaching/



Before I start ...



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Outline of lectures

I - 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

2 - Floquet concepts

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

3 - From Floquet to cavity

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



Can we employ light-matter interactions to change materials properties?

laser driving strength / photon numbe



Article Talk

WIKIPEDIA The Free Encyclopedia

Fine-structure constant

From Wikipedia, the free encyclopedia

$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c} = \frac{\mu_0}{4\pi}\frac{e^2c}{\hbar} = \frac{k_{\rm e}e^2}{\hbar c} = \frac{e^2}{2\varepsilon_0ch} = \frac{c\mu_0}{2R_{\rm K}} = \frac{e^2Z_0}{2h} = \frac{e^2Z_0}{4\pi\hbar}$$



strong laser driving

nonthermal quantum materials, **Floquet engineering**



many-body groundstates

light-matter strong coupling

vacuum: $g = \alpha$

light-matter coupling strength

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Stroboscopic investigations of dynamic phenomena



Muybridge 1887



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



Stroboscopic investigations of dynamic phenomena



Image source: FHI Berlin



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



Can one engineer the Haldane model dynamically?

Graphene + circularly polarized light (breaks trs) Haldane model (PRL 61, 2015 (1988))





Local flux φ Staggered field *m* Fictitious fields!









Kapitza pendulum: dynamical stabilization of metastable state







Floquet theory in a nutshell (more details later)

time periodic system

$$i\partial_t\psi = H(t)\psi$$

=discrete Fourier trans.

Floquet Hamiltonian (static eigenvalue problem)

$$\sum_{m=-\infty}^{\infty}\mathcal{H}^{mn}\phi^m_\alpha=\varepsilon_\alpha\phi^n_\alpha\qquad \text{s: Floquet quasi-energy}$$

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

 $H_m = \mathcal{H}^{m0}$

$$H(t) = H(t+T) \qquad \Omega = 2\pi/T$$

$$t) = e^{-i\varepsilon t} \sum_{m} \phi^{m} e^{-im\Omega t}$$

comes from the $i\partial_t$ term ~ absorption of *m* "photons"



Dirac fermion with circularly polarized laser



coupling to AC field

time dependent Schrödinger equation

 $i\partial_t\psi_k = \Big(\bar{k} +$

Floquet theory



Oka & Aoki, Phys. Rev. B 79, 081406(R) (2009) Kitagawa et al., Phys. Rev. B 82, 235114 (2010)

 $\boldsymbol{k} \rightarrow \boldsymbol{k} + \boldsymbol{A}(t)$

$$k = k_x + ik_y$$

$$A(t) = (F/\Omega \cos \Omega t, F/\Omega \sin \Omega t)$$

$$A = F/\Omega$$

$$\begin{array}{c} 0 & k + A e^{i\Omega t} \\ A e^{-i\Omega t} & 0 \end{array} \right) \psi_k$$

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

$$\begin{bmatrix} 0 & 0 & 0 - \Omega & k \\ 0 & A & 0 & \bar{k} - \Omega \end{bmatrix}$$

 $k-\Omega$) truncated at m=0,+1, -1 for display

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Dirac fermion with circularly polarized laser



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

Oka & Aoki, Phys. Rev. B 79, 081406(R) (2009) Kitagawa et al., Phys. Rev. B 82, 235114 (2010)



0-photon absorbed state

-1-photon absorbed state

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Dirac fermion with circularly polarized laser





Oka & Aoki, Phys. Rev. B 79, 081406(R) (2009) Kitagawa et al., Phys. Rev. B 82, 235114 (2010)

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

sign of mass term determined by chirality of light

Haldane, PRL 61, 2015 (1988)



Oka and Aoki, PRB 79, 081406 (2009)

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Floquet topology across platforms

Photonic Floquet topological insulators

M. Rechtsman et al., Nature 496, 196 (2013)



Haldane model with ultracold fermions

G. Jotzu et al., Nature 515, 237 (2014)



review:

M. Rudner and N. Lindner, Nat. Rev. Phys. 2, 229 (2020)

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Floquet sidebands in materials



MAS et al., Nature Communications 6, 7047 (2015)

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Floquet sidebands in materials

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



Y. H. Wang et al., Science 342, 453 (2013) F. Mahmood et al., Nature Physics 12, 306-310 (2016) [Nuh Gedik group at MIT]

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)

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Light-induced anomalous Hall effect



T. Oka & H. Aoki, PRB (2009)

J.W. McIver et al., Nature Physics 16, 38-41 (2020)



Floquet-engineered Haldane Model Kitagawa *et al.* PRB (2011)



Graphene

+0

0



Femtosecond science on-chip



J.W. McIver et al., Nature Physics 16, 38-41 (2020)



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J.W. McIver et al., Nature Physics 16, 38-41 (2020)

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J.W. McIver et al., Nature Physics 16, 38-41 (2020)

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observations:

- 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 (S.A. Sato et al., Phys. Rev. B 99, 214302 (2019))

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Summary part I





- Floquet theory as a basis to understand dynamics in periodically driven systems
- experimental probes of light-induced states of matter

• Floquet topological insulator: induce the nontrivial Haldane mass term with circularly polarized light • Time-resolved photoemission spectroscopy and ultrafast (femtosecond) transport as efficient



Il Floquet concepts

[whiteboard]



III From Floquet to cavity



[whiteboard]

