Quantum fluids of light

Alberto Bramati
Quantum Fluids

Liquid Helium

Helium-4 (boson)
Helium-3 (fermion)

Ultracold atomic condensates

Rubidium-87 (boson)
Lithium-6 (fermion)

See e.g.,
What about Light?

Light field/beam are composed by a large number of photons but in the vacuum photons do not interact.

Optics is typically dominated by single particle behaviour, however..

• Can we give photons a mass?
• Can photon-photon interactions make light behave as a fluid?

• Main ingredients

• $\chi^{(3)}$ non linearities $\rightarrow$ photon-photon interactions
• Spatial confinement $\rightarrow$ effective photon mass

Collective behaviour of a photonic quantum fluid
Diffraction non linéaire

Yves Pomeau et Sergio Rica

Résumé – Une expérience classique en mécanique des fluides est la formation de structures vorticales à l'arrière d'un obstacle, comme par exemple l'écoulement de Bénard-von-Kármán. Est-il possible d'imaginer une expérience similaire en optique ? C'est-à-dire, en illuminant un obstacle pourrait-on engendrer des structures tourbillonnaires caractéristiques d'un régime pré-turbulent ? Cette Note est consacrée au problème de la génération de vorticité dans les ondes électromagnétiques.

Nonlinear diffraction

Abstract – A classical experiment in fluid mechanics is the formation of vortical structures in wakes as for instance the Bénard-von-Kármán flow. Is it possible to imagine a similar experiment in optics ? i.e., is it possible to generate vortical structures characteristics of a pre-turbulent regime by sending light to an object ? This Note is devoted to the problem of generation of vortices in electromagnetic waves.

Bogoliubov dispersion relation and the possibility of superfluidity for weakly interacting photons in a two-dimensional photon fluid

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Two families of fluids of light

Cavity configuration

- Photons fluids in microcavity polaritons
- Photon BEC in optical cavity with dye molecules

Cavity-less configuration

- Photon fluids in propagating geometry (Rb vapors, photorefractive crystals, thermo-optic liquids)
Quantum fluids of light

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Polaritons
- Introduction
- Superfluidity
- Vortices, solitons and more

Outlook
- Fluids of light for analogue physics?
Polaritons: half-light half matter states coming from strong coupling between excitons and photons

Polaritons are weakly interacting composite bosons
An ideal system to study out of equilibrium quantum fluids
Microcavity Polaritons

Polaritons are weakly interacting composite bosons

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

Photonic part: very small effective mass \( m \sim 10^{-5} m_e \)

Excitonic part: strong non linear interactions

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

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

and

mean distance between polaritons \( d \sim 0.1\text{-}0.2 \mu m \)

This enables the building of many-body quantum coherent effects: condensation, superfluidity
Polariton BEC


Carusotto&Ciuti, Rev. Mod. Phys.85, 299 (2013)
Hydrodynamics of polariton quantum fluids

Superfluidity and Cerenkov waves
(Nature Physics 2009)

Dark solitons and vortices
Microcavity Polaritons: Mean field approach

Generalized Gross-Pitaevskii equation

\[ i\hbar \frac{\partial}{\partial t} \psi = -\frac{\hbar^2}{2m} \nabla^2 \psi + V_{\text{ext}} \psi + g^2 |\psi|^2 \psi + i\gamma \psi + F_p \]

Driven dissipative system, out of equilibrium quantum fluids

Steady state solutions: Bistability
Study of superfluidity
Weak excitations and Bogoliubov dispersion

Weakly excited states: bosonic modes obtained by linearizing the Gross Pitaevskii equation around the steady state solutions

\[\psi(r, t) = \left(\psi_0(r, t) + \delta\psi(r, t)\right)\]

\[i \frac{\hbar}{\partial t} \begin{bmatrix} \delta\psi(r, t) \\ \delta\psi^*(r, t) \end{bmatrix} = \mathcal{L}_{\text{Bog}} \begin{bmatrix} \delta\psi(r, t) \\ \delta\psi^*(r, t) \end{bmatrix}\]

Bogoliubov operator

\[\mathcal{L}_{\text{Bog}} = \begin{bmatrix} \frac{\hbar^2k^2}{2m} + g|\psi_0|^2 & g|\psi_0|^2 e^{2ik_0x} \\ -g|\psi_0|^2 e^{-2ik_0x} & -\frac{\hbar^2k^2}{2m} - g|\psi_0|^2 \end{bmatrix}\]

