Probing the ground state of Landau polaritons with transport and ultrafast field measurements

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Engineering the vacuum via cavities

**Casimir effect**

**Light-matter coupling (weak)**

\[ \Omega = d \times E_{\text{vac}} / \hbar \]

**Mathematics.** — *On the attraction between two perfectly conducting plates.* By H. B. G. CASIMIR.

(Communicated at the meeting of May 29, 1948.)

Strong light-matter coupling

\[ H = \hbar \omega_{cav} a^\dagger a + \hbar \omega_c b^\dagger b \]
\[ + i\hbar \Omega(a^\dagger b - ab^\dagger) \]

Ultra-strong light-matter coupling (Hopfield model)

\[ H = \hbar \omega_{cav} a^\dagger a + \hbar \omega_c b^\dagger b \]
\[ + i \hbar \Omega (a^\dagger b - ab^\dagger) + D(a^\dagger a + aa^\dagger) \]
\[ + i \hbar \Omega (ab - a^\dagger b^\dagger) + D(aa + a^\dagger a^\dagger) \]


Vacuum Rabi frequency \( \Omega \)

anti-resonant and diamagnetic terms
Ultra-strong light-matter coupling (Hopfield model)

Energy

Tuning parameter

Polaritons

cavity exc.
matter exc.

2Ω

Energy

Vacuum Rabi frequency Ω

anti-resonant and diamagnetic terms

Ground state contains photons!

What are the implications for the material?


\[ H = \hbar \omega_{ca} a^\dagger a + \hbar \omega_c b^\dagger b \]
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\[ + i\hbar \Omega (ab - a^\dagger b^\dagger) + D(aa + a^\dagger a^\dagger) \]
New phases of matter

Superradiant phase transition in Graphene

Cavity QED of the Graphene Cyclotron Transition

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Superradiant phase transition in excitonic insulators

Cavity QED of Strongly Correlated Electron Systems: A No-go Theorem for Photon Condensation

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Cavity-induced superconductivity

How can we probe these phases?
Systems in the ultrastrong light-matter coupling

- Studying the Landau polariton system
- Engineering strong coupling via metamaterial
  - Enhancing the vacuum field
- Probe the ultrastrong coupling beyond optical response?
  - Electro-optic sampling
  - Transport
Maximize Coupling strength

- The coupling energy is given by

\[ \hbar \Omega_R = q \sqrt{N} d_{ij} \mathcal{E}_v \]

- Increase the number of oscillators
- Large dipole
- Matrix element

- The vacuum electric field for a single photon:

\[ \mathcal{E}_v = \sqrt{\frac{\hbar \omega}{2 \varepsilon_r \varepsilon_0 V}} \]

- Minimize volume V:
Landau levels of a 2D electron gas

- Tunable frequency
- Large transition dipole moment

\( d \sim e \times \text{cyclotron radius} \)

\[ \omega_c = \frac{eB}{m^*} \]

Hagenmüller et al., PRB 81, 235303 (2010)
G. Scalari et al., Science, 335, 1323 (2012)
Our system: SRR resonator as Cavity

Split-ring resonator (SRR)

- Subwavelength Cavity $V_{cav} \sim 10^{-4} \left(\frac{\lambda}{2\pi n}\right)^3$
- Strong Vacuum field $E_{\text{vac}} \sim 50$ V/m

Ratio of Rabi to transition $\Omega_R/\omega$ of unity or above

$$\frac{\Omega}{\omega} = 0.78$$

Recent results: $\Omega/\omega = 1.43$

G. Scalari et al., Science, 335, 1323 (2012)
Can vacuum change electronic transport?
Carrier transport enhanced by coupling to vacuum fields

Conductivity in organic semiconductors hybridized with the vacuum field


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Transport in SRR cavity

Split-ring resonator (SRR)

Transport in SRR cavity

Split-ring resonator (SRR)

