Observation of low-energy collective oscillations of an exciton-polariton condensate

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We report the observation of low-energy, low-momenta collective oscillations of an exciton-polariton condensate in a round “box” trap. The oscillations are dominated by the dipole and breathing modes, and the ratio of the frequencies of the two modes is consistent with that of a weakly interacting two-dimensional trapped Bose gas. The speed of sound extracted from the dipole oscillation frequency is smaller than the Bogoliubov sound, which can be partly explained by the influence of the incoherent reservoir. These results pave the way for understanding the effects of reservoir, dissipation, and finite temperature on the superfluid properties of exciton-polariton condensates and other two-dimensional open-dissipative quantum fluids.

Introduction.— Low-energy collective excitations represent a direct probe of the propagation of sound in quantum fluids and gases, which in turn provides critical information on the thermodynamic and superfluid properties of these systems. In particular, propagation of sound in two-dimensional (2D) quantum fluids [1–3] has attracted a lot of attention since it is governed by Berezinskii–Kosterlitz-Thouless (BKT) rather than Bose-Einstein condensation (BEC) physics. Furthermore, collective excitations can be used to probe quantum corrections to classical symmetries, as demonstrated in experiments on 2D Fermi gases [5, 6], and to verify quantum phase transitions [7–9] in dipolar gases.

Condensates of exciton polaritons (polaritons hereafter) are 2D non-equilibrium quantum fluids [10, 11] that exhibit a wide range of phenomena including BKT [12–14] and Bardeen–Cooper–Schrieffer (BCS) [15–17] physics, as well as superfluid-like behavior [18–21]. Their collective excitation spectrum is expected to differ from the Bogoliubov prediction for an equilibrium BEC, especially at small momenta, due to dissipation [22, 23] and coupling to an incoherent excitonic reservoir [24]. Contrary to expectations, recent experiments [25–28] revealed a renormalized dispersion consistent with Bogoliubov theory. However, these experiments either could not accurately probe the low-momenta region of the excitation spectrum [26, 27], or were performed in a near-equilibrium regime [28]. Moreover, polariton condensates are typically treated in the zero-temperature limit despite existing in a relatively high-temperature environment. Hence, direct access to the low-energy excitations (sound waves) is needed to understand the effects of dissipation, coupling to the reservoir, and finite temperature on polariton superfluid dynamics.

In this Letter, we report the observation of low-energy collective oscillations of a trapped 2D polariton condensate. Using an optically-induced round box trap in the pulsed excitation regime [29], we create an interaction-dominated condensate undergoing long-lived “sloshing” (see Fig. 1). By using principal component analysis (PCA), we identify two normal modes corresponding to center-of-mass (dipole) and breathing (monopole) oscillations.
lutions. In sharp contrast to the harmonic trapping case [30, 32], oscillation frequencies in a box trap depend on interparticle interactions, and hence can be used to probe collective properties of the condensate. In particular, we find that the ratio of the monopole to the dipole mode frequencies is consistent with that of a weakly interacting Bose gas. The speed of sound extracted from the dipole mode frequency is lower than expected and displays a non-trivial dependence on the interaction energy, indicating a strong influence of the incoherent reservoir on the dynamics of the low-energy collective excitations. Our estimate of the Landau damping of the oscillations is consistent with a 2D Bose gas in a collisionless regime.

Experiment.—The polariton condensate is created in a high-quality GaAs/AlAs $3\lambda/2$ microcavity made of 32(top) and 40(bottom) pairs of distributed Bragg reflectors (DBR) with 12 embedded GaAs quantum wells of nominal thickness of 7 nm [33]. A high-density condensate in the Thomas-Fermi regime is created in an optically induced round trap [see Fig. 1(a)] using off-resonant pulsed excitation in a geometry similar to Ref. [29]. The spatial hole-burning effect [29, 34] ensures that the pump-induced trapping potential is box-like, which is reflected by the sharp edges of the condensate density distribution (see SI). Time-resolved spectral imaging of real space (RS) and $k$-space (KS) dynamics is enabled by a streak camera. The condensate forms on a timescale of $\sim 50$ ps and then decays, which results in a fast rise and slow fall of the time-resolved photoluminescence (PL) signal, as shown in Fig. 1(b). Decay of the condensate density is accompanied by the decrease of the well-defined energy blueshift $\Delta E$ associated with condensate formation (see SI), which results in a one-to-one correspondence between time and the condensate energy.

The condensate decay typically occurs on a timescale of $\sim 200$ ps, which makes it impossible to track the slow dynamics associated with collective oscillations. To overcome this limitation, we use a high-energy photo-excitation $\sim 150$ meV above the lower polariton resonance. This excitation produces a long-living condensate, replenished by a large excitonic reservoir, as evidenced by the long PL decay time (up to 1.5 ns), that is much greater than the polariton lifetime [Fig. 1(b)]. This also results in a bright low-energy tail of the energy-resolved PL spectrum [see Fig. 1(c)]. Slow decay of the pulsed PL is the key ingredient of our measurements.

