search & discovery

Experiments reveal a Bose–Einstein condensate of photons

Key to the achievement is the confinement of photons and molecules in an optical cavity long enough for them to reach thermal equilibrium.

A Bose–Einstein condensate (BEC) is the remarkable state of matter that spontaneously emerges when a system of bosons becomes cold enough that a significant fraction of them condenses into a single quantum state to minimize the system's free energy. Particles in that state then act collectively as a coherent wave. The phase transition for an atomic gas was predicted by Albert Einstein in 1924 and experimentally confirmed with the discovery of superfluid helium-4 in 1938. Once the techniques to trap and cool atoms to nanokelvin temperatures were developed more than half a century later, it was finally observed in dilute rubidium clouds in 1995 (see the articles by Wolfgang Ketterle and by Keith Burnett, Mark Edwards, and Charles Clark in PHYSICS TODAY, December 1999, pages 30 and 37).

Atoms aren't the only option for a BEC. Photons, as massless, chargeless, and structureless particles of integer spin, are the simplest of bosons. They're also omnipresent. One need only switch on a light bulb for a cheap and ready supply. Moreover, Satyendra Nath Bose had photons in mind in 1924 when he first proposed a new way of counting indistinguishable particles, work that led to Einstein's prediction the same year.

Yet, as Einstein surely knew, blackbody photons—those in thermal equilibrium with walls of a cavity—simply do not go through the phase transition. Unlike atoms, whose number is strictly conserved as the temperature is varied, photons are easily created and annihilated. As the photons are cooled in a cavity, they simply diminish in number by disappearing into its walls. Indeed, the blackbody spectrum is precisely that of a critical Bose gas, stubbornly on the verge of condensation, with the maximum possible number of uncondensed photons residing in the cavity at any given temperature.

Also unlike atoms, photons do not usually interact with each other. That's not an issue in systems such as a laser, whose coherent light is achieved under conditions far from equilibrium. But their lack of interaction complicates how the photons might reach thermal equilibrium among themselves, a key prerequisite to achieve a BEC.

Martin Weitz and colleagues at the University of Bonn have now overcome both obstacles using a simple and elegant approach: By confining laser light within a thin cavity filled with dye at room temperature and bounded by two concave mirrors, they create the conditions required for light to thermally equilibrate as a gas of conserved particles rather than as ordinary blackbody radiation.[1]

When photons act like atoms

Figure 1 illustrates the experimental design. The mirrors' curvature provides a trapping potential. And their extremely high reflectivity ensures that laser-generated photons remain trapped long enough to scatter among the dye molecules, which repeatedly absorb and reemit the light.

Only those photons resonant with the dye and with the mirrors' separation—1.5 μm along their center, or just 7 half-wavelengths—are supported by the cavity. That restricts their energies to a minimum cutoff of 2.1 eV or higher. Because those energies are so much larger than the dye's thermal energy (1/40 eV), spontaneous thermal excitations of photons are negligible. So although the number of photons can change locally during the exchange of energy and momentum with the dye, the mean number is determined entirely by the pump-laser intensity.

The cavity geometry and the dye's absorption and fluorescence properties also limit the scattered photons to just one longitudinal electromagnetic mode of the cavity. But they are free to vary among several transverse modes as they equilibrate with the dye heat bath. The fixed longitudinal mode number adds a constant energy offset to the energy associated with the propagation of a photon in the transverse resonator plane. One can show that the Hamiltonian for photons in the trapping potential is, in fact, equivalent to that for a 2D gas of massive bosons—with each photon acquiring an effective mass of $\hbar\omega_{cutoff}/c^2 \sim 10^{-35}$ kg, some 10 orders of magnitude less than a Rb atom.

The canonical condition for a BEC is that the thermal de Broglie wavelength of the bosons be comparable to the distance between them. Lowering their temperature—below a microkelvin in the case of atoms—is the usual approach to reaching that regime. But for cavity photons, whose effective masses are so small that quantum effects

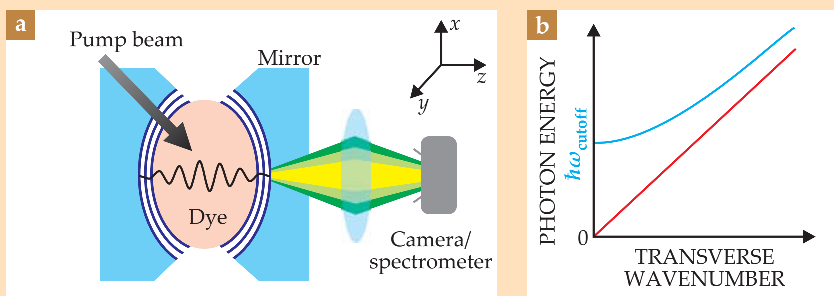

Figure 1. (a) Photons from a laser illuminate and become trapped inside an optical cavity filled with dye and bounded by two reflective mirrors. The photons thermally equilibrate by exchanging energy with dye molecules through multiple scattering. Photons eventually escape from the cavity and their emission is captured by a camera or spectrometer. While they're inside, the small mirror spacing restricts the photons to one longitudinal electromagnetic mode along *z*, but allows any of several transverse modes along *x* and *y* to be occupied. **(b)** Within the cavity, the photons' dispersion curve becomes quadratic, their minimum ground-state energy given by $\hbar\omega_{cutoff}$. (Adapted from ref. 1.)

