Dynamical Condensation of Exciton Polaritons

Stanford University, National Institute of Informatics

International School of Physics “Enrico Fermi”:
Quantum Coherence in Solid State Systems
Varenna (Italy) (July 1 - 11, 2008)
Outline

- Blue detuning: Cooling time vs. decay time of exciton-polaritons
- Spin polarization dynamics (new trick: linear polarization pumping)
- Stokes parameters and Poincaré representation
- Polarization-dependent measurements
  - Linearly-polarized and circularly-polarized pumping
  - Linearly-polarized and circularly-polarized detection
- Interpretation in terms of the interplay between energy and spin relaxation
  - Spin-dependent Boltzmann equations
  - Simple two-state model

Quantum degeneracy at thermal equilibrium condition is reached but in a short time window!
Recap: Experimental Tricks toward Thermal Equilibrium BEC

Problem 1. \( k=0 \) polariton leakage lifetime < cooling time

- Non-equilibrium polariton laser

Cavity resonant energy > QW exciton energy

(\text{blue detuning}<10\text{meV}, X=80\%)

\[
\Delta = \omega_c - \omega_e > 0
\]

- Increased lifetime
- Decreased cooling time

Problem 2. Transition to weak coupling regime at high exciton density

- Single quantum well \( \rightarrow \) multiple quantum wells \( (N_{QW} = 12) \)

- Polariton splitting \( = 4\text{meV} \times \sqrt{N_{QW}} \approx 15\text{meV} \)

- Polariton density per QW \( \propto \frac{1}{N_{QW}} \)

- High density (faster cooling)
Polariton Cooling Time vs. Decay Time in Three Detuning Regimes

Relaxation Time / Polariton Lifetime

- red detuning ($\Delta = -6.6\text{ meV}$)
- on resonance ($\Delta = 0$)
- blue detuning ($\Delta = 8.5\text{ meV}$)
- non-equilibrium
- equilibrium

Outline

- Blue detuning: Cooling time vs. decay time of exciton-polaritons
- **Spin polarization dynamics (new trick: linear polarization pumping)**
- Stokes parameters and Poincaré representation
- Polarization-dependent measurements
  - Linearly-polarized and circularly-polarized pumping
  - Linearly-polarized and circularly-polarized detection
- Interpretation in terms of the interplay between energy and spin relaxation
  - Spin-dependent Boltzmann equations
  - Simple two-state model
- Quantum degeneracy at thermal equilibrium condition
  is reached but in a short time window!
Relaxation Bottleneck under Circularly Polarized Pumping

**Linearly-polarized pumping:**
- Below threshold, there is luminescence from all momenta and positions
- Above threshold, the luminescence narrows in momentum and real space and in energy (~0.1meV) (condensation)
- Far above threshold, the condensate broadens in space and energy, and blue-shifts

**Circularly-polarized pumping:**
- Relaxation bottleneck at threshold (polaritons condense into the excited state)
  - Typically attributed to inefficient polariton-polariton scattering
Far-Field Images under Circularly-Polarized Pumping

- Pump incident at \((k_x,k_y)=(0,-7)\) / \(\mu m\)
- Relaxation bottleneck followed by anisotropic polariton condensate distribution (off-center)
- Inefficient polariton-polariton scattering
Spin/Polarization Dynamics

- Pump laser circularly polarized
  - $P < P_{\text{th}}$: spin relaxation time $t_{\text{spin}} < \text{energy relaxation time } t_E \Rightarrow$ depolarization of LPs
  - $P > P_{\text{th}}$: $t_{\text{spin}} > t_E \Rightarrow$ preservation of the pump polarization

- Pump laser linearly polarized:
  - $P < P_{\text{th}}$: equal population of spin-up & down LPs
  - $P \geq P_{\text{th}}$: condensation into single spin LP
  - $P \gg P_{\text{th}}$: condensation of both spin LPs


Old trick (detuning): Cooling time vs. decay time of exciton-polaritons

Spin polarization dynamics (new trick: linear polarization pumping)

Stokes parameters and Poincaré representation

Polarization-dependent measurements
  - Linearly-polarized and circularly-polarized pumping
  - Linearly-polarized and circularly-polarized detection

Interpretation in terms of the interplay between energy and spin relaxation
  - Spin-dependent Boltzmann equations
  - Simple two-state model

Quantum degeneracy at thermal equilibrium condition is reached but in a short time window!
State of spin polarization is defined by the Stokes parameters

\[ S_1 = \frac{I_{0^\circ} - I_{90^\circ}}{I_{0^\circ} + I_{90^\circ}}, \quad S_2 = \frac{I_{45^\circ} - I_{-45^\circ}}{I_{45^\circ} + I_{-45^\circ}}, \quad S_3 = \frac{I_L - I_R}{I_L + I_R}. \]

Liquid crystal polarization optics

Automatically control the pump power

Pump with and observe arbitrary linear or circular polarization

- Poincaré sphere representation
Under circularly-polarized pumping far above threshold the circular polarization is preserved

- Short cooling/decay time compared to spin-relaxation time

Under linearly-polarized pumping both non-zero linear and circular degrees of polarization develop

- A signature of the spin dependent relaxation mechanism
Results for Linear-Polarization Pumping

- Investigate the case of pump wave with varying direction of linear polarization
- Degree of linear polarization and principal axis of elliptical polarization derived from the Stokes parameters
  \[ \text{DOLP} = \sqrt{S_1^2 + S_2^2}, \quad \psi = \frac{1}{2} \arctan \left( \frac{S_2}{S_1} \right). \]

Universal behaviour for the DOLP
- \( \psi \) deviates from the pumping angle \( \theta_p \) by \( \sim 90^\circ \)
- Non-zero circular polarization. The handedness of the observed circular polarization is correlated to the deviation of \( \psi - \theta_p \) from \( 90^\circ \)
Due to crystal asymmetry (for $k_x = 0$) and to the properties of the planar waveguide (for $k_x \neq 0$).

