Cavity quantum materials


Cavity control of Hubbard model
MAS, J. Li, F. Künzel, M. Eckstein,
PRResearch 2, 033033 (2020)

Light-matter coupling and quantum geometry in moiré materials,
G. E. Topp, C. J. Eckhardt, D. M. Kennes, MAS,
P. Törmä, arXiv:2103.04967

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Max Planck-New York Center for Nonequilibrium Quantum Phenomena

https://www.simonsfoundation.org/flatiron/center-for-computational-quantum-physics/
key importance of nonequilibrium for life

key importance of light-matter interactions for ...

photosynthesis
- light
- carbon dioxide
- water
- oxygen
- carbohydrates

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

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

Can we employ light-matter interactions to change materials properties?
Optical control of quantum materials

Light-induced superconductivity
D. Fausti et al. Science (2011)

Metastable hidden phases

Photo-induced phase transitions
C. Kübler et al. PRL (2007)
M. K. Liu et al. PRL (2011)

Band structure engineering

Ferroelectric switching
R. Mankowsky et al. PRL (2017)
Li et al. Science (2019)

Ultrafast magnetism
Colloquium: Nonthermal pathways to ultrafast control in quantum materials

We review recent progress in utilizing ultrafast light-matter interaction to control the macroscopic properties of quantum materials. Particular emphasis is placed on photoinduced phenomena that do not result from ultrafast heating effects but rather emerge from microscopic processes that are inherently nonthermal in nature. Many of these processes can be described as transient modifications to the free-energy landscape resulting from the redistribution of quasiparticle populations, the dynamical modification of coupling strengths and the resonant driving of the crystal lattice. Other pathways result from the coherent dressing of a material’s quantum states by the light field. We discuss a selection of recently discovered effects leveraging these mechanisms, as well as the technological advances that led to their discovery. A road map for how the field can harness these nonthermal pathways to create new functionalities is presented.
Dynamical phase transitions in quantum magnets

Dynamical critical behavior in optically pumped 214 iridate
de la Torre et al., unpublished

Noninteracting-magnon theory of a driven-dissipative phase transition:

[N. Walldorf et al. Phys. Rev. B 100, 121110(R) (2019)]

Driving Amplitude E

Distribution of Spin waves n(ω_q)

E > E_{crit}:

n diverges faster than ω_q^{-1}

superthermal Magnons

E < E_{crit}

n diverges as \frac{T_{eff}}{ω_q}

\frac{T_{eff}}{ω_q} = 0.6

Max Planck Institute for the Structure and Dynamics of Matter
Dynamical phase transition in 2D Heisenberg AFM

\[ \mathcal{H}_{XXZ} = J \sum_{\langle ij \rangle} \left\{ \frac{1}{2} \left( S_i^+ S_j^- + S_i^- S_j^+ \right) + \Delta S_i^z S_j^z \right\} \rightarrow \mathcal{H} = E_0 + H_0 + V \]

- **\( E_0 \)**: Ground State Energy
- **\( H_0 = \hbar \sum_k \omega_k \left( \alpha_k^\dagger \alpha_k + \beta_k^\dagger \beta_k \right) \)**: Bilinear Hamiltonian
- **\( V \)**: Magnon Interactions

**Nonlinear kinetic equation** for noninteracting magnons:

\[ \partial_t n = g_{\text{in}} (1 + n) - \gamma_{\text{out}} \left( n + \left( \frac{n}{n_{\text{F}}(\omega)} \right)^2 \right) \]

with \( g = \frac{g_{\text{in}}}{\gamma_{\text{out}}} \)

**Dynamical Critical Point** \( g = 1 \)

- \( g > 1 \) \( \rightarrow \) \( n(\omega) \) diverges faster than \( 1/\omega \)
- \( g < 1 \) \( \rightarrow \) \( n(\omega) \) is finite for all \( \omega \)
- \( g = 1 \) Thermal Distribution at temperature \( T \)

**Interacting theory:**

Magnon-magnon scattering at semiclassical Boltzmann level

**Summary**

- \( g > 1 \) \( \rightarrow \) Diverges faster than \( \frac{1}{\omega} \)
- \( g = 1 \) Bose-Einstein distribution \( n_{\text{th}}(T, \omega) \)
- \( g < 1 \) \( \rightarrow \) Finite Occupation

**Magnon-magnon scattering:** Stronger divergence in superthermal phase \( g > 1 \)
Dynamical phase transition in 2D Heisenberg AFM

magnon-magnon scattering: stronger divergence in superthermal phase $g>1$; finite size scaling analysis: thermal + $\delta$-function at $\omega=0$ in thermodynamic limit

**Tentative nonthermal phase diagram**

- Superthermal (thermal + $\delta$)
- Disordered subthermal
- Ordered subthermal
- Thermal line
- Disordered superthermal (thermal + $\delta$)
- Ordered superthermal (thermal + $\delta$)
- Critical end point