Look for eigenvalues of the Bogoliubov operator
Bogoliubov dispersion

- Solutions of Bogoliubov equation
  - healing length $\xi = \sqrt{\hbar^2/m gn}$
  \[ \hbar \omega_{Bog}(k) = \pm \sqrt{\frac{\hbar^2 k^2}{2m} \left( \frac{\hbar^2 k^2}{2m} + 2gn \right)} \]

- Large $k$ ($k \xi \gg 1$):
  - parabolic dispersion
  - "normal" fluid

- Small $k$ ($k \xi \ll 1$):
  - sonic dispersion
  - superfluidity

  Speed of sound: $c_s = \sqrt{gn/m}$
Coherent probe spectroscopy

- **Probe**: excitation of small perturbations on top of the polaritons fluid
  - @ different $k_{pr}$
  - energy scan: $\Delta \omega_{pr} \sim 100 \text{Ghz}$

- Probe absorption (transmission) when $(k_{pr}, \omega_{pr}) = (k_{pol}, \omega_{pol})$
Bogoliubov dispersion

- $k \xi \gg 1$ parabolic dispersion (same as the linear regime)
- $k \xi \ll 1$ sonic dispersion: fit of the speed of sound $c_s$

Claude et al., submitted
• Changing the fluid density (proportional to the detuning $\delta$)

• The speed of sound $c_s$ is proportional to $\sqrt{n}$
Ghost branch

\[ \hbar \omega_{Bog}(k) = \pm \sqrt{\frac{\hbar^2 k^2}{2m} \left( \frac{\hbar^2 k^2}{2m} + 2gn \right)} \]

Claude et al., submitted
Probing the superfluidity

We probe the behaviour of the fluid through its interaction with defects

Control parameters

- Polariton density (pump intensity)
- Fluid velocity (excitation angle)
- Oscillation frequency (laser frequency)
Polariton flow around a defect:

- **Defect**: 4 µm diameter
- **Point [A]**
  - Low momentum
  - \( v_f < C_S \)
Transition to the superfluid regime

Čerenkov regime

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

- Emission angle (degrees)
- Energy (eV)
- $k_y$ ($\mu$m$^{-1}$)

- Exciton mean-field energy (meV)
- Pump (arb. units)
- $E - E_0$

- Available states

- Normalized photon intensity
- $Y$ [$\mu$m]
- $X$ [$\mu$m]

- $k_y$ [$\mu$m$^{-1}$]
- $k_x$ [$\mu$m$^{-1}$]
Cerenkov effect

$v > v_{\text{sound}}$ supersonic flight
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

Frisch et al., PRL 69, 1644 (1992)
Resonant excitation

✓ Shaped pump: free evolution for the fluid phase
**Vortices and Solitons**

Big defect (15µm) >> healing length

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

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

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

Real space

Superfluidity

Vortex ejection

Solitons

Interferogram

Superfluidity

Turbulence

Solitons

Constant phase

Phase dislocations

Phase jumps

Resonant excitation

✓ Problem: short propagation due to the dissipation

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

✓ Problem: the polariton density decreases rapidly; only short propagation is achieved (about 30-40 µm)
The idea: to exploit the bistability

Proposal: S. Pigeon et al, NJP, 2018

Low polariton density

Strong phase fixing

Signal intensity (arb. units)

Input intensity (arb. units)


Bistability: high polariton density and no phase fixing
Vortex stream generation

Vortices are continuously generated and propagate for very long distances

Dark Soliton Enhanced Propagation

Up to 150µm propagation distance

New feature: solitons are parallel each other and to the direction of the flow

All-optical imprinting of solitons

High density regime: the phase of the pump is copied onto the fluid

In the bistable region the phase of the fluid is not fixed by the pump: solitons propagate through the bistable region for very long distances

Equilibrium between two opposite forces:

- Driving \(\rightarrow\) \(\leftarrow\)

- Solitons repulsion \(\leftrightarrow\)

The soliton separation distance is independent of the initial one and of the fluid parameters.

The separation distance is solely determined by the dissipation.

Solitons arrays

Scalable technique to create in a controlled way soliton arrays
Colliding Solitons

Flexible technique to study in a controlled way the soliton interactions
Polaritons

- Superfluidity
- Quantized Vortices
- Dark Solitons
- All-optical technique to generate steady-state topological excitations and control their macroscopic propagation
The team

Thank you for your attention