In-plane effective magnetic field

Non-zero degree of circular polarization (depending on the direction of the initial linear polarization)

Self-induced Larmor precession
Spin-dependent interaction:

- Iso-spins interact stronger than hetero-spins
- Each spin evolves in the effective field created by all other spins

\[
\langle \uparrow \uparrow | V | \uparrow \uparrow \rangle = \langle \downarrow \downarrow | V | \downarrow \downarrow \rangle = V_1, \\
\langle \uparrow \downarrow | V | \uparrow \downarrow \rangle = V_2, \\
\Rightarrow V_{\text{int}} = n_{\text{iso}} V_1 + n_{\text{hetero}} V_2
\]

- Vertical effective magnetic field when there is spin population imbalance
- Rotation of the linear polarization axis
- Not enough to explain the \sim 90^\circ rotation
Old trick (detuning): Cooling time vs. decay time of exciton-polaritons

Spin polarization dynamics (new trick: linear polarization pumping)

Stokes parameters and Poincaré representation

Polarization-dependent measurements
  - Linearly-polarized and circularly-polarized pumping
  - Linearly-polarized and circularly-polarized detection

Interpretation in terms of the interplay between energy and spin relaxation
  - Spin-dependent Boltzmann equations
  - Simple two-state model

Quantum degeneracy at thermal equilibrium condition is reached but in a short time window!
Spin Dependence of Polariton-Polariton Scattering

- Strong repulsive interaction between iso-spins and weak attractive interaction between hetero-spins

\[
\langle \uparrow \uparrow | V | \uparrow \uparrow \rangle = \langle \downarrow \downarrow | V | \downarrow \downarrow \rangle = V_1, \quad \langle \uparrow \downarrow | V | \uparrow \downarrow \rangle = V_2,
\]

\[V_1 > 0, \quad V_2 < 0, \quad |V_2| \ll V_1.\]

- Scattering between linearly polarized polaritons

\[
|\phi\rangle = \frac{1}{\sqrt{2}} (|\uparrow\rangle + e^{2i\phi} |\downarrow\rangle)
\]

\[
\langle \phi, \phi | V | \phi, \phi \rangle = \frac{1}{2} (V_1 + 2V_2),
\]

\[
\langle \phi + 90^\circ, \phi + 90^\circ | V | \phi, \phi \rangle = \frac{1}{2} (V_1 - 2V_2).
\]

- Quantum interference between iso-spins and hetero-spins scattering channels

- Possible relaxation mechanism: Several spin-preserving polariton-phonon scattering followed by one and only one polariton-polariton scattering
Comparison to the Parametric Oscillator

- Resonant pumping at an angle which allows scattering to the ground state with energy and momentum conservation.
- Rotation of the linear polarization axis by 90 degrees was also observed.
- Interpreted as a quantum interference effect.


Assume that the reservoir at a magic angle is populated by fast and spin preserving polariton-phonon scattering.

Monitor the reservoir-condensate dynamics in a two-state model:
- Spin-dependent polariton-polariton interaction
- Polarization splitting

Horizontally-polarized pump

$S_1 = -1: \theta_p = 90^\circ$

Images not provided in the text.
Old trick (detuning): Cooling time vs. decay time of exciton-polaritons
Spin polarization dynamics (new trick: linear polarization pumping)
Stokes parameters and Poincaré representation
Polarization-dependent measurements
  - Linearly-polarized and circularly-polarized pumping
  - Linearly-polarized and circularly-polarized detection
Interpretation in terms of the interplay between energy and spin relaxation
  - Spin-dependent Boltzmann equations
  - Simple two-state model

Quantum degeneracy at thermal equilibrium condition is reached but in a short time window!
Temporal BE distribution observed at blue detuning regime
(\(\Delta = 6.7\ \text{meV},\ t=40\text{ps}\))

\(T_{LP} = 4.4\ K,\ \mu = -0.04\ \text{meV} < \text{BEC threshold} (\sim 0.35\ \text{meV})\)

LP cooled to a lowest \(T_{LP}\) @ \(t \sim 35\ \text{ps}\)

\(T_{LP} \approx T_{LP}\) for \(\Delta = 6.7\ \text{meV},\ 9.0\ \text{meV}\)

\(\mu \sim -0.1k_B T_{LP}\)

when LP reaches equilibrium
Ultra-high-Q cavity toward Steady State and Equilibrium BEC

Ultra-high-Q cavity @Wurzburg

Conclusion

- Blue detuning (<10meV, X~0.8) works for efficient cooling
- Linearly polarized pumping accelerates cooling process and avoids bottle-neck condensation
- Rotation of the linear polarization axis by 90 degrees suggests multiple spin preserving polariton-phonon scattering, and one and only one polariton-polariton scattering
- Iso-spin scattering and hetero-spin scattering amplitudes quantum mechanically interfere
- Relaxation bottleneck at threshold under circularly polarized pumping → inefficient scattering with only iso-spins
- Quantum degeneracy at thermal equilibrium condition (operational definition of BEC) is reached but the condensate survives for only 20psec
- A new experiment with a ultra high-Q planar microcavity is in progress