BOSONIC CONDENSATES

Polariton pendulum

A macroscopic quantum pendulum has now been created by confining a polariton condensate in a parabolic optical trap. Spectacular images of multiparticle wavefunctions are obtained by purely optical means.

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In a simple gravity pendulum, the potential energy of the bob depends quadratically on its angular displacement — at least in the vicinity of its equilibrium position. Similarly, a quantum pendulum can be approximated by a parabolic potential well, where the eigenfrequencies of a massive particle form an equidistant spectrum. Now, as reported in *Nature Physics*[1], Guilherme Tosi and his co-workers have realized a pendulum in which the role of the massive bob is played by a macroscopic coherent state, or condensate, comprising hundreds of identical quasiparticles. The spontaneously formed condensate occupies a ladder of equidistant quantum states confined in an optically induced potential trap (Fig. 1) and oscillates inside the trap at terahertz frequencies.

An exciton polariton is a quasiparticle formed of a photon and an exciton (an electron–hole pair bound by the Coulomb interaction) combined in a Fabry–Pérot microcavity. They exhibit a number of unusual properties linked to their mixed light–matter nature. The work of Tosi *et al.* is the latest element in a chain of experimental discoveries that began in 1992 with the observation by Claude Weisbuch and co-workers[2] of strong exciton–light coupling in microcavities. This idea was further developed in 1998 when Le Si Dang *et al.*[3] reported the condensation of exciton polaritons in momentum space. In 2000, Pavlos Savvidis and colleagues[4] realized a polariton parametric amplifier, which was based on bosonic stimulation of polariton–polariton scattering. In 2006 and 2009, features of Bose–Einstein condensation[5] and superfluid propagation[6] of exciton polaritons were observed. And in 2010, a macroscopically extended polariton condensate was seen in a microcavity stripe[7]. Although the scientific community is still divided about the proper terminology for describing polariton gases and fluids, the physics behind these observed effects is sufficiently clear: exciton polaritons occupy *en masse* single quantum states — states that may have spatial dimensions spanning tens of micrometres. In contrast to atomic condensates, polariton condensates can be produced at high temperatures, even at room temperature[8].

Tosi *et al.* studied a microcavity in which the light mode confined between two dielectric mirrors was resonant with the exciton transition of the quantum wells embedded within. Exciton polaritons were created inside the sample frozen to liquid-helium temperature using two spatially separated laser beams. The exciton polaritons were cooled down through interactions with the crystal lattice, and eventually formed condensates with spatial dimensions as large as several tens of micrometres.

The team handled their polariton condensate using a minimum of tools. The tunable parameters of the system were the distance between the two pump beams and the lasers' intensity. To create a one-dimensional trap for the condensate, they made use of exciton–exciton repulsion. The two pump beams produced two potential hills, and the valley between the hills played the role of a parabolic trap. The condensate was quantized inside this trap, forming a ladder of equidistant quantum states with multiparticle wavefunctions (Fig. 1). Splitting between the confined states was sensitive to the size of the trap: that is, the distance between the pump beams. The coherence time in this system was shown to be longer than the single polariton lifetime, so the observed multiple condensates remain coherent. As a result, a macroscopic quantum harmonic oscillator or pendulum was realized.

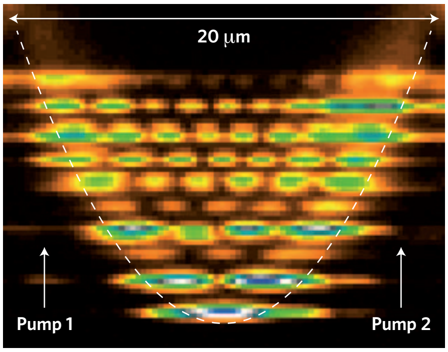

Figure 1 | Polariton pendulum. A parabolic optical potential generated using two pump laser beams creates a trap for an exciton–polariton condensate. The multiparticle wavefunctions can be imagined using optics alone. Figure adapted from ref. 1.

In the time domain, the condensate was found to oscillate in the trap with a terahertz frequency, which could be tuned by changing the spacing between the pump spots. Comparison of the experimental data with a theoretical model based on the complex Ginzburg–Landau equation enabled the researchers to conclude that the condensates that occupied different quantum states of the 'pendulum' were mutually coherent. They argue [**AUTHOR: OK?**] that the energy-conserving polariton–polariton scattering populates the ladder of confined states with exciton polaritons that are correlated in phase. Moreover, the authors suggest that this scattering, which is efficient only if the involved initial and final states are separated by equal energy intervals, is responsible for formation of the parabolic confining potential. This latter statement still needs verification, as it looks like the parabolic confining potential is governed by the strongly populated exciton reservoir rather than by the polariton condensate.

The experiments on polariton condensation at non-resonant optical pumping present a challenge to theorists. The description of an incoherent reservoir of optically pumped polaritons together with a coherent condensate fed by this reservoir is not a straightforward task. As an essentially non-equilibrium system, microcavities with polariton condensates seem to require a theoretical treatment going beyond the mean-field approximation. In my view, a nonlinear Liouville equation applied to the density matrix of the whole system would be an adequate theoretical tool.

The experiment opens a way towards engineering polariton condensates by optical means. Manipulation of bosonic particles with macroscopic coherent states is crucial for realizing optical logic elements such as polariton neurons[9] or Aharonov–Bohm [**AUTHOR: this spelling OK?**] rings[10]. Also, bosonic transport of exciton polaritons is a new and promising direction for polaritonics. When moving in the plane of the microcavity by fractions of a millimetre, the polaritons conserve their coherence and polarization; this is important for realizing spin–optronic devices based on bosonic spin currents. To this end, it would be interesting to repeat the experiment while varying the polarization of the pump light in an attempt to create spin-selective polariton traps. ❒

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