Phase fluctuations in microcavity exciton polariton condensation

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Quantum mechanical gas

Classical gas

Increase density or lower temperature

Quantum gas

- Matter also has a wave character
- At high densities or low temperatures, wavepackets overlap → quantum mechanics is noticeable
- A large number of particles can behave as a single wave
- We are interested in systems in which such a collective behavior occurs in a controlled way
- Two classes of particles
  - Fermions
  - Bosons
- The correlation function quantifies how well distant parts of this wave are synchronized
Quantum simulation (or emulation)

- Study the properties of a microscopic model system by engineering a larger system that follows the same “rules” (lattice potential and interactions) and performing measurements on the large system.

- Experiments in atoms have reached a high level of sophistication, so their limitations appear:
  - Matter wave interference and particle statistics challenging to measure
  - No truly low-dimensional gases
  - Lattice potentials limited to very periodic structures

- A solid state implementation promises to solve all of the above problems:
  - Interference and photon statistics through optics
  - Perfect confinement in 2D or 1D in quantum well or quantum wire
  - Any lattice potential is feasible in principle
Bose-Einstein condensation in 3D

- A Bose gas behaves collectively as one wave when the wavepackets of every particle start to overlap

\[ n \lambda_T^3 = n \left( \frac{2\pi \hbar^2}{mk_BT} \right)^{3/2} \sim 1 \]

- Atomic gases (numbers given are for Rb)
  - Large mass \( \sim 87m_p \sim 10^5 m_e \)
  - Small density (otherwise molecules form) \( \sim 10^{12} cm^{-3} \sim 10^{-7} n_{air} \)
  - Need extremely low temperature (trapping and cooling techniques) \( \sim 100nK \)

- Solid state quasiparticles
  - Smaller mass \( \sim m_e \)
  - Cannot cool down to very low temperature \( \sim 1K \)
  - Need large density \( \sim 10^{16} cm^{-3} \rightarrow \) spurious nonlinear effects

- Our approach is to study quasiparticles with extremely low mass by coupling a solid state excitation with a photon \( m \sim 10^{-4} m_e \)
  - Difficult to confine photons \( \rightarrow \) non-equilibrium
Exciton polaritons

- Non-equilibrium condensation: enhanced scattering rate into the ground state when a large enough seed of particles is already present (Bosons)

- Differences from laser
  - Both the exciton and photon fields are coherent
  - Relaxation (and not decay) is stimulated

- Experiments performed at low temperature (7-8K)
Kosterlitz-Thouless (KT) transition


- Quantized angular momentum around the vortex axis: $mv r = \hbar$

- Consider a condensate with one vortex

$$E = \int 2\pi r dr \frac{1}{2} \rho v^2 = E_0 \ln \left( \frac{R}{\xi} \right)$$

$$S = k_B \ln \left( \frac{\pi R^2}{\pi \xi^2} \right) \Rightarrow F = E - TS = (E_0 - 2k_B T) \ln \left( \frac{R}{\xi} \right)$$

- The correlation function at large distance decays exponentially for $T>T_c$ and as a power law for $T<T_c$.

- The transition can also be crossed by increasing the density

- We want to study the relevance of the theory to our system by measuring the spatial correlation function and the condensate phase distribution

- This transition not possible in 3D
Outline

- Exciton polariton condensation and how we observe it

- Measurement of first order spatial correlation function $g^{(1)}(r)$ (Phys. Rev. Lett., submitted)
  - Compare results to equilibrium and non-equilibrium theory

- Observation of single vortex-antivortex pair (Nature Phys., accepted)
Setup for a homogeneous pumping spot

- The main tunable parameter of the system is the polariton density
- We would like to create a homogeneous polariton distribution over a large area
- Use a refractive beam shaper for high pumping efficiency
One-to-one correspondence between angle of emission and in-plane momentum

We can select emission from a particular spot on the sample, and study the spectrum $\rightarrow$ dispersion curve
Polariton condensation in momentum space

