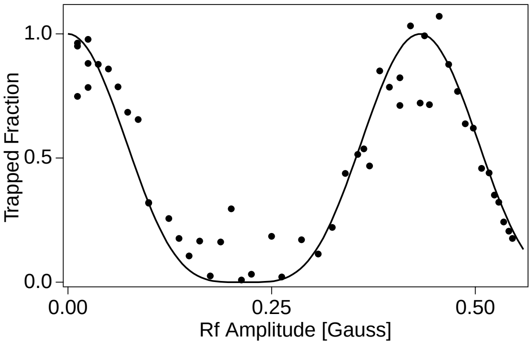
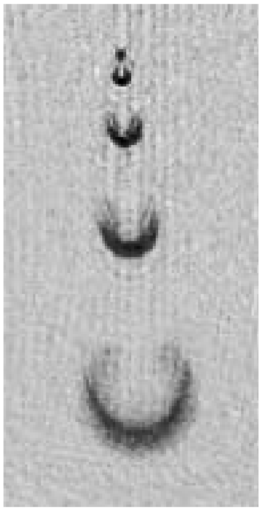
Progress in year 1997

1. An output coupler for Bose condensed atoms

The observations of BEC have stimulated interest in atom lasers, coherent sources of atomic matter waves. The build-up of atoms in the ground state of a magnetic trap is analogous to stimulated emission into a single mode of an optical laser. An important element of a laser is an output coupler, which provides a controlled way of generating a coherent propagating beam. We demonstrated a scheme for doing this with Bose condensed atoms [1]. A variable fraction of atoms was extracted coherently from the condensate by applying rf radiation to the cloud, thereby coupling atoms to untrapped hyperfine states (see figure).



Fraction of atoms remaining trapped after the rf pulse which couples atoms out of the magnetic trap. The population undergoes Rabi oscillations. The solid line is the theoretical prediction.

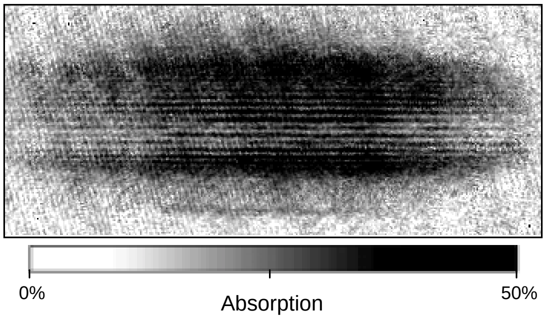


The MIT atom laser operating at 200 Hz. The image (field of view 1.8 mm x 3.9 mm) shows pulses of coherent sodium atoms coupled out from a Bose-Einstein condensate confined in a magnetic trap. Every five milliseconds, a short rf pulse rotated the magnetic moment of the trapped atoms, transferring a fraction of these atoms into a quantum state which is no longer confined (“non-magnetic”m=0 state). These atoms were accelerated downward by gravity and spread out. The atom pulses were observed by absorption imaging. Each of them contained between 10^5 and 10^6 atoms.

2. Observation of interference between two Bose condensates

The spatial coherence of a Bose condensate was demonstrated by observing interference between two Bose condensates [2]. They were created by cooling atoms in a double-well potential formed by magnetic and optical forces. High-contrast matter-wave interference fringes with a period of 15 micrometers were observed after switching off the potential and letting the condensates expand for 40 milliseconds and overlap (see figure). This demonstrates that Bose condensed atoms are “laser-like”; that is, they are coherent and show long-range correlations. Furthermore, we observed high-contrast interference of two atom pulses coupled out from a split condensate using the rf output coupler described above. This proves that the rf output coupler preserves the coherence of the condensates. The controlled generation of coherent atomic beams is the first realization of a basic atom laser.

The observation of interference between two Bose condensates opens up the study of coherent atom beams. It should be possible to study processes like phase diffusion and loss and build-up of coherence in the near future.

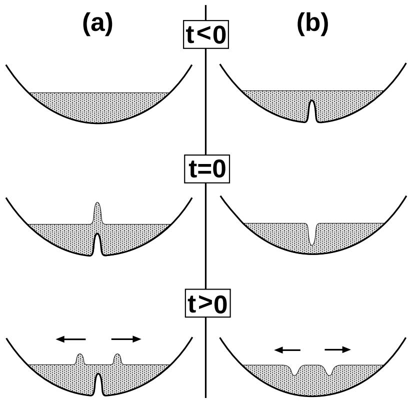


Interference pattern observed by overlapping two expanding Bose condensates. The fringe period was 15 μm, and the field of view is 1.1 mm by 0.5 mm.

