Sculpting Quantum Matter with Light

Jeremy Baumberg and Natasha Berloff demonstrate how quantum phenomena can be observed on the macroscopic scale opening up remarkable future possibilities.

Quantum Mechanics is counterintuitive but as physicists we become familiar with it, working far outside our normal human experience, with individual atomic-scale particles. Much of the history of the Cavendish has been punctuated by the development of new ways of exploring quantum systems through probes that extend our senses into this domain. What would it be like, however, if we could directly watch quantum mechanics in action, sitting on a table in front of us? As undergraduates, we drew wavefunctions with graceful oscillations and nodes, but might we literally create a box to confine them and see quantum evolution in front of our eyes?

In our recent collaboration with the experimental team at the NanoPhotonics Centre, we are exploring a system which allows us to do just that. We investigate the properties of a 'quantum liquid' which spreads out in sheets hundreds of microns wide but which, unlike normal liquids, possesses a global macroscopic quantum phase over distances visible to the naked eye. In 1937, Pyotr Kapitsa, after whom our building is named, discovered the peculiar properties of quantum liquids and more recently Brian Josephson showed how electrons in superconducting states could dance to the same tune. But in our recent work, the particles making up the liquid are not the 'fundamental' or 'natural' ones, such as helium atoms or electrons in lead, but are created inside semiconductors built into nano-structures of exquisite precision.

Designing and growing stacked layers of selected atomic species such as gallium, arsenic, indium and aluminium, we can control where electrons move and how they interact with light. In our devices, we sandwich the electrons into thin sheets, in which they absorb and emit light of a specific colour. Around these 'quantum wells' we grow extremely shiny mirrors which efficiently trap light in between them, but only of a colour set by the micron-sized gap between the mirrors because of the need to recirculate the light to return in phase after each round trip. By matching the colour of this microcavity light and the electronic emission, radiated photons from relaxing electrons are immediately returned back into the semiconductor, re-exciting electrons into an identical state. So energy continually oscillates between light and matter. This coherent mixture of electrons and photons forms a new quasiparticle called a 'polariton', with completely new properties that we can control through clever design.

The photon component of polaritons makes them thousands of times lighter than electrons, billions of times lighter than typical atoms, and achieves sufficient densities to form polariton Bose-Einstein condensates (BECs). In a BEC the quantum phase of the bosonic particles synchronises and creates a single macroscopic quantum object. This was first achieved with atoms at ultra-cold temperatures, on the scales of nanoKelvins. The achievement of a polariton BEC in 2006 by a team at the Cavendish [1] was followed by a blossoming of experimental activity eventually allowing us even to reach room temperatures [2].

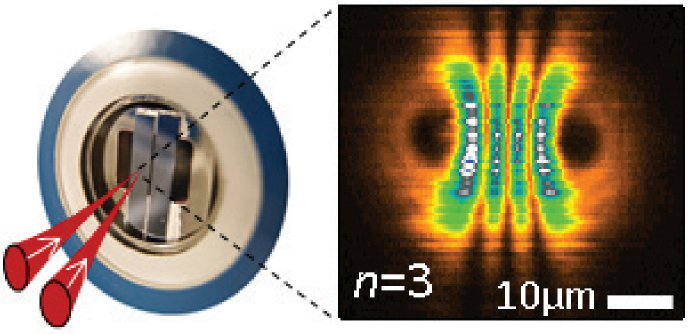

Fig.1. Two CW pump lasers focussed 20µm apart onto the microcavity (black holes on right image) create a trap for the polariton condensate in between. Photon emission shows the spontaneously formed n=3 quantum harmonic oscillator state [3].

Our recent work published in *Nature* and *Science* this year is based on producing samples so uniform that the polaritons can skate sideways at will inside their sheets, unfettered by imperfections, allowing the direct study of the two-dimensional quantum liquids they form. Shining light from above onto a spot on the surface excites polaritons, which diffuse out sideways and condense into a BEC when they are dense enough. Above this threshold a single quantum phase describes the wavefunction of all the polaritons together. Now we can easily inject two condensates in close proximity and watch them interact. One discovery has been the spontaneous emergence of patterns and dynamics in these condensates, which is only possible because they are not closed systems since polaritons continually decay into light escaping through the slightly leaky mirrors. We see coherent packets of polaritons oscillating back and forth, forming a precise version of the simple quantum harmonic oscillator states (Fig.1) but now on the scale of tens of microns across and so easily seen through a magnifying lens [3]. Creating arbitrary configurations of condensates on the fly, we can trap polariton condensates and start to teach them tricks. For instance we can create polariton interferometers which respond exquisitely sensitively to their environment. We have achieved a long held dream of creating macroscopic quantum states which we can tweak and prod on the human scale.

One of our major goals is the creation of such condensates at room temperature and by electrical excitation creating truly quantum devices. We have found that by stacking double sheets of electrons inside these structures, we can enable the polaritons to undergo quantum mechanical tunnelling which can be measured electrically [4]. And we have devised new ways of coaxing polariton condensation at higher temperatures. No fundamental limits now stand in the way of quantum devices operating in the palm within the next few years.

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