- Above a critical particle density, condensation is observed
- Accumulation of particles near zero momentum
- Blue shift partly because of repulsive polariton-polariton interactions
- Non-linear increase of luminescence from the $k=0$ state
Michelson interferometer setup

- Two copies of the same image interfere on the camera
- Because they follow different paths, one of them is tilted with respect to the other
- Moving one of the interferometer arms shifts the fringe pattern
- Fringe visibility and phase difference information
In this interference experiment, we measure
\[ |\mathcal{E}(r_1) + \mathcal{E}(r_2)|^2 \]
so \( g^{(1)}(r_1, r_2) \) gives the fringe visibility if the intensities are the same.

\[ g^{(1)}(r_1, r_2) = \frac{\langle \mathcal{E}^*(r_1)\mathcal{E}(r_2) \rangle}{\sqrt{\langle |\mathcal{E}(r_1)|^2 \rangle \langle |\mathcal{E}(r_2)|^2 \rangle}} \]

\[ R + R \rightarrow \text{interfere (x,y) with (-x,y)} \quad \rightarrow g^{(1)}(x, -x) \]

\[ R + B \rightarrow \text{interfere (x,y) with (x,-y)} \quad \rightarrow g^{(1)}(y, -y) \]
The two phase fronts we interfere are tilted one with respect to the other, so we expect a constant phase gradient across the whole spot.

Measuring the phase along with the fringe visibility allows to identify noise from useful signal.
$g^{(1)} (r)$ at short distances

- Results can be understood using the non-interacting equilibrium model
  \[
g^{(1)} (r) = \frac{1}{4\pi^2 n} \int d^2 k \, n(k) e^{ik \cdot r}
\]

- Gaussian decay, the width proportional to the thermal de Broglie wavelength
  \[
  \lambda_T = \frac{\hbar}{\sqrt{2\pi m k_B T}}
  \]
$g^{(1)}(r)$ at long distances, equilibrium theory

- Long-distance decay depends on the low-momentum excitations

$$g^{(1)}(r) = \frac{1}{4\pi^2 n} \int d^2 k \, n(k) e^{i \mathbf{k} \cdot \mathbf{r}}$$

$$N_{exc} = \int_0^\infty \frac{1}{\exp \left( \frac{\epsilon(k)}{k_B T} \right) - 1} \, d\mathbf{k} \approx \int_0^{k_T} \frac{1}{\epsilon(k) / k_B T} \, d\mathbf{k} = \int_0^{k_T} \frac{2mk_B T}{\hbar^2 k^2} \, d\mathbf{k}$$

$$N_{exc} = \begin{cases} 
1D: \, d\mathbf{k} = dk & \Rightarrow N_{exc} \text{ diverges} \\
2D: \, d\mathbf{k} = 2\pi k \, dk & \Rightarrow N_{exc} \text{ log divergence} \\
3D: \, d\mathbf{k} = 4\pi k^2 \, dk & \Rightarrow N_{exc} \text{ finite}
\end{cases}$$

- Low-temperature behavior

$$g^{(1)}(r) \big|_{r \to \infty} \propto \begin{cases} 
1D: \, e^{-r/l} & \text{non-interacting: } e^{-r/l} \\
2D: \, \begin{cases} 
\text{no vortices: } r^{-a} \\
\text{free vortices: } e^{-r/l}
\end{cases} \\
3D: \, \text{const}
\end{cases}$$
Fit to a power law

\[ g^{(1)}(r) = \left( \frac{\lambda_p}{r} \right)^{a_p} \]

Similar to the low-temperature KT phase, but correlations decay with a higher exponent.