Results.—Time-integrated images of the condensate similar to the one in Fig. 1(a) typically capture the whole life cycle of the polariton emission, thus washing out all dynamics. In contrast, due to the well-defined energy of the condensate at any given time [see Fig. 1(b)], the energy-resolved RS distribution shown in Fig. 1(c) displays modulations of the PL intensity, indicating underlying density oscillations. Indeed, the time-resolved RS distribution, Fig. 1(d), reveals the spatial density oscillations, while the KS distribution shows that the majority of the polaritons occupy the $k = 0$ state (see SI).

It is important to stress that the images in Fig. 1(c,d) are accumulated over millions of the condensation realizations. The persistent density modulations indicate that the dynamics recur despite the stochastic nature of the condensate formation in every experimental realisation [34]. This recurrence is due to a significant wedge of our microcavity (effective linear potential) [33] oriented along the diagonal $x$-$y$ direction, as evidenced by the off-centred RS image in Fig. 1(a) and the tilted low-energy tail of the energy-resolved RS distribution in Fig. 1(c).

To analyze the observed condensate oscillations, we perform time-resolved tomography on the RS $n_r(x,y)$ and KS $n_k(k_x, k_y)$ density distributions (see SI). The distributions, with snapshots shown in Fig. 2(a,b), clearly display “sloshing” of the condensate along the diagonal direction, i.e. along the wedge of the cavity (see SI for movies of the condensate dynamics). When most of the polaritons are on one side of the trap, the $n_k$ is centred at $k = 0$, as shown by the right panels in Fig. 2(a,b), corresponding to zero-average momentum (kinetic energy) as the particles are changing directions at the classical turning point of the confining potential. When the $n_r$ is symmetric, $n_k$ is peaked at an extremum, as shown by left panels in Fig. 2(a,b), corresponding to a large average momentum as the particles move towards the other direction.

This harmonic motion with the frequency $\sim 10$ ns$^{-1}$ is summarized in Fig. 2(c,d), where the expectation values of position $\langle x \rangle$ and momentum $\langle k \rangle$, are calculated using the formula: $\langle x \rangle = \int x n_r dxdy / \int n_r dxdy$.
The normal mode solutions have the form:
\[
\omega_{l,m} = c q_l m R / R,
\]

where \( \omega \) is the angular frequency and \( c \) is the speed of sound. This wave equation is subject to the boundary conditions \( \nabla \delta n = 0 \) at the edge of the condensate \((r = R)\) and the continuity condition in the azimuthal direction. The normal mode solutions have the form:
\[
\phi_{l,m} \propto J_m \left( \frac{q_l m R}{R} \right) e^{im\phi},
\]

with \( J_m \) the Bessel function of the 1st kind and \( q_l m \) is the \( l \)-th root of its derivative \( J_m' \). The indices \( l, m \) denote the radial nodes and the orbital angular momentum of the mode, respectively, resulting in the dispersion:

\[
\omega_{l,m} = c q_l m R / R.
\]

Of particular interest are the dipole \((l = 1, m = \pm 1)\) and the breathing \((l = 1, m = 0)\) modes with the spatial profiles shown in Fig. 3(c,f) (see SI for other modes) and frequencies \( \omega_D \approx 1.84c/R \) and \( \omega_B \approx 3.83c/R \), respectively. The dipole mode is a center-of-mass oscillation, which for a purely \( m = \pm 1 \) state is a rotational “vortex”-like motion around the center of the trap. However, in an elliptical trap the degeneracy between the two dipoles is lifted, leading to oscillations along the short (long) axis of the trap at a slightly higher (lower) frequency. The breathing mode shown in Fig. 3(f) becomes a mixture of the monopole and quadrupole modes with a pronounced oscillation of the condensate width that does not affect its center of mass. The dominant modes extracted by PCA [Fig. 3(c,d)] are now readily identified as the dipole and breathing modes by comparison with Fig. 3(e,f). The time dependence of the respective weights [Fig. 3(a,b)] confirms that the center-of-mass and width oscillations are the dipole and breathing modes, respectively.

The dependence of the mode frequencies on the speed of sound, Eq. 3, which for a 2D quantum gas is a function of the interaction strength and the thermodynamic properties of the gas, is one of the remarkable advantages of a box trap. In contrast, in harmonic traps the frequencies do not depend on the interaction strength. In order to analyze the frequencies of the two dominant oscillations in our experiment, we perform a time-frequency analysis of the oscillation signals using a wavelet synchrosqueezed transform. This method is particularly useful in extracting the instantaneous frequency of a signal as well as separating multiple modes. Fig. 4(a) shows the frequencies extracted from the signals presented in Fig. 3(a,b) featuring two down-chirped
interacting 2D Bose gas in a box trap. For a 2D weakly interacting Bose gas in a harmonic potential, \( \omega_B/\omega_D = 2.0 \) [41]. In a slightly elliptical box trap with the aspect ratio \( a/b \approx 1.2 \), one also expects \( \omega_B/\omega_D \approx 2 \) (see SI). The consistent experimental ratio \( \omega_B/\omega_D \approx 2.0 \) presented in Fig. 4(b) suggests that the polariton condensate indeed behaves as a weakly-interacting 2D Bose gas in a box trap.

