Quantum fluid phenomena with Microcavity Polaritons

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Quantum Optics Team: topics

Quantum fluid phenomena in polariton gases

⇒ An ideal system to study out of equilibrium quantum fluids

Superfluidity, hydrodynamic dark solitons and vortices

Spin dependent non linearities in microcavities

⇒ Towards integrated optoelectronic devices

Logic gates, All Optical Spin Switches

Quantum Effects in semiconductor nano and microcavities in strong coupling regime

⇒ Towards a compact, integrable nano- source of entangled beams

Microcavities, quantum wires, micropillars
(PRL 2007, APL 2010, PRB 2011)
Quantum fluid phenomena

- Introduction
- Superfluidity and Čerenkov regime
- Hydrodynamic Vortices and Dark Solitons
- Towards Vortex Lattices
- Perspectives and conclusion
Microcavity Polaritons

Linear combination of excitons and photons

\[
\begin{align*}
P_+ &= -C a + X b \\
P_- &= X a + C b
\end{align*}
\]
Microcavity Polaritons

Polaritons are weakly interacting composite bosons

\[ P_+ = -C a + X b \]
\[ P_- = X a + C b \]

Very small effective mass \( m \sim 10^{-5} m_e \)

Large coherence length \( \lambda_T \sim 1-2 \, \mu m \) at 5K

\[ \lambda_T = \left( \frac{2\pi \hbar^2}{mk_B T} \right)^{\frac{1}{2}} \]

and

mean distance between polaritons \( d \sim 0,1-0,2 \, \mu m \)

This enables the building of many-body quantum coherent effects: condensation, superfluidity
Bose Einstein condensation of polaritons

- 2D system
- Out of equilibrium system:
  - Creation and recombination (polariton life time ~5 ps)

Boson quantum fluids: polaritons

Coherent propagation

Amo et al., Nature 457, 295 (2009)

Vortex and half vortex

Wertz et al., Nature Phys. 6, 860 (2010)

Long-range order phases


Superfluidity

This talk

Hydrodynamics: vortex

Hydrodynamics: solitons

This talk

Persistent currents

Sanvitto et al., Nature Phys. 6, 527 (2010)

1D BEC arrays

Cerda-Méndez et al., PRL 105, 116402 (2010)
Wave equation for polaritons

Evolution of exciton and cavity fields, in the presence of exciton–exciton interaction

Gross-Pitaevskii equation in the presence of defects

\[
\frac{d}{dt} \begin{pmatrix} \psi_C(x, t) \\ \psi_X(x, t) \end{pmatrix} = \begin{pmatrix} F_p e^{i(k_p x - \omega_p t)} & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} e^{-\frac{(x-x_0)^2}{2\sigma^2}} & \end{pmatrix} + \begin{pmatrix} h^0 + \left( V_C(x) - i \frac{\gamma_C}{2} \right) & 0 \\ 0 & \end{pmatrix} \begin{pmatrix} V_X(x) - i \frac{\gamma_X}{2} + g|\psi_X(x, t)|^2 \end{pmatrix} \begin{pmatrix} \psi_C(x, t) \\ \psi_X(x, t) \end{pmatrix}
\]

with \[ h^0 = \begin{pmatrix} \omega_C(-i\nabla) & \Omega_R \\ \Omega_R & \omega_X(-i\nabla) \end{pmatrix} \]
Quantum fluid effects: superfluidity

The Landau Criterion for superfluidity
Quantum fluid effects: superfluidity

The Landau Criterion for superfluidity

Galilean boost

$V_f < c_s$

Superfluid

Flow
Quantum fluid effects: superfluidity

The Landau Criterion for superfluidity

Galilean boost
\[ v_f \lessgtr c_s \]

critical flow velocity for the onset of excitations: \( c_s \)
We probe the behaviour of the fluid through its interaction with defects.

Linear regime, interactions between polaritons are negligible. Elastic scattering is possible.

Nonlinear regime

strong interactions between polaritons, dispersion curve modified

a sound velocity appears

$$c_s = \sqrt{\hbar g |\psi|^2 / m}$$

*If* \( v_f < c_s \) *and density large enough*

Landau criterion for superfluidity is fulfilled: no states available any more for scattering

**Observation of a linear spectrum of excitation for polaritons:**

- Kohnle *et al.*, PRL, 106, 255302 (2011)

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**Superfluid regime**
Landau criterium: \( E_{LP}^{ren} > E_{\text{signal}} \) \( k \neq k_{\text{signal}} \)

No elastic scattering

Control parameters

✓ Polariton density (pump intensity)
✓ Fluid velocity (excitation angle)
✓ Oscillation frequency (laser frequency)
defect : 4 µm diameter

Point [A] low momentum $v_f < c_s$

Superfluidity appears for a polariton density of $\sim 10^9$/cm$^2$

$v_p = 5.2 \times 10^5$ m/s
Polariton flow around a defect: far field image = momentum space

**experiment**

Point [A]
low momentum
\( v_f < c_s \)
Landau criterion ✓

**theory**

Collapse of the ring

Transition to the superfluid regime

Čerenkov regime

Point [B] high momentum \( v_f > c_{\text{sound}} \) supersonic regime Landau condition

![Diagram of Čerenkov regime](image)

Available states

![Energy vs. Momentum](image)

