Are non-equilibrium Bose-Einstein condensates superfluid?

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We theoretically study the superfluidity properties of a non-equilibrium Bose-Einstein condensate of exciton-polaritons in a semiconductor microcavity. The dynamics of the condensate is described at mean-field level in terms of a modified Complex Ginzburg Landau equation. A generalized Landau criterion is formulated which estimates the onset of the drag force on a small moving defect. Metastability of supercurrents in multiply connected geometries persists up to higher flow speeds.

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Superfluidity is among the most remarkable consequences of macroscopic quantum coherence in condensed matter systems and manifests itself in a number of fascinating effects [1, 2]. A unified description of these phenomena is obtained in the framework of the so-called two-fluid hydrodynamics, in which the macroscopic condensate wavefunction adds up to the standard hydrodynamic variables [3]. The phenomenon of macroscopic coherence is not restricted to systems at (or close to) thermodynamical equilibrium such as liquid Helium, ultracold atomic gases, or superconducting materials, but has been observed also in systems far from thermodynamical equilibrium, whose state is determined by a dynamical balance of driving and losses. Most remarkable examples are lasers and, more recently, Bose-Einstein condensates of magnons in magnetic solids [4] and exciton-polaritons in semiconductor microcavities [5, 6]. In particular, the issue of superfluidity in this latter system has attracted a significant interest from both the theoretical [7, 8] and experimental [9–11] points of view.

Recent experiments with resonantly pumped polariton condensates [9] have demonstrated superfluidity as a dramatic reduction in the intensity of resonant Rayleigh scattering as originally predicted in [7]. The situation is less clear in the case of non-resonant [5] or parametrical (OPO) [10] pumping schemes: recent experiments [10] have observed propagation of polariton bullets without apparent friction, which is in contrast with the predictions of a naïve Landau criterion based on the elementary excitation spectrum predicted in [12]. Another aspect of superfluidity, namely metastability of supercurrent in multiply-connected geometries was investigated theoretically in [8] and experimentally confirmed in [11]. The present paper reports a comprehensive theoretical investigation of the meaning of superfluidity for polariton condensates under a non-resonant pumping. Emphasis will be given to the novel features that originate from their non-equilibrium character.

At the mean-field level, the condensate dynamics can be described in terms of the so-called Gross-Pitaevskii equation (GPE) [1], which was recently generalized to non-equilibrium condensates by including the effect of pumping and losses [13, 14]. This mean-field description has been able to explain a number of experimental observations on polariton condensates, e.g. the ring-shaped momentum distribution of spatially narrow condensates [6, 15], the synchronization/desynchronization transition [16], the spontaneous appearance of vortices [17]. Nonetheless, the implicit assumption that the pumping mechanism is not frequency-selective can lead to unphysical predictions, e.g. that in a spatially homogeneous or ring-like geometry condensation is equally likely to occur in any momentum state. Kinetic calculations [18] have pointed out the significant energy dependence of the polariton-polariton scattering processes that are responsible for replenishing the condensate. Including this feature as an energy-dependent amplification mechanism turned out to be crucial in order to extract physically meaningful predictions for the condensate fluctuations in the Wigner Monte Carlo simulations of [19].

A simplest generalization of the GPE to include frequency-dependent pumping has the form:

$$i\frac{d\psi}{dt} = \left\{ -\frac{\hbar}{2m}\nabla^2 + V_{ext} + \frac{i}{2}\left[P\left(1 - \frac{i}{\Omega_K}\frac{d}{dt}\right) - r|\psi|^2 - \gamma \right] + g|\psi|^2 \right\}\psi. \quad (1)$$

The energy zero has been set for convenience at the bottom of the lower polariton branch; the efficiency of amplification (proportional to the pumping strength P) decreases to zero a frequency interval Ω_K above it. Assuming a linear form of the frequency dependence of the amplification, the generalized GPE (1) maintains a temporally local form. The others terms describing gain saturation (r), losses (γ), polariton mass (m), polariton-polariton interactions (g), external potential (V_{ext}) have the same meaning as in previous works [13, 14].

We first consider the evolution of the system starting from an initial state with no condensate $\psi = 0$. If the strength of pumping is enough to overcome losses $P > \gamma$, the $\psi = 0$ state is dynamically unstable against the creation of a finite condensate amplitude in all the low-momentum modes for which $\hbar k^2/2m < \Omega_K(1 - \gamma/P)$. The rate of this instability is maximum at $k = 0$ and