Bose–Einstein condensation in a dilute atomic vapour

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A team of researchers working at the Joint Institute for Laboratory Astrophysics (JILA) in Boulder, Colorado, has just announced[1] having observed three distinct signatures for the occurrence of Bose–Einstein condensation (BEC) in a dilute ultracold vapour of atomic rubidium-87 (^{87}Rb). The most distinctive signal claimed for the onset of the BEC was an abrupt appearance (and gradual growth) at (and below) a threshold temperature of an anisotropic momentum distribution sharply peaked about zero against a diffuse, isotropic thermal background that reflected the lowest-energy *single*-particle state, now being occupied *macroscopically* (i.e. extensively) by the bosonic ^{87}Rb atoms. And that is precisely what the Bose–Einstein condensation is all about – a *macroscopic* (*finite* fraction of the total) number of particles occupying the lowest-energy *single*-particle state, leaving the higher states sparsely populated.

The experiment involved (i) confining a sample of about 2000 ^{87}Rb atoms to a volume about 10 µm across, thus compressing the vapour to a number density of about 2.6×10^{12} cm^{-3}, and (ii) cooling it to an abysmally low temperature of about 170 nk and maintaining the BEC so obtained for a reasonable length of time of about 15 s for diagnostic studies. All this necessitated a synergetic combination of novel experimental techniques for trapping and cooling of atoms. Thus, the magnetic trap used was essentially a quadrupolar magnetic field that dotted with the antiparallel-aligned magnetic moments of ^{87}Rb atoms ($F = 2$, $m_F = 2$) so as to give a confining potential well. This potential well, however, had at its central minimum the magnetic field equal to zero, allowing the atoms to flip their moments freely through unavoidable perturbations and escape. This *leak* was *plugged* in an ingenious manner by superimposing a rotating magnetic field, slow enough for the moments to follow adiabatically but fast enough to yield a time-averaged orbiting potential (TOP) which was parabolic, and with a non-zero averaged magnetic field at the minimum that prevented the spin flip. The TOP was a uniaxial 3D harmonic potential giving an oblate ground state wavefunction. The latter was reflected in the anisotropic momentum (velocity) distribution of the BEC recorded by shadow imaging. As for the cooling, the atomic gas was precooled by the laser Doppler technique, in which the atoms are retarded by a set of counterpropagating laser beams with their frequency tuned slightly below that for an atomic resonant absorption. The Doppler shift then ensures that the moving atom has the sisyphean task of always having to climb up a potential hill and hence get retarded to a near-zero speed. This is then followed by a *forced evaporative cooling* in which the more-than-average energetic atoms are allowed to escape the magnetic trap at the edges, leaving the tardier atoms to thermalize to a lower temperature. The evaporation is ingeniously *forced* by an rf magnetic field that flips the spins of the energetic atoms near the edge. This instantly inverts the potential well, thus facilitating escape. These techniques, developed and perfected over the years building on the work of several research groups, enabled the researchers to create finally the extreme condition of phase space density $n\lambda_T^3 = 2.621$ required for BEC. Here n is the number density and $\lambda_T = h/(2\pi m k_B T)^{1/2}$ is the thermal de Broglie wavelength of the condensing atoms.

Now, the idea of Bose–Einstein condensation is by itself not new, having been predicted by Einstein in 1925 for ^{4}He, basing on the then new quantum Bose statistics for particles with integral spin, such as photons, proposed by Satyendra Nath Bose[2]. Unlike their half-integral 'exclusive' cousins, the fermions (such as electrons or ^{3}He), bosons are gregarious, and arbitrarily large number of them are allowed (in fact, are *encouraged* to) occupy a given single-particle state. At a sufficiently low (high) temperature (density) this creates an overpopulation crisis and a macroscopic (finite fraction of the total) number condenses into the lowest single-particle state. This, of course, happens only for permanent bosons with a fixed given number (e.g. ^{4}He) and not for photons, say, where the number keeps diminishing as the temperature is lowered and hence no BEC. At this phase-space density, the de Broglie wavelength is comparable to the mean interparticle spacing (overlapping wavefunctions), and the quantum-mechanical indistinguishability of identical particles asserts itself by making the condensate behave as a single coherent entity. Stable BEC is known to exist in liquid ^{4}He below 2.2 K, where it is implicated in superfluidity. It has been achieved transiently in a gas of excitons, electron-holes ($e^- - e^+$) bound pairs created optically in a semiconductor like cuprous oxide[3]. Spin-polarized hydrogen (H$\downarrow$) has been for the last 15 years a strong candidate: it remains gaseous down to absolute zero of temperature[4]. Then why so much excitement about BEC in ^{87}Rb, one may ask. Of course, the threshold phase-space density for BEC is easier to obtain for the lighter atoms. But, the purely quantum-statistical effects are corrupted by the strongly interacting nature of these dense systems. By comparison, for the dilute ^{87}Rb gas in question, the mean interparticle spacing ($\sim 10^{-4}$ cm) >> the scattering length ($\sim 10^{-6}$ cm) and hence the near-ideal Bose gas condition prevails. (The magnetically trapped gas is metastable against crystallization at nanokelvin temperatures). Also, ^{87}Rb with conveniently accessible electronic transitions is manipulable, even its interactions are optically tunable. One can probe the entire quantum phase diagram – dilute gaseous BEC, dense liquid BEC, superfluidity, quantum solid and possibly superfluid solid! Also, the kinetics of the Bose–Einstein condensation itself[1]. Besides, compared to the aristocratic quantum fluids, e.g. ^{4}He, the rubidium-87 (an alkali) is really ordinary!

In what sense is BEC *coherent matter*? This is best illustrated by its possible interaction with light, e.g. photoassociation[5]. For a condensate of N atoms, the optical transition-dipole will be $\sqrt{N}$ times that for a single atom even if the condensate size is less than the wavelength of light. Coherent matter analogue of optical laser is also being speculated upon!

One could envisage several other basic studies – Anderson localization (and confinement) of BEC by random potential created by an optical speckle pattern simulating quenched disorder. One could also examine the fundamental question of the effect of frictional (γ) decoherence on BEC – one may not have any BEC at all for $\gamma > (\hbar/m)\, n^{2/3}$ even at the absolute zero of temperature. The friction γ can be tuned optically, or by dilution with noncondensing (fermionic) atoms. One expects a BEC to have a negative temperature coefficient of expansion. And so on

One may conclude by saying that if phase and coherence are to dominate our thinking in the years to come, then the coherent matter (BEC) may well be a laboratory of choice.

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