The dipole mode can be used to measure the speed of sound in the trapped condensate using the dispersion law Eq. 3, \( c = \omega_D R/1.8412 \). At zero-temperature and with negligible quantum depletion of the condensate, the speed of sound should be equal to the Bogoliubov sound \( c_B = \sqrt{\gamma n/m} \), where \( \mu = gn \) is the condensate interaction energy, \( g \) is the polariton-polariton interaction strength, \( n \) is the polariton density, and \( m \) is the effective mass. The interaction energy in our experiment can be inferred from the instantaneous blueshift of the condensate PL [Fig. 1(b)], provided that only the polariton-polariton interaction contributes to the blueshift [29].

Fig. 4(c) summarizes the measured speed of sound as a function of the blueshift for different excitation powers. As expected, the extracted speed of sound decreases with the diminishing interaction energy (or with time). The results for different trap sizes and effective masses (see SI) show that, at early times, the extracted speed of sound is independent of the trap or condensate size but decreases with increasing effective mass. At large blueshifts (or early times), the measured speed of sound follows the predicted square-root law but deviates from it when \( \Delta E < 1 \) meV. This results in an apparent linear dependence on \( \Delta E \). More importantly, the measured speed of sound at large blueshifts is approximately three times smaller than the Bogoliubov sound \( c_B \) [see Fig. 4(c)].

In contrast to our previous work [29], where we used a lower energy excitation, here the reservoir density is not fully depleted, as evidenced by the slow decay of the condensate PL. This means that the polariton-reservoir interaction also contributes to the measured blueshift, i.e.

\[
\Delta E \approx g(n + |X|^2 n_R),
\]

where \( n_R \) is the reservoir density, and \( |X|^2 \) is the excitonic Hopfield coefficient. Consequently, \( c_B = \sqrt{\gamma n/m} < \sqrt{\Delta E/m} \). Without a direct measurement of the instantaneous polariton density, it is impossible to accurately quantify the ratio \( n/n_R \). However, we can estimate the ratio to be \( n_B/n \approx 4 \) at early times and \( n_B/n \approx 1.5 \) at later times (see SI). The latter value agrees with previous measurements under off-resonant CW [27] and resonant [26] excitation conditions.

It is important to note that the condensate is in the interaction-driven collisionless rather than the hydrodynamic regime [3]. For polaritons near zero detuning, the dimensionless interaction constant is \( \tilde{g} = mg/\hbar \sim 10^{-3} \), where \( g \approx 2 \) \( \mu \)eV\cdot\mu m\(^2\) is the polariton-polariton interaction strength per quantum well [29]. The resulting effective collision frequency [41] is \( \Omega = \hbar \tilde{g}^2 n/m \sim 0.1–1 \) ns\(^{-1}\) for \( gn \sim 0.1–1 \) meV. Since the oscillation frequency \( \omega \) is much larger than the collisional rate, \( \omega \gg \Omega \), the collisional hydrodynamic regime is not reached.

Finally, although the condensate densities are much higher than the threshold density [29], the thermal energy (assuming \( T \approx 10 \) K [27]) is comparable to the interaction energy, i.e. \( k_B T/gn \sim 1 \). Moreover, \( k_B T \) is an order of magnitude higher than the oscillation energy \( \hbar \omega \sim 0.1 \) meV. Hence, the thermal excitations play an
important role in Landau damping of the condensate oscillations, which arises from the absorption of quanta of oscillations by thermal excitations \( \gamma \). An estimate of the damping rate from Fig. 3(a,b) gives \( \gamma_D \sim 1 \text{ ns}^{-1} \) for the dipole mode and \( \gamma_B \sim 2 \text{ ns}^{-1} \) for the breathing mode, resulting in a \( Q \)-factor of \( Q = \omega/\gamma \approx 60 \). This estimate agrees with the predictions for the Landau damping of a 2D Bose gas in the collisionless regime [3,4].

**Conclusions.**—We have observed long-lived collective oscillations of a polariton condensate in a box trap. The oscillations are dominated by the dipole and breathing modes, with the ratio of frequencies well described by a model of 2D weakly interacting bosons. The speed of sound determined from the dipole frequency is lower than the Bogoliubov sound, assuming the condensate blueshift is only due to polariton-polariton interactions. This discrepancy points to the significant presence of the reservoir in the system. Apart from the contribution of the polariton-reservoir interaction to the blueshift, the presence of the reservoir and dissipation can strongly modify the excitation spectrum at low momenta [22,23]. This can affect the method used here to extract the speed of sound, which relies on low-momenta density waves. Our future studies will focus on selective collective mode excitation by using a pulsed perturbation of a steady-state reservoir, dissipation, and finite temperature [3,4,43] on the superfluidity of 2D open-dissipative systems. Further investigations of the breathing mode frequency can also lead to experiments on quantum corrections beyond the mean-field approximation [5,6], as well as signatures of crossovers between the quantum phases of polaritons.

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