**Static and dynamic criticality at $g=1$**

- $g=0.5$
- $g=1$
- $g=0.95$
- $g=1.05$
- $g=1.5$

**Number of magnons, $N_m$**

- Interacting
- Noninteracting

**Energy, $\varepsilon$**

- Subthermal
- Thermal distribution
- Superthermal

**Decay Rate $\Delta N_c [J/\hbar]$**

- $\ell = 120$
- $\ell = 100$
- $\ell = 80$

**Dynamical phase transition in a driven-dissipative Heisenberg antiferromagnet**

Dynamics with neural quantum states (NQS)

Role of generalization error in the dynamics of neural quantum states

trace numerical instability to overfitting of MC noise diagnosed by validation error

Also cf. Long Range Colloquium on May 28 by Giuseppe Carleo

https://www.netket.org/
Floquet engineering of quantum materials

Rudner & Lindner, Nat. Rev. Phys. 2020

Floquet engineering of spin exchange
Mentink, Balzer, and Eckstein, Nat. Commun. 6, 6708 (2015)

(a) Equilibrium
(b) Band engineering
Topological invariants
Excitons
Magnetism
Fractional quantum Hall
Superconductivity

Optically dressed

Photon dressing of intermediate states modifies kinetic exchange

Question: can we control spin exchange with cavities?
Answer: yes, if we replace strong fields by strong light-matter coupling

But: need for strong lasers, problems with heating, short-lived effect

Michael Sentef — Max Planck Institute for the Structure and Dynamics of Matter
QED quantum materials: strong light-matter coupling

Polaritonic chemistry
J. Feist et al., ACS Photonics 5, 205 (2017)
R. F. Riceiro et al., Chem. Sci. 9, 6325 (2018)
J. Flick et al., Nanophotonics 7, 1479 (2018)

Our work: cavity control of spin exchange
Crossover from quantum to classical Floquet engineering

Quantum materials: towards cavity-controlled electron-boson coupling, superconductivity

Polaritons: quantum-electrodynamic polaritonically enhanced electron-phonon coupling and its influence on superconductivity

QED quantum materials: quantum to classical crossover

Hubbard model in cavity

Quantum system -> Floquet system for \( n \to \infty, \ g/\sqrt{n} \text{ fixed} \)

(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 \( g \) – coherent states not required!

Question: can we control spin exchange with cavities?
Answer: yes, if we replace strong fields by strong light-matter coupling

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M.A. Sentef, J. Li, F. Künzel, M. Eckstein,
PRResearch 2, 033033 (2020)
QED quantum materials: how to reach strong coupling?

Non-trivial quantum geometry enables light-matter coupling in flat bands

Can we reach strong light-matter coupling by quenching electronic kinetic energy?

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G. E. Topp, C. J. Eckhardt, D. M. Kennes, M. A. Sentef, P. Törmä,
arXiv:2103.04967

Also cf. Iskin PRA 2019;
Ahn, Guo, Nagaosa, Viswanath arXiv 2021
Quantum chain in cavity

\[ H = \Omega \left( a^\dagger a + \frac{1}{2} \right) - \sum_i t_0 e^{i g(a^\dagger a)} c^\dagger_{i+1} c_i + \text{h.c.} \]

\[ = \Omega \left( a^\dagger a + \frac{1}{2} \right) + \cos(g(a^\dagger + a)) \hat{T} + \sin(g(a^\dagger + a)) \hat{J} \]

\[ \hat{T} = \sum_k -2t_0 \cos(k) c^\dagger_k c_k \quad \text{kinetic energy} \]

\[ \hat{J} = \sum_k 2t_0 \sin(k) c^\dagger_k c_k \quad \text{current} \]

Electronic spectral function

Photon wavefunction is a squeezed state

\[ P(n) \]

\[ \Delta p/\Delta x \]

\[ n_{\text{ph}} \]

quantum to classical crossover of Floquet shakeoff peaks in ARPES signal

An exactly solvable model for a quantum chain in a cavity

C. J. Eckhardt, G. Passetti, M. Othman, C. Karrasch, F. Cavaliere, M. A. Sentef, D. M. Kennes, \textit{in prep.}

Christian Eckhardt  Giacomo Passetti  Moustafa Othman  Dante Kennes
Summary

Dynamical phase transition in a driven-dissipative Heisenberg antiferromagnet

Role of generalization error in the dynamics of neural quantum states

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An exactly solvable model for a quantum chain in a cavity

Colloquium: Nonthermal pathways to ultrafast control in quantum materials,
Looking for PhD students

next IMPRS-UFAST call expected to open in September 2021

get in touch anytime if interested

https://lab.sentef.org
michael.sentef@mpsd.mpg.de

This could be your PhD topic:
• moiré cavity dynamics with neural quantum states
• cavity Kitaev materials
• dynamical correlations in 2D materials
• quantum-geometric light-matter coupling in moiré TMDs
• … [insert your research idea here]