Normalized photon intensity

![Phonon Dispersion](image)
Čerenkov effect in an atomic BEC

Čerenkov shock waves of a BEC against an obstacle at supersonic velocities

$v_f = 13c_s$  \hspace{1cm}  FLOW  \hspace{1cm}  v_f = 24c_s$

E. Cornell’s talk at the KITP Conference on QuantumGases
http://online.itp.ucsb.edu/online/gases_c04/cornell/.

Observation of Čerenkov waves indicates
the existence of a well defined sound velocity in the system
Čerenkov waves: near field image

Characteristic linear density wavefronts of the Čerenkov waves

Experiment

Theory

Polariton density

Polariton density (µm⁻²)

Excitation density (arb. units)

0.0 0.5 1.0 1.5 2.0 2.5

0 5 10 15 20

Experiment

Theory
Transition to the Čerenkov regime

Supplementary Video 2

Figure 3: transition to the Čerenkov regime

Superfluidity breakdown: vortices and solitons formation?

The case of spatially extended defects; the size of the defect is larger than the healing length

\[ v_f = v_\infty < c_s \]

Acceleration of the fluid near the defect: the Landau criterion is locally violated

\[ v_f = 2v_\infty \]

The currents formed in the fluid passing around a large obstacle can give rise to turbulence in its wake

Quantized vortices
Dark Solitons
Superfluidity breakdown: vortices and solitons formation?

The case of spatially extended defects; the size of the defect is larger than the healing length

S. Pigeon et al. PRB (2010)
Superfluidity breakdown: vortices and solitons formation?

The case of spatially extended defects; the size of the defect is larger than the healing length

S. Pigeon et al. PRB (2010)
Experimental set-up

Key points

- **CW laser** (precise control of the fluid quantum state)
- **Mask** (free evolution for the superfluid phase)
- Possibility to generate topological excitations
Big defect (15µm) >> healing length

\[ \frac{v_f}{c_s} = 0.25 \]

\[ \frac{v_f}{c_s} = 0.4 \]

\[ \frac{v_f}{c_s} = 0.6 \]

Superfluidity Vortex ejection Solitons

Real space

Superfluidity Turbulence Solitons

Interferogram

Constant phase Phase dislocations Phase jumps

First order coherence

Amo et al., Science, 332, 1167 (2011)

Polariton density
Hydrodynamic Dark Solitons

\[ \nu_f = 1.7 \ \mu m/ps \]
\[ k = 0.73 \ \mu m^{-1} \]

\[ \cos \frac{\phi}{2} = \left( 1 - \frac{n_s}{n} \right) \]

\[ \phi = \pi \]

\[ \Delta y = 14 \ \mu m \]

\[ \Delta y = 26 \ \mu m \]

\[ \Delta y = 36 \ \mu m \]
Soliton doublet and quadruplet

Big defect (17µm) >> healing length

Low momentum; \( k = 0.2 \, \mu m^{-1} \)  \quad \text{High momentum; } \( k = 1.1 \, \mu m^{-1} \)

Amo et al., Science, 332, 1167 (2011)
Oblique Dark Solitons in Supersonic Flow of a Bose-Einstein Condensate

G. A. El, A. Gammal, and A. M. Kamchatnov

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(Received 21 April 2006; published 1 November 2006)

Not yet observed in atomic BEC; the dissipation in polariton fluids helps in stabilizing dark solitons (Kamchatnov et al. arXiv:1111.4170)
Light engineering of the polariton landscape:

using polariton-polariton interactions
Engineered landscape

Sample from R. Houdré

probe $\sigma^+$

Defect-free area
Engineered landscape

Probe $\sigma^+$

Control $\sigma^-$

Strong field: renormalization of the polariton energy

$g_{\uparrow\downarrow} \approx 0.1g_{\uparrow\uparrow}$
Engineered landscape

**Strong field:** renormalization of the polariton energy

$g_{\uparrow\downarrow} \approx 0.1 g_{\uparrow\uparrow}$

Amo et al., PRB Rapid Comm. (2010)
Engineered landscape

probe $\sigma^+$ + control $\sigma^-$ + probe $\sigma^+$ + control $\sigma^-$

strong field: renormalization of the polariton energy

Real defect

$g_{\uparrow\downarrow} \approx 0.1g_{\uparrow\uparrow}$

Amo et al., PRB Rapid Comm. (2010)
Engineered landscape

- Probe only
  - No control
- Probe +
  - Linear control
- Probe +
  - Diagonal control

30 µm
Optical control of vortex formation

All-optical control of the quantum flow of a polariton condensate

Tailoring the potential landscape to trap vortices


Triangular Trapping Mask behind the defect:
the vortices created in the wake of the defect are trapped inside the trap
Towards spontaneous formation of vortex lattices

Small triangular trap

Experiment

Theory

Polariton density

Phase

Self-organization of vortices and anti-vortices in hexagonal lattices
Towards spontaneous formation of vortex lattices

Increasing the size of the trap, a larger number of hexagonal unit cells is formed.
Conclusion and perspectives

- Polariton Quantum Fluids
  - Superfluidity
  - Čerenkov regime
  - Hydrodynamic vortices and dark solitons

- Perspectives
  - Engineering of polariton landscape: Dynamical Potentials, Optical traps for polaritons
  - Study and control of Quantum turbulence?
  - Lattices of vortices?

- Spinor polariton condensates
  (Hivet et al. arXiv:1204.3564)
Collaborations

EXPERIMENTS

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