Effect of phonon in the condensation of exciton-polaritons

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Quantum light-matter interactions

- Weak and medium coupling

  $\gamma = \frac{2\pi}{\hbar}|\langle e|H_I(\mathbf{r})|i\rangle|^2 \underline{\rho(\mathbf{r},\omega)}$ LDOS $\propto \mathrm{Im}[\mathbf{G}_{\hat{p}\hat{p}}(\mathbf{r},\mathbf{r},\omega)]$
- Strong coupling (dressed quasiparticle)

  New excitation, e.g. cavity-atom polaritons and exciton-polaritons

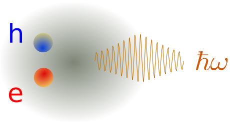
Potential Appliation

- Quantum information technology
- Security, biology and chemistry
- Imaging with ultra-high resolution
- Renewable energy, such as solar cell
- Nanotechnology and Fundamental physics, etc.

Exciton-Polaritons

Strong coupling between exciton and cavity photon

$$a|\mathrm{Exciton}\rangle + b|\mathrm{Photon}\rangle$$



Properties:

- bosonic statistics below Mott density
- small effective mass: $\mu \sim 10^{-5}m_{\mathrm{e}}$—$10^{-4}m_{\mathrm{e}}$
- finite life time: $\tau \sim 10^{0}\mathrm{ps}$—$10^{2}\mathrm{ps}$
- weak interaction: nonlinearity $(a \neq 0)$

Outline

Motivation
- Energy relaxation
- Acoustic Phonon — it could be important

Theoretical model
- DDGP equation
- Quasinormal mode theory
- Rate-equation

Numerical calculation and result

Conclusion

Outline

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Incoherent pump — how does condensation happen

History: free carries $\xrightarrow{\text{fast}}$ exciton $\longrightarrow$ **exciton-polariton**

- **Polariton-Polariton Interaction** (instability)

  Refs.[A. Kavokin *et al.*, Cavity Polaritons (2003);Phys. Rev. B **82**, 245315 (2010);Phys. Rev. B **91**, 085413 (2015)]

- Polariton-Phonon Interaction (Optical > Acoustic)
- Polariton-free carrier interaction (negligible)
- Polariton-disorder interaction

  Refs. [Phys. Rev. Lett. 98, 206402 (2007); J. Phys.: Cond. Mat. **19**, 295208 (2007)]

Could Polariton-Acoustic phonon interaction be important ?

Outline

Incoherently pumped with external electric field

Ref.[M. Klaas, *et al.*, Appl. Phys. Lett., 110, 151103 (2017)]

Optical probing of the Coulomb interactions of an electrically pumped polariton condensate

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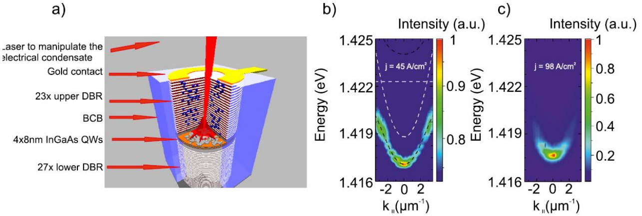
modulational/fracture instability is not found:
phonon induced energy relaxation is important



Outline

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Driven-dissipative Gross-Pitaevskii equation

$$i\hbar\partial_t\Psi = [\frac{i\hbar}{2}(Rn-\gamma) - \frac{\hbar^2}{2\mu}\nabla^2 + \alpha|\Psi|^2 + gn]\Psi$$

$$\partial_t n = P - (\Gamma + R|\Psi|^2)n$$

At low density limit ($|\Psi|^2$)

$$i\hbar\partial_t\Psi = [\frac{i\hbar}{2}(R\beta N_p-\gamma) - \frac{\hbar^2}{2\mu}\nabla^2 + g\beta N_p]\Psi(\mathbf{r}).$$

Non-Hermitian system

$$\hat{H} = \frac{i\hbar}{2}(Rn-\gamma) - \frac{\hbar^2}{2\mu}\nabla^2 + gn$$

Outline

Quasi-normal modes (QNM)

- Eigenmodes $\hat{H}\Psi_\alpha(\mathbf{r}) = E_\alpha\Psi_\alpha(\mathbf{r})$
  - Hermitian normal modes
    $$\mathrm{Im}[E_\alpha] = 0$$
  - **Non-Hermitian quasi-normal modes**
    $\mathrm{Im}[E_\alpha] \neq 0$ indicates the gain and loss
    widely used in **astronomy** *and* **electromagnetic system**
- Localized modes VS extended modes
  - Localized: physically relevant modes
  - Extended: physically irrelevant modes
- Decoupling between localized and extended modes
  Their overlap is extremely small

