Light-induced states of matter
from Floquet engineering to cavity materials

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Engineering materials with light

**condensed matter**
quantum materials
atomic-scale control

Y. Cao et al., Nature 556, 43 (2018)

**nonequilibrium materials engineering**

R. Chikkaraddy et al., Nature 535, 127 (2016)

**ultrafast spectroscopy**
revealing elementary couplings
light-induced new states of matter

Image courtesy: J. Sobota

**pump-probe: strong classical fields**

Y. Cao et al., Nature 556, 43 (2018)

**quantum optics**
nanoplasmonics
polaritonic chemistry

QED: vacuum fluctuations

Max Planck Institute for the Structure and Dynamics of Matter
Outline

1. Floquet engineering
   coherent laser driving can induce topology
   
   M. A. Sentef et al., Nat. Commun. 6, 7047 (2015)
   H. Hübener et al., Nat. Commun. 8, 13940 (2017)
   G. E. Topp et al., PRResearch 1, 023031 (2019)

2. Cavity engineering
   light-induced topology from pure vacuum fluctuations of light
   
   cavity superconductivity
   

3. Cavity to Floquet crossover
   strong light-matter coupling: Floquet effects without coherence
   
   M. A. Sentef, J. Li, F. Künzel, M. Eckstein, PRResearch 2, 033033 (2020)
1. Floquet engineering
Floquet states of matter

by Koichiro Tanaka (Kyoto university)

electrons in solids

Floquet state (photo-dressed state)

\[ H \]

\[ H_{\text{eff}} = H_0 + \frac{[H_{-1}, H_1]}{\Omega} + \mathcal{O}(\Omega^{-2}) \]
Floquet states of matter

time periodic system

\[ i \partial_t \psi = H(t) \psi \]

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

“Floquet mapping”
=discrete Fourier trans.

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

Floquet Hamiltonian (static eigenvalue problem)

\[ \sum_{m=-\infty}^{\infty} \mathcal{H}^{mn} \phi^m_{\alpha} = \varepsilon_{\alpha} \phi^n_{\alpha} \quad \varepsilon: \text{Floquet quasi-energy} \]

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

comes from the \( i \partial_t \) term

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

~ absorption of \( m \) “photons”
### Floquet states of matter

**Time-periodic quantum system**

\[ i \partial_t \psi = H(t) \psi \]

\[ H(t) = H(t + T) \]

**Floquet theory (exact)**

\[ \mathcal{H} \phi = \varepsilon \phi \]

**Effective theory**

\[ H_{\text{eff}} = H_0 + \frac{[H_{-1}, H_1]}{\Omega} + \mathcal{O}(\Omega^{-2}) \]

**Fictitious fields!**

projection to the original Hilbert space

**Hilbert space size**

\[ = \text{original system} \]

**Two states + periodic driving**

\[ \Omega \]

\[ \Delta \]

\[ n\text{-photon dressed state} \]

Floquet side bands
Dirac fermion + circularly polarized laser

coupling to AC field

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

\[ k = k_x + ik_y \]
\[ A(t) = (F/\Omega \cos \Omega t, F/\Omega \sin \Omega t) \]
\[ A = F/\Omega \]

time dependent Schrödinger equation

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

Floquet theory

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

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

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

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

1-photon absorbed state
0-photon absorbed state
-1-photon absorbed state
Dirac fermion + circularly polarized laser

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

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

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

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

Oka and Aoki, PRB 79, 081406 (2009)
Dirac fermion + circularly polarized laser

Projection to the original Hilbert space near Dirac point

\[ H_{\text{eff}} = H_0 + \frac{[H_{-1}, H_1]}{\Omega} + \mathcal{O}(A^4) \]

Dynamical gap

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

2nd order perturbation

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

\[ \sim v \left( k_x \sigma_y - \tau_z k_y \sigma_x \right) \pm \frac{v^2 A^2}{\Omega} \sigma_z \]

\( A = F/\Omega \)
... but many more theory Floquet proposals than experiments in materials. Issues:
- need for strong lasers
- need for coherence
- detrimental heating effects
possible resolution: *cavities* (next part of talk)
2. Cavity engineering
Recent years: Placing atoms and molecules in cavities shown to sometimes dramatically change their properties and chemical reactions. Scientists talk about „light-matter (collective) strong coupling“.