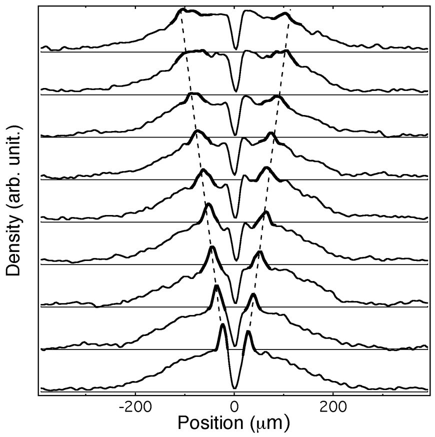
3. Propagation of sound in a Bose-Einstein condensate

The study of quantum liquids has revealed a wealth of physics such as superfluidity, second sound, and quantized vortices. A microscopic picture of these macroscopic quantum phenomena was developed based on elementary excitations and quantum hydrodynamics. For a long time such studies were limited to He-3 and He-4. The realization of Bose-Einstein condensation in atomic vapors has provided a new class of macroscopic quantum fluids which are dilute gases. An important issue, which applies both to quantum liquids and quantum gases, is the characterization of the system by its collective excitations.

Previous experiments on Bose condensed clouds had focused on the lowest collective excitations [3, 4]. They showed a discrete spectrum due to the small size of the trapped clouds, in contrast to the continuous spectrum of quantum liquids, which is phonon-like at low frequencies. In this study, we observed sound propagation in a Bose condensate [5]. Localized density perturbations, much smaller than the condensate, were induced by suddenly modifying the trapping potential using the optical dipole force of a focused laser beam (see figure). The resulting propagation of sound was directly observed using a novel technique, rapid sequencing of non-destructive phase-contrast images (see figure). The speed of sound was found to be consistent with the predictions of Bogoliubov theory [6], which were formulated 50 years ago, but had not yet been directly tested.



Excitations of wave packets in a Bose condensate. A condensate is confined in the potential of a magnetic trap. At time t=0, a focused, blue-detuned laser beam is suddenly switched on (a) or off (b) and, by the optical dipole force, creates respectively two positive or negative perturbations in density which propagate at the speed of sound.



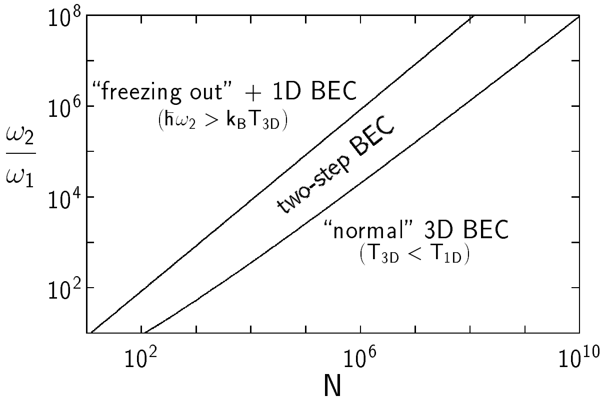
Observation of sound propagation in a condensate by non-destructive rapid phase-contrast imaging. Shown are axial density profiles of the condensate, taken every 1.3 ms, beginning 1 ms after switching on the argon ion laser. Two pulses traveled outward with the speed of sound (compare with figure above).

4. Second-order coherence of a Bose-Einstein condensate

The interference observed between two Bose-Einstein condensates demonstrated clearly the long-range coherence of a Bose condensate [2]. The fringe contrast is directly related to first-order coherence. Our paper [7] showed that previous measurements of the interaction energy of a condensate can be reinterpreted as a measure for second-order coherence and therefore provide direct evidence for the suppression of density fluctuations in a condensate compared to a thermal cloud. The same conclusion was reached for third-order coherence, which was measured through the observation of three-body collisions [8].

5. Two-step condensation of the ideal Bose gas in highly anisotropic traps

The ideal Bose gas in a highly anisotropic harmonic potential was studied theoretically [9]. It was found that Bose-Einstein condensation occurs in two distinct steps as the temperature is lowered. In the first step the specific heat shows a sharp feature, but the system still occupies many one-dimensional quantum states. In the second step, at significantly lower temperature, the ground state becomes macroscopically occupied. It should be possible to verify these predictions using present-day atom traps. The two-step behavior can occur in a rather general class of anisotropic traps, including the box potential.



Overview of the three different regimes of BEC in an anisotropic harmonic oscillator potential with $\omega_1 << \omega_2=\omega_3$ as a function of particle number N, and trap anisotropy ω_2/ω_1. The two-step BEC regime separates the regime of "normal" three-dimensional BEC and the regime of extreme anisotropy where the system first becomes one-dimensional and then undergoes 1D BEC as a second step.

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