Electromagnetic field is a different story

Normalization of QNM

- Non-degenerate modes, $\hat{H} = \hat{H}^T$

$$\int \Psi_\alpha(\mathbf{r})\Psi_\beta(\mathbf{r})d\mathbf{r} = \delta_{\alpha\beta}.$$

- Degenerate, rotational symmetry (2D)

$$\int \Psi_{nm}(\mathbf{r})\Psi_{kl}(\mathbf{r})d\mathbf{r} = \delta_{nk}\delta_{ml}$$

with

$$\Psi_{mn}(\mathbf{r}) = \rho_{mn}(r)\exp(\pm im\theta)\exp(-iE_{mn}t/\hbar).$$

Outline

Exciton-phonon interaction

- Hamiltonian

$$H_{\text{phon}} = \sqrt{\frac{\hbar|\mathbf{q}|}{2\rho_D S L u}}(D_e e^{i\mathbf{q}\cdot\mathbf{r}_e} - D_h e^{i\mathbf{q}\cdot\mathbf{r}_h}).$$

- Scattering rate

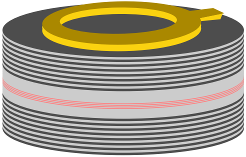
$$W_{\alpha\to\beta} = \frac{L_{\text{eff}}}{\hbar^2 u}\left(n_{\text{phon}}(|\Delta E^{\text{r}}_{\alpha\beta}|) + \Theta(E^{\text{r}}_{\alpha\beta})\right)\sum_{\mathbf{q}_{x,y}} |M_{\alpha,pj}(\mathbf{q}_x, \mathbf{q}_y, |\Delta E^{\text{r}}_{\alpha\beta}|)|^2 \times E_{\text{phon}}/\sqrt{E^2_{\text{phon}} - (\mathbf{q}_x^2 + \mathbf{q}_y^2)(\hbar u)^2}.$$

- Rate equation

$$\partial_t n_\alpha = \frac{2E^{\text{i}}_\alpha}{\hbar} n_\alpha + \sum W_{\beta\to\alpha}(n_\alpha + 1)n_\beta - \sum W_{\alpha\to\beta}(n_\beta + 1)n_\alpha - S n_\alpha^2$$

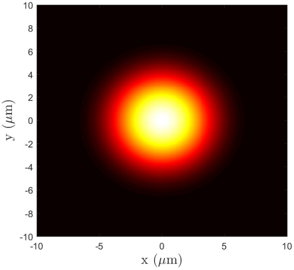
Outline

Electrical pumping with rotational symmetry

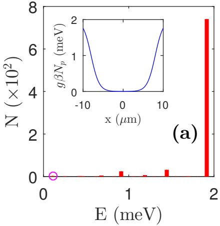


$$V_e^p = g\beta N_p = \frac{V_e}{1+\exp\left(-(\sqrt{x^2+y^2}-r_0)/L\right)}$$

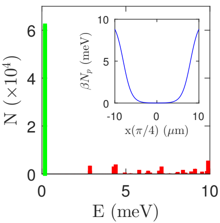
$\mathrm{Im}[\mathrm{E}_\alpha]$ is "minimum" for ground state



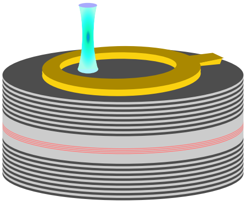
$V_e = 2$ meV



$V_e = 10$ meV

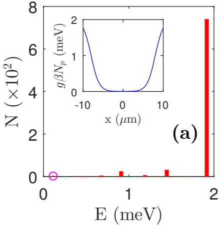


With additional optical pumping

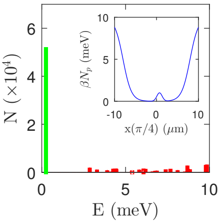


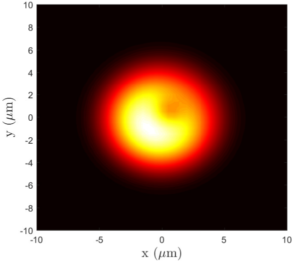
$$V = V_e^p + V_o^p \text{ with}$$
$$V_o^p = V_o \exp\left(-\frac{(x-x_0)^2+(y-y_0)^2}{2\Delta}\right)$$

$V_e = 2$ meV
$V_o = 0.5$ meV



$V_e = 10$ meV
$V_0 = 1$ meV





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Conclusion

- Phonon effect could be important for non-equilibrium condensation
- We developed a QNM theory to take the effect of the phonon into account intuitively

Ref. "Phonon induced reconfiguration of exciton-polariton condensates in ring traps", R.C. Ge, C. Schneider, and T. C. H. Liew, in review.

acknowledgement

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