Higher enhancements. Another direction is to check physical phenomena that are sensitive to phonon energy. Metal—insulating and superconducting transitions for instance might be significantly modified under strong coupling.

Changing the vacuum changes the matter!

J. Feist et al., ACS Photonics 5, 205 (2017)
R. F. Ribeiro et al., Chem. Sci. 9, 6325 (2018)
J. Flick et al., Nanophotonics 7, 1479 (2018)
From classical to quantum light

**collective strong light-matter coupling**
when many atoms interact with the same cavity photon mode

cavity materials: many atoms interact with the same modes

R. Chikkaraddy et al., Nature 535, 127 (2016)
Cavity-induced topology

Cavity-induced quantized anomalous Hall effect in graphene
X. Wang et al., PRB 99, 235156 (2019)
Dirac fermion in cavity

X. Wang et al., PRB 99, 235156 (2019)

Dirac cone couples to cavity modes:

\[ \gamma(\vec{k} - \hat{A}) \rightarrow \hbar v_F (k_x + i k_y - \sqrt{2} A_0 a^\dagger) \]

\[
H = \sum_{\vec{k}} \left( \begin{array}{c} c_{A,\vec{k}}^\dagger \\ c_{B,\vec{k}}^\dagger \end{array} \right)^T \begin{pmatrix} 0 & \gamma(\vec{k} - \hat{A}) \gamma(\vec{k} - \hat{A})^\dagger \\ \omega_{\lambda} & 0 \end{pmatrix} \left( \begin{array}{c} c_{A,\vec{k}} \\ c_{B,\vec{k}} \end{array} \right) + \sum_{\lambda} \omega_{\lambda} a_{\lambda}^\dagger a_{\lambda},
\]

\[ \hat{A} = A_0 \sum_{\lambda} (\tilde{\epsilon}_{\lambda} a_{\lambda} + \tilde{\epsilon}_{\lambda}^* a_{\lambda}^\dagger) \]

\[ A_0 = \sqrt{\hbar/(\epsilon \epsilon_0 V \omega)} \]

cavity coupling controlled by mode volume V, dielectric environment \( \epsilon \), and mode frequency \( \omega \)

exchange of virtual photons with the cavity vacuum
Using a right-handed circularly polarized cavity reduces the photon field to a single branch with $\bar{e}_\lambda \equiv \bar{e}$, operators $a^\dagger_\lambda \equiv a^\dagger$, and frequency $\omega_\lambda \equiv \omega$, with unit polarization vector $\hat{e} = \frac{1}{\sqrt{2}} (1, i)$. In this case, $\gamma (\vec{k} - \vec{A}) \to \hbar v_F (k_x + ik_y - \sqrt{2}A_0 a^\dagger)$

band renormalization due to electron-photon self-energy

$$\Sigma_{0,aa}^R (\vec{k} = 0, \epsilon) = \frac{g^2 / 2}{\epsilon + i0^+ - \omega},$$

$$\Sigma_{0,bb}^R (\vec{k} = 0, \epsilon) = \frac{g^2 / 2}{\epsilon + i0^+ + \omega},$$

$g \equiv v_F A_0 \sqrt{2}$
Dirac fermion in cavity

X. Wang et al., PRB 99, 235156 (2019)

Energy gap at Dirac point:

\[ \Delta = \sqrt{2g^2 + \omega^2} - \omega. \]

In the limit \( 2g^2/\omega^2 \ll 1 \), we obtain

\[ \Delta \approx \frac{g^2}{\omega} = \frac{2\hbar^2 v_F^2 A_0^2}{\omega} \]

... looks like Floquet result but different interpretation of \( A_0 \):
- Floquet = classical limit: \( A_0 \) is the laser field amplitude
- dark cavity = quantum limit: \( A_0 \) is the amplitude of quantum fluctuations
energy gap and photon sidebands, controlled by light-matter coupling strength
quantized light-induced Hall conductance at low temperatures, controlled by cavity geometry
Cavity superconductivity?