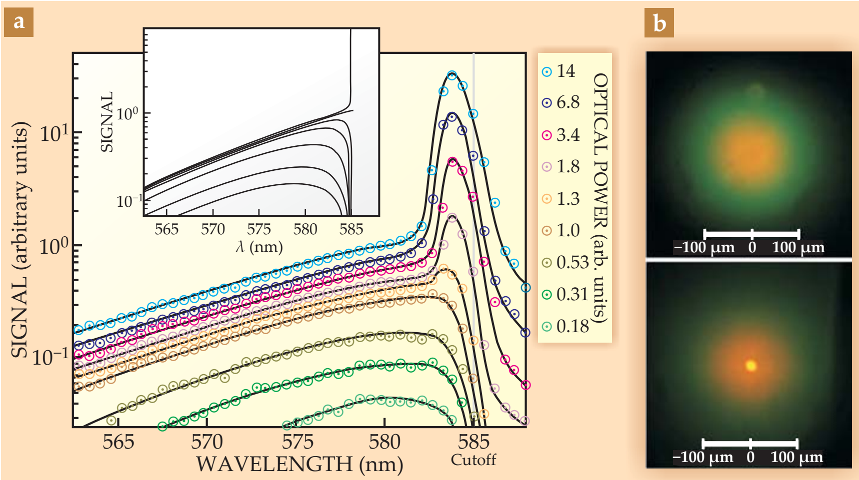

Figure 2. Spectral and spatial intensity distributions. (a) Below a critical photon density, photons captured by a spectrometer outside one of the mirrors exhibit a broad Boltzmann distribution of wavelengths. As the laser power increases, so does the photon density, and a spectrally sharp condensate peak eventually emerges at the cutoff wavelength of 585 nm. The inset shows the theoretical spectra based on a Bose–Einstein distribution for different photon numbers at room temperature. **(b)** The top panel shows the photons' thermal spatial distribution just prior to condensation. The bottom panel shows the emission of photons condensed into a single macroscopic state (the TEM_{00} mode) against a thermal background of higher-energy photons. (Adapted from ref. 1.)

emerge even at room temperature, density is the more convenient knob to turn. For evidence of the transition to a BEC, Weitz and colleagues dialed up the pump-laser power to increase the cavity photon number and captured the spectral intensity and spatial distribution of light leaking out one of the mirrors.

At low pump power, the spectral emission is broad and fits a Boltzmann distribution of photon wavelengths below the cavity's cutoff of 585 nm, as shown in figure 2a, indicative of a thermal distribution of photons in the transverse modes of the cavity. With increased power, the emission from the cavity starts to resemble a Bose–Einstein distribution, as the wavelength of maximum intensity shifts toward the cutoff. Above a threshold number of about 63 000 photons in the cavity, a sharp peak emerges at the cutoff wavelength, a signature of photons piling into the lowest-energy transverse mode. The BEC emission from that so-called TEM_{00} mode appears as a bright spot against a thermal background (figure 2b).

Interestingly, the spot's spatial profile widens as more photons are added to the BEC state. That shouldn't happen for an ideal gas of noninteracting photons. But each additional photon circulating in the dye alters the medium's index of refraction, a nonlinear effect that reflects a weak mean-field photon–photon interaction. To convince themselves that the light emission comes from a condensate rather than from some nonlinear artifact of the pump light, the researchers focused laser photons at a spot well away from the center of the trapping potential. Reassuringly, the BEC light emission still developed and migrated to the trap center.

The weak and the strong

In 1930, shortly after Bose and Einstein described the quantum statistics of photons and atoms, Felix Bloch applied it to excitations in a ferromagnet. And just a few years ago, researchers experimentally produced condensates of magnons,[2] quasiparticles that represent collective spin excitations in a solid, and condensates of polaritons, quasiparticles formed from the quantum mechanical superposition of a photon and an electron–hole pair in a semiconductor[3] (see the article by David Snoke and Peter Littlewood in PHYSICS TODAY, August 2010, page 42).

Like photons, polaritons also condense in a system composed of a pump laser and microcavity mirrors that confine the quasiparticles for longer than it takes them to thermalize. Indeed, the experimental geometry and pumping schemes in both types of experiments are quite similar, though one uses an external cavity and the other uses a quantum well trapped between dielectric layers in a semiconductor. The essential difference is the nature of the systems' interactions.

Polaritons at high density in microcavities experience strong repulsive scattering interactions, which allow them to thermalize in less than a picosecond, important because polaritons only survive for a brief 5–20 ps before tunneling out of the cavity. The photons and their electron–hole pairs are thus strongly coupled through the matter–light interactions, which lock the two polariton constituents in phase. But in the purely photon BEC, photons and dye molecules remain distinctly separate and weakly coupled reservoirs. The photons hardly interact with each other, so the experiment is ideally suited to explore the weak-interaction limit of what is a very active field.

In a BEC, Bose–Einstein statistics force every photon above some critical number into a single coherent wavefunction. According to Weitz, preliminary interferometry measurements using photons from the long-wavelength peak of figure 2 bear out the expected coherence to some extent. The coherence length of the photon condensate leaking from the cavity is at least 200 μm, given the resolution limit of their spectrometer. Follow-up experiments, he says, include measuring the actual coherence length and investigating the system's intensity fluctuations inside the BEC. Because the photon number can vary in a grand-canonical way due to energy exchange with the dye, those fluctuations should be far greater than the typical coherent state of a laser.

For Dan Stamper-Kurn at the University of California, Berkeley, the simplicity of the new light source offers particular appeal. An all-optical BEC avoids cryogenic temperatures and ultrahigh-vacuum chambers, is potentially amenable to all the tools of nonlinear and quantum optics, and presents an easily detectable signal. "When I read their paper, after having slaved so often to build complicated cold-atom experiments," he says, "I was stunned it worked out so well and that their system could get at much the same physics as an atomic BEC. I immediately turned to my graduate students and asked, 'Should we be doing this?'"

Mark Wilson

References

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