Complex behavior of topological excitations in polariton quantum fluids

Sergei Koniakhin, Dmitry Solnyshkov, Guillaume Malpuech, Olivier Bleu, Daniil Stupin*
Institut Pascal, PHOTON-N2, Université Clermont Auvergne, CNRS

Alberto Bramati, Simon Pigeon, Quentin Glorieux, Anne Maitre, Giovanni Lerario, Ferdinand Claude
Laboratoire Kastler Brossel, Sorbonne Université, CNRS

25ème Congrès Général de la Société Française de Physique
Plan of talk

- Cavity polaritons
- Solitons and vortex streets in resonantly pumped polariton quantum fluid
  - The story of domain wall propagation in bistable regime
  - Solitons stability and vortex street formation
  - Preliminary experimental results
- 2D Quantum turbulence in polariton condensates
  - Incompressible kinetic energy spectrum
  - Fractal properties of quantum vortex clusters
Exciton-polaritons - particles of fluid light

|polariton⟩ = X_k|exciton⟩ + C_k|photon⟩

Exciton-exciton non-linear repulsive interaction
Due to photon component: excitation by laser (including SLM) and luminescence detection

Non-linear Schrödinger equation (Gross-Pitaevskii Equation, GPE):

\[ i\hbar \frac{d\psi}{dt} = -\frac{\hbar^2}{2m} \Delta \psi + g|\psi|^2\psi - i\Gamma_0\psi + S \cdot \exp(-i\omega_p t) \]

- Repulsion
- Losses
- Laser Pump
Bistability in driven-dissipative GPE

\[ i\hbar \frac{d\psi}{dt} = -\frac{\hbar^2}{2m} \Delta \psi + g|\psi|^2\psi - i\Gamma_0\psi + S \cdot \exp(-i\omega_p t) \]

- Repulsion results in blueshift
- At upper bistability branch polaritons are in phase with Laser
- At lower branch polaritons have \( \approx \pi \) phase shift
Solitons in the corridor with pump walls
Domain wall propagation in free space

The domain wall velocity can be found as

\[ v = \frac{\partial n}{\partial t} \frac{\Delta x}{\Delta n} \quad \text{and} \quad \frac{\partial \psi}{\partial t} = \frac{S - S_c}{i\hbar} \]

\[ \rightarrow \quad v \approx \sqrt{n_0} \frac{S - S_c}{\hbar} \frac{\xi}{n_0} \]

Domain wall moves left \((S < S_c)\) or right \((S > S_c)\) depending on the value of the support \(S\).

Critical support:

\[ S_c = \frac{2(\hbar \omega_p)^{3/2}}{3\sqrt{3}g^{1/2}} \]
The dispersion $\text{Im}\{E(k_y)\}$ defines the intervortex distance:

$$\frac{\pi}{D_{\text{intervortex}}} = k_{y}^{\text{max}}$$

- Number of unperturbed solitons $= \text{number of peaks in dispersion}$
- Bonding and anti-bonding "orbitals" in bogolon "molecules"
Phase diagram Pump/Support
The solitons can be used to solve the maze

- Soliton goes out of a dead-end. This is also domain wall motion but along ”Y direction”
- One sees the periodical pattern along the solitons in long corridors. This is again a modulation instability
- Oscillations are stabilized by already developed instability
... the really big maze
Vortex streets guided by dislocations

Lowering the power

- High dens.
- Bist. loop
- Linear

Preliminary experimental data by LKB, Sorbonne Universite, CNRS
2D quantum turbulence
Main issues of 2D quantum turbulence

- In classical 3D turbulence the direct energy cascade exists and Incompressible Kinetic Energy (IKE) spectrum $E(k) \propto k^{-5/3}$ (Kolmogorov exponent)
- In 2D quantum turbulence existence and direction of the cascade are not a closed questions
- Are cavity polaritons suitable quantum fluid system to experimentally study the energy cascade?
- Their favorable features are control of wave function by SLM and possibility to fully reconstruct phase and amplitude of wave function

Here we study **conservative** case (no $\Gamma$ term in GPE) to trace long-time evolution inaccessible at present level:

$$i\hbar \frac{\partial \psi}{\partial t} = \left[ -\frac{\hbar^2 \Delta}{2m} + V(t) + g |\psi|^2 \right] \psi$$
Stirring by moving potential $V(t)$

IKE spectra for all vortices and for clustered vortices

$k^{-5/3}$ is seen for clustered vortices

$k^{-1}$ is for single vortex spectrum
Fractal nature of vortex clusters

Example of box counting for clustered vortices a) and all vortices b)

Fractional Minkowski dimension

$$\frac{\ln N(\varepsilon)}{\ln(1/\varepsilon)}$$

Box count $N$ vs IKE spectrum $E(k)$

The region of fractional dimension matches with region -5/3 exponent in IKE spectrum
Time dynamics of IKE spectrum formation

IKE spectra at various time moments

Ratio of energy stored at long wavelengths and short wavelengths
Thanks for your attention!