Cavity quantum-electrodynamical polaritonically enhanced electron-phonon coupling and its influence on superconductivity


Exploring Superconductivity under Strong Coupling with the Vacuum Electromagnetic Field arXiv:1911.01459

A. Thomas¹, E. Devaux¹, K. Nagarajan¹, T. Chervy¹, M. Seidel¹, D. Hagenmüller¹, S. Schütz¹, J. Schachenmayer¹, C. Genet¹, G. Pupillo¹ & T. W. Ebbesen¹*

suggested enhanced electron-phonon coupling due to polariton formation and mode softening
3. Cavity to Floquet crossover
Motivation: Ultrafast and reversible control of exchange interaction with classical field

*Mentink, Balzer, and Eckstein, Nat. Commun. 6, 6708 (2015)*

What about the cavity limit? Can we investigate the crossover?
Cavity to Floquet crossover

M. A. Sentef, J. Li, F. Künzel, M. Eckstein, PRResearch 2, 033033 (2020)

Quantum system -> Floquet system for (large photon number, weak light-matter coupling strength $g$)

Photon number states are good enough to see Floquet-engineering effects at sufficiently large coupling strength – coherent states not required!
Driven cavity

M. A. Sentef, J. Li, F. Künzel, M. Eckstein, PRResearch 2, 033033 (2020)
Driven cavity

M. A. Sentef, J. Li, F. Künzel, M. Eckstein, PRResearch 2, 033033 (2020)

Time-resolved spin susceptibility in resonantly driven cavity (peak position \( \sim J_{\text{ex}} \))

\( J_{\text{ex}} \) always reduced by vacuum fluctuations
- blue-detuned: \( J_{\text{ex}} \) further reduced by driving;
- red-detuned: \( J_{\text{ex}} \) enhanced by driving
**Floquet engineering without macroscopic laser fields**

*M. A. Sentef, J. Li, F. Künzel, M. Eckstein, PRResearch 2, 033033 (2020)*

At fixed photon number, Floquet limit is reached as the light-matter coupling strength is increased!

**Note:**

photon number states have zero macroscopic field

-> coherence is not required at sufficiently strong coupling!
Floquet topological magnons


also see: Claassen et al., Nat. Commun. 8, 1192 (2017); Kitamura et al., PRB 96, 014406 (2017); Owerre, Journal of Physics Communications 1, 021002 (2017)

Light-induced scalar spin chirality in 2D honeycomb magnets

\[ \mathcal{H} = \sum_{\langle ij \rangle} J_{ij} \hat{S}_i \cdot \hat{S}_j + \sum_{\langle\langle ik \rangle\rangle} J'_{ik} \hat{S}_i \cdot \hat{S}_k + \sum_{\langle\langle ik \rangle\rangle} \chi_{ik} \hat{S}_j \cdot (\hat{S}_i \times \hat{S}_k). \]

Floquet topological magnon edge states
Summary

1. **Floquet engineering**
   
   coherent laser driving can induce topology
   
   *M. A. Sentef et al., Nat. Commun. 6, 7047 (2015)*
   *H. Hübener et al., Nat. Commun. 8, 13940 (2017)*
   *G. E. Topp et al., PRResearch 1, 023031 (2019)*

2. **Cavity engineering**
   
   light-induced topology from pure vacuum fluctuations of light
   
   *X. Wang, E. Ronca, M. A. Sentef, PRB 99, 235156 (2019)*

   cavity superconductivity
   
   *M. A. Sentef, M. Ruggenthaler, A. Rubio, Science Advances 4, eaau6969 (2018)*

3. **Cavity to Floquet crossover**
   
   strong light-matter coupling: Floquet effects without coherence
   
   *M. A. Sentef, J. Li, F. Künzel, M. Eckstein, PRResearch 2, 033033 (2020)*
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Thank you for your kind attention!