Threshold

\( g^{(1)}(r) \) at long distances, experiment
Exponent of power law decay

- In equilibrium, the exponent is $<1/4$ (a competition of two effects)

- Thermal phase fluctuations $\rightarrow g^{(1)}(r) \propto r^{-a}$
  - The exponent increases as the temperature is increased

- At $T_{\text{KT}}$, vortex-antivortex pairs unbind $\rightarrow g^{(1)}(r) \propto \exp(-r/l)

- The noise in our system behaves differently than thermal noise
  - significant phase fluctuations without breaking the vortex-antivortex pairs

- What is the noise source? Open question
  - Laser power fluctuations $\rightarrow$ particle density modulation $\rightarrow$ interaction energy modulation $\rightarrow$ dephasing

- Nonequilibrium model:
  - Predicts a power law decay of the correlation function.
    The exponent depends on the distribution of excitations
  - For flat distribution, the exponent is proportional to the “noise strength” (we could not associate it with a measurable quantity)
  - Exponent can be higher than possible in equilibrium
Condensate shape in real space (I)

- Below threshold: Airy-like pattern because of diffraction effects
- Above threshold: a population dip at the center of the condensate
- The reservoir has a complementary profile with a population peak at the center
- Repulsive interaction between reservoir and condensate stabilize this distribution
The previous model was homogeneous. This is an inhomogeneous effect


Coupled equations for the reservoir and condensate dynamics

\[
\frac{i\hbar}{\partial t} \frac{\partial \psi(\vec{r}, t)}{\partial t} = \left( -\frac{\hbar^2 \nabla^2}{2m^*} + V_{\text{ext}}(\vec{r}) - \frac{i\hbar}{2} [\gamma_C - R(n_R(\vec{r}, t))] + g_C |\psi(\vec{r}, t)|^2 + g_R n_R(\vec{r}, t) \right) \psi(\vec{r}, t)
\]

\[
\frac{\partial n_R(\vec{r}, t)}{\partial t} = \frac{P_{\text{las}}(\vec{r}, t) - \gamma_R n_R(\vec{r}, t) - R(n_R(\vec{r}, t)) |\psi(\vec{r}, t)|^2}{\partial t}
\]

The model explains the condensate shape (in addition to other features of polariton condensation) without fine-tuning its parameters.
Generation of vortex-antivortex pairs

- A zero in density corresponds to a superposition of a vortex and antivortex
- Given enough energy from an external source, they can be separated
- The center of the condensate is a source of vortex-antivortex pairs
- Open question: what this external source exactly is
Vortex-antivortex pair motion

- We imprint a vortex-antivortex pair and numerically calculate its evolution.
- Because of drag from the reservoir, the vortex and antivortex recombine before reaching the edge of the condensate.
- The signature in the phase map is two $\pi$-phase shift areas.
- The vortex and antivortex follow a correlated motion, and the pair does not break (consistent with the observed power law decay of the correlation function).
One pair with random polarization

- Assume a vortex-antivortex pair at the center
- If the vortex and antivortex can flip positions, areas with $\pi$-phase shift are observed surrounded by minima in the fringe visibility
Experimental result

- Areas of $\pi$-phase shift surrounded by minimum of the fringe visibility
  - Vortex-antivortex pair with random polarization

- No phase defect when the prism is rotated by $90^\circ$
  - The pair has a definite orientation, due to a small spot asymmetry

**Numerical model**

- **Experiment**

**Different prism orientation**
Different prism orientations

- The pair sits along a fixed direction
- The two different prism orientations create two distinct situations
Gaussian pumping spot

- A gaussian pumping spot does not develop a density dip at the center, so vortex-antivortex pairs are not created.
Summary of results

- We directly measured the spatial correlation function $g^{(1)}(r)$
  - Gaussian decay at short distances → de Broglie thermal wavelength
  - Power Law decay at long distances with an exponent close to 1

- With a suitable laser pumping spot, vortex-antivortex pairs are generated, and they remain bound.
Relevance to Kosterlitz-Thouless theory

We found

- Power law decay of the correlation function
- Correlated motion of vortex and antivortex
- The state of our condensate is consistent with the KT low-temperature phase
- Large number of the exponent $\rightarrow$ non-equilibrium physics
Future directions

- What is the source of phase fluctuations
  What type and strength of noise is required for vortex proliferation

- Samples with longer lifetime (closer to thermal equilibrium)
- Electrical pumping (easier to engineer the pumping noise)

- Observe the motion of vortex-antivortex pairs in time-resolved measurements
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Hello world!