2DEG stripe
Transport in SRR cavity

Split-ring resonator (SRR)
Transport in SRR cavity

Split-ring resonator (SRR)

current

2DEG stripe

V_{xx}

GaAs

Ti/Au Cavity

Cavity

z

40 \mu m

current
Vacuum fields change magneto-transport
no real photons!

\[ \langle n_{\text{photons}} \rangle < 10^{-3} \]

\[ T_{\text{mix}} = 10 \text{ mK} \]
\[ T_{\text{electrons}} = 100 \text{ mK} \]

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Theory: Kubo approach

The main idea is to follow a Kubo approach to determine the dc magneto conductivity.

\[
\sigma_{ij}^{dc} = i \sum_{\xi' \neq \xi} \frac{e^{-\beta E_{\xi'}} - e^{-\beta E_\xi}}{AZ(E_{\xi'} - E_\xi)} \frac{\langle \xi | \hat{J}_j | \xi' \rangle \langle \xi' | \hat{J}_i | \xi \rangle}{(\omega_\xi - \omega_{\xi'}) + i/\tau_{\xi\xi'}}
\]

→ Bright excitations control also transport!

→ Low T: dc conductivity depends on transitions from ground to excited states
Comparison to experiment

\[ \sigma_{dc} = \frac{n_e e^2}{m_*} \sum_r \left| x_r - z_r \right|^2 \tau_r \frac{\left( \begin{array}{cc} \frac{\omega_r}{\omega_{cyc}} & -\frac{\omega_r \tau_r}{\omega_{cyc}} \\ \frac{\omega_r}{\omega_{cyc}} & \frac{\omega_r \tau_r}{\omega_{cyc}} \end{array} \right)}{1 + \left( \frac{\omega_r}{\omega_{cyc}} \right)^2 } \right) \]

\[ r \in \{LP, UP\} \]

Comparison to experiment

\[ \sigma_{dc} = \frac{n_e e^2}{m_*} \sum_r \frac{|x_r - z_r|^2 \tau_r}{1 + (\omega_r \tau_r)^2} \left( \begin{array}{cc} \frac{\omega_r}{\omega_{cy}c} & -\omega_r \tau_r \\ \omega_r \tau_r & \frac{\omega_{cy}c}{\omega_r} \end{array} \right) \]

\[ \uparrow r \in \{LP, UP\} \]

\[ \frac{1}{\tau_r} = \frac{W_{e,r}}{\tau_e} + \frac{W_{p,r}}{\tau_p} \]

Comparison to experiment

![Graphs comparing theoretical and experimental data in the context of magnetic field and resistance.](image)

How to probe a ground state optically? (start with vacuum)
Revisit field correlation function: $G^{(1)}(\tau)$

Typical measurement: an interferometer

$$G^{(1)}(\tau, \delta \vec{r}) = \langle E^*(t, \vec{r}) E(t + \tau, \vec{r} + \delta \vec{r}) \rangle$$

The correlation of fields is inferred from an intensity measurement at the detector

$$\langle I_1(\tau) \rangle \sim (1 + \Re\{g^{(1)}(\tau)\})$$

The correlation of fields is inferred from an intensity measurement at the detector

$$\langle \hat{a}^\dagger \hat{a} \rangle$$

Will yield zero if applied to the ground state of the radiation

$$G^{(1)}(\tau, \delta \vec{r}) = \langle 0 | \hat{E}^- (t, \vec{r}) \hat{E}^+ (t + \tau, \vec{r} + \delta \vec{r}) |0 \rangle = 0$$
Revisit field correlation function: $G^{(1)}(\tau)$

Typical measurement: an interferometer

$$G^{(1)}(\tau, \delta \vec{r}) = \langle E^*(t, \vec{r}) E(t + \tau, \vec{r} + \delta \vec{r}) \rangle$$

What about measuring the field directly?
Measuring the fields directly

- Implementing a field measurement enables a direct construction of the correlator

\[
G^{(1)}(\tau, \delta \vec{r}) = \langle \hat{E}(t, \vec{r}) \hat{E}(t + \tau, \vec{r} + \delta \vec{r}) \rangle
\]

