Polariton Condensation

Intrinsic decoherence mechanisms in the microcavity polariton condensate

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Phys. Rev. Lett. **101**, 067404 (2008)

Quantized vortices in an exciton-polariton condensate

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Nature Physics, **4**, 706 (2008)

Observation of Bogoliubov excitations in exciton-polariton condensates

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Nature Physics, **4**, 700 (2008)

Persistent currents and quantised vortices in a polariton superfluid

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Recommended with a Commentary by Peter Littlewood, University of Cambridge

Over the last few years, strong evidence has built for a new kind of condensate, that of exciton polaritons, which are a coherent superposition of a photon and an electron-hole pair, i.e. a composite boson. Following on from strong evidence for thermal condensation[1], further experiments have made traps[2,3] demonstrated driven condensates[4] and the headlined papers demonstrate further some of the special features of these new systems.

The systems under study are two-dimensional cavity polaritons in III-V or II-VI semiconductor structures: by growing a Bragg mirror on top of a $\lambda/2$ cavity, see Figure, one makes two-dimensional wave-guide modes with a quadratic energy-in-plane-momentum dispersion and an energy tuned near the semiconductor band gap. At the antinode of the photon wavefunction, one or several quantum wells are grown; the thickness of the cavity is tuned to the excitation energy of excitons. In these direct gap semiconductors, an exciton can dipole-decay into a photon. In the dilute limit, we have a system of coupled bosons, and

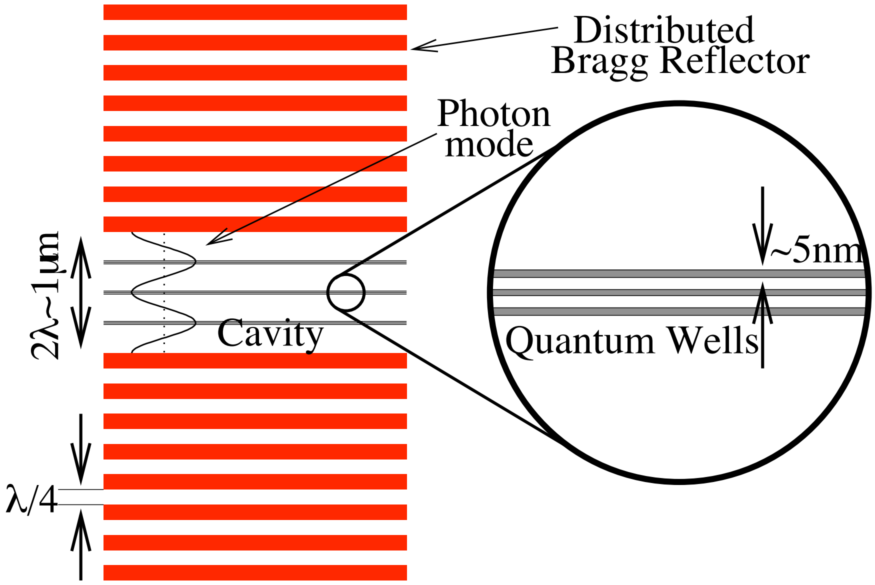

FIG. 1: Schematic diagram of a microcavity, formed by a pair of distributed Bragg reflector stacks, with quantum wells at the antinodes of the cavity photon mode. [From[5]]

mixing and level repulsion leads to two highly dispersive polariton modes near $q = 0$, with effective mass $\sim 10^{-5}$ m_e, consisting of particles with roughly equal character of photon and exciton. The decay rate from the cavity has to be much smaller than the Rabi splitting between lower and upper polariton modes (which here is in the range 10-30 meV and sets the coupling); with cavity quality factors around 10^4 that are now routinely achieved polaritons are thus long-lived (though with lifetimes still measured in psec).

The decay into external photons provides an added bonus nonetheless: If the mirrors are smooth enough, the emerging photon carries away the transverse momentum of the polariton that produced it. Thus by measuring the angular dependence of emission, one gets direct measure of $n(q)$, the population as a function of momentum; and by measuring the energy dependence one sees not only the polariton dispersion but any changes in quasiparticle lifetime. Moreover, since the emission is inelastic, phase information is preserved, and so interference between emitted photons can be used to map directly the phase coherence of the polariton fluid. Lastly, one can use the out-coupling to drive the system coherently by an external laser, a new twist unavailable to a superconductor.

The spontaneous coherence temperature of a dilute Bose gas varies proportional to the ratio of density to mass, so with such light particles one has the attraction of a high-temperature condensate. The challenge is of course to prepare an equilibrium system (and measure it) on a picosecond time-scale; or to continously pump the system gently enough that equilibrium is established by polariton-polariton collisions and that inelastic and decay processes cause not too much decoherence. This has not been easy, and although cavity polaritons were first demonstrated in the 90's, it has required a substantial effort of several different groups over a long period to reach the conditions for a thermalized polariton fluid.

Spatial mapping of the coherence is now common, and two of the recommended papers discuss quantised vortex observation and driven vortex dynamics; the other papers demonstrate temporal coherence, both through a direct analysis of the order parameter dynamics, and through the excitation spectrum.

These and other experiments establish fairly conclusively that exciton-polaritons have been induced to form a new coherent state of matter. Is there a difference between this system and the generic dilute Bose gas?

One issue is diluteness: a dilute limit only makes sense to the extent that $T_c \ll g$, the Rabi splitting, and since $T_c \propto (n/m_{eff})$ this crossover happens at around 10^9 cm^{-2}, in the vicinity of the range of the current experiments. Another way to put this is to realise that the mass ratio of photon to exciton means that the photon introduces nearly infinite-range interactions between the excitons, treated as few-level systems. This is the range of strong-coupling mean-field theory (as opposed to BCS which is successful precisely because of *weak*-coupling). But this will allow not only quantitative modelling of a strong coupling problem, but also careful analysis of finite-size quantum to classical crossover, both in thermal equilibrium, and in quantum dynamics.

Another point is decoherence: the particles have a finite lifetime. This is not a "proper" superfluid; owing to the decay the excitation spectrum at the longest wavelengths is diffusive, with a crossover length determined by the decay time. The order parameter (XY-like) is eventually classical, diffusing because of the addition and removal of particles with random phase. Here is another classical-quantum crossover to study, which should give rise to a crossover of propagating Bogoliubov modes to diffusive waves at the largest length scales.

One should interject here the difference between a polariton condensate and a conventional laser, because *both* emit coherent light. A regular laser is sometimes called "weak coupling", meaning that the electronic spectrum is not strongly modified by the interaction with light."Weak" means that the Rabi splitting is small in comparison to the decay rate, so the split polariton spectrum does not emerge. The electronic system is then (very nearly) incoherent, which means that lasing action occurs only if the levels are *inverted.* In contrast, the polariton condensate maintains coherence of *both* photons and the electronic excitations; it is a laser without inversion. But it's now also clear that one can also have a situation of a polariton laser that arises not from thermal equilibrium: such has indeed been seen in GaN at room temperature.

For the future: Having struggled so hard to make systems in thermal equilibrium, it's clear that one direction is back to quantum dynamics. It may be possible to prepare well-defined initial microscopic states of excitons and follow the quantum dynamics, returning in a new guise to some of Dicke's original thinking of more than half a centure ago

A longer review (mostly of theory) is here[5]. The 4th International Conference on the Spontaneous Coherence of Excitons (Sept 2008) has most of the speakers' talks available to download.[6]

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