Field measurement: electro-optic sampling


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Field measurement: electro-optic sampling


Field correlation using electro-optic sampling

Interpretation:

- Pulse length shorter than $1/\text{bandwidth}$ experimental setup:

- Vacuum field fluctuations should show correlations at short time scales
Quantum mechanical interpretation

- Electro-optic measurement is basically a field measurement

\[ \hat{S}_{eo}(t, \vec{r}) = \sqrt{C} \sum_{\Omega} \sqrt{\frac{\hbar \Omega}{2 \epsilon_0 \epsilon_r}} (\hat{a}(\Omega) R(\Omega)) e^{-i(\Omega t - \vec{k} \vec{r})} - h.c. \]

Responsivity: phase matching, pulse length.

- Therefore the "electro-optic" \( G^{(1)} \) is

\[ \hat{G}^{(1)}_{eo} = -\frac{1}{2C} \left\{ \hat{S}_{eo}(t + \tau, \vec{r} + \delta \vec{r}), \hat{S}_{eo}(t, \vec{r}) \right\} \]

- Yields on a thermal photon state

\[ G^{(1)}_{eo}(\tau, 0) = \sum_{\Omega} \frac{\hbar \Omega}{2 \epsilon_0 \epsilon_r V} (1 + 2\langle \hat{n}(\Omega) \rangle) |R(\Omega)|^2 \cos(\Omega \tau) \]

Non-zero even on the vacuum state!

\[ \langle 0 | \hat{a} \hat{a}^\dagger | 0 \rangle = 1 \]
Experimental setup

To control the thermal population, the measurement must be performed in a cryostat.
Signal-to-noise properties

\[ \Delta \hat{E}_{\text{vac}} = \sqrt{\int_0^\infty d\Omega \frac{\hbar \Omega}{2\varepsilon_0 \varepsilon V} |R(\Omega)|^2} \sim \frac{1}{\lambda^2} \]

SNR single pulse
Field measurement 0.001
G\(^{(1)}\)(\(\tau\)) measurement 3\(\times 10^{-6}\)

Integration over at least \(10^{11}\) pulses!
Room temperature measurement

\[ G_{eo}^{(1)}(\tau, 0) = \sum_{\Omega} \frac{\hbar \Omega}{2 \varepsilon_0 \varepsilon_r V} \left( 1 + 2 \langle \hat{n}(\Omega) \rangle \right) |R(\Omega)|^2 \cos(\Omega \tau) \]

Response dominated by thermal photons

![Graphs showing the response and spectrum](image-url)
Going to 4K \((\langle n \rangle = 0)\)

\[
G_{eo}^{(1)}(\tau, 0) = \sum_{\Omega} \frac{\hbar \Omega}{2\epsilon_0 \epsilon_r V} \left(1 + 2\langle \hat{n}(\Omega) \rangle\right) |R(\Omega)|^2 \cos(\Omega \tau)
\]

Check: $T = 45K$

Enables the comparison because refractive index (phase matching) are approximately the same

Spatial coherence

Measuring the field at two different spatial locations

Spatial coherence

Interpretation of the measurement

- In contrast to the coherent state, the vacuum state has no well-defined time dependence of the electric field.

- Classical value of the two-time correlation should be 0!
- Correlation arises from the effect of the first measurement.

Conclusion

- In the ultra-strong light-matter coupling, the ground state is modified
- Measured the effect on electronic transport
  - Transport is driven by the polaritons!
  - See a strong change in the Shubnikov-de Haas oscillations as predicted.
- Developed a THz field correlation measurement
  - Performed the measurement on both thermal and vacuum state
  - Found correlation function as function of delay and displacement, a maximum value of 0.25V²/m² is measured
  - Result requires the back-action of one measurement on the second one, and can be interpreted in the framework of a spontaneous parametric down conversion.
  - Could be a technique to generate entangled photon pairs
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