Introduction and overview

The observation of Bose-Einstein condensation (BEC) in dilute atomic gases in 1995 was the realization of many long-standing goals: (1) to cool neutral atoms into the ground state of the system, thus exerting ultimate control over the motion and position of atoms limited only by Heisenberg’s uncertainty relation; (2) to generate a coherent sample of atoms all occupying the same quantum state (this was subsequently used to realize an atom laser, a device which generates coherent matter waves); and (3) to create a quantum fluid with properties quite different from the quantum liquids He-3 and He-4. This provides a test-ground for many-body theories of the dilute Bose gas which were developed many decades ago, but never tested experimentally. BEC offers intriguing possibilities for further research, in directions as varied as superfluidity in a gas and atom interferometry, precision measurements and atom optics.

The year 2002 was a year of amazing productivity for our group. Ten papers were published in Phys. Rev. Lett. Nature, and Science, and five more papers have been submitted to Phys. Rev. Lett. Several of these papers were profound studies of phenomena like vortices, four-wave mixing and amplification in Bose-Einstein condensates. This demonstrates how the field has matured.

However, the most impactful work was in the area of “quantum engineering”, realizing new capabilities of preparation and control of ultracold atoms. We are now one of the few groups worldwide who are working on two-component Fermi system with the goal of observing superfluidity by Cooper pairing. We also have a leadership position in the area of atom chips, where Bose-Einstein condensates are guided and manipulated by microscopic wires, which are created by micro-lithography.

The most flashy accomplishment was the realization of continuous BEC. In analogy with the optical laser, we have taken the step from pulsed BECs to continuous-wave BECs. This work was featured in Science.
Propagation of Bose-Einstein condensates in a magnetic waveguide

Progress in the field of atom optics depends on developing improved sources of matter waves and advances in their coherent manipulation. Miniaturizing the current carrying structures used to confine Bose-Einstein condensates offer prospects for finer control over the clouds. We have demonstrated that a gaseous Bose-Einstein condensate transported with optical tweezers [1] can be transferred into a magnetic trap microfabricated on a silicon substrate (see figure) [2]. This has opened up a front on which further techniques for coherent condensate transport and manipulation can be explored.

We released the condensate from the magnetic microtrap into a single-wire magnetic waveguide and studied its propagation. Condensates were observed to propagate 12 mm before exiting the field-of-view of our imaging system. We observed single-mode (excitation-less) condensate propagation along homogeneous segments of the waveguide. Transverse excitations were created in condensates propagating through perturbations in the guiding potential. These perturbations resulted from geometric deformations of the current carrying wires on the substrate. Finer imperfections were observed when trapped condensates were brought closer to the microchip as evidenced by the longitudinal fragmentation of the cloud. Such imperfections have to be controlled in order to use atom chips for precision atom interferometry.

A continuous source of Bose-Einstein condensed atoms

Unlike other macroscopic quantum systems such as superfluid $^4$He and optical lasers, dilute gas Bose-Einstein Condensates have so far been only produced in a pulsed mode. We have realized a continuous BEC source by periodically replenishing a condensate held in an optical dipole trap with new condensates [3]. A moving optical tweezers for Bose-Einstein condensates [1] was used to transport condensates from where they were produced into a reservoir optical trap. The freshly produced condensates periodically replenished the condensate in the reservoir trap, thereby continuously maintaining a condensate of more than $10^6$ atoms (see figure).

The crucial step in realizing a continuous BEC source was to make sure that the new cooling cycle did not destroy the condensate held in the reservoir trap. This involved shielding it from light during laser cooling, keeping it far away from the incoming hot atoms, and to hold it in an optical trap which made it immune against stray magnetic fields which were created during the evaporative cooling phase.

An interesting aspect of the continuous BEC is its phase. The freshly prepared condensates have a random phase relative to the condensate in the reservoir trap, and therefore, in the current experiment, the phase of the source after replenishment was random relative to the phase before the merger. In principle, it would be possible to replenish a stationary continuous BEC source with an incoming moving...
condensate using phase coherent amplification [4, 5]. By outcoupling atoms from a continuous BEC source one can realize continuous atom lasers.

A continuous source of Bose-Einstein condensed atoms. The solid circles in the semi-log plot represent the atom number in the continuous reservoir and the open squares show the number of condensate atoms transferred from the production chamber. The dashed lines indicate the beginning of a new cycle and the solid lines are exponentially decaying curves determined by a simultaneous fit to the three cycles after the first cycle. The number of atoms for each data point was obtained from separate absorption images.

**Generation of macroscopic pair-correlated atomic beams by four-wave mixing in Bose-Einstein condensates**

By colliding two Bose-Einstein condensates we have observed strong bosonic stimulation of the elastic scattering process. When a weak input beam (third wave) was applied as a seed, it was amplified by a factor of 20, and an initially unpopulated conjugate wave was created [6]. This large gain atomic four-wave mixing resulted in the generation of two macroscopically occupied pair-correlated atomic beams. Since each collision process adds one atom each to the seed and conjugate waves, fluctuations in the relative atom number are suppressed (squeezed). For the observed gain of twenty, the number fluctuations should be below the shot noise by a factor of $40^{1/2}$. We have also identified some limitations for using collisions to create twin beams, including loss by subsequent collisions, and competition between other modes with similar gain.

![High-gain four wave mixing of matter waves.](image)

High-gain four wave mixing of matter waves. The wavepackets separated during 43 ms of ballistic expansion. (a) Only a 1% seed was present (barely visible), (b) only two source waves were created and no seed, (c) two source waves and the seed underwent the four-wave mixing process where the seed wave and the fourth wave grew to a size comparable to the source waves. The crosses mark the center position of the unperturbed condensate. The field of view is 1.8 mm wide.

**Topological vortex formation in a Bose-Einstein condensate**

Following the theoretical suggestion [7], we have demonstrated a new method to create vortices in Bose-Einstein condensates. Vortices were imprinted into the condensate wavefunction using topological
phases. Sodium condensates held in an Ioffe-Pritchard magnetic trap were transformed from a non-rotating state to one with quantized circulation by adiabatically inverting the magnetic bias field along the trap axis [8]. During this process, the magnetic fields rotated around position-dependent axes, and the associated Berry's phase resulted in a vortex singularity.

Using surface wave spectroscopy, the axial angular momentum per particle of the vortex states was found to be consistent with $2\hbar$ or $4\hbar$, depending on the hyperfine state of the condensate.

Surface wave spectroscopy. A quadrupolar deformation precessed with the rotating condensate. The graph shows the precession angle vs. normalized time in the presence of a vortex for condensates in the $|1, -1>$ state measured after a delay of 0 ms (open circles), 5 ms (open squares), and 20 ms (open triangles) from the completion of the inversion of the axial bias field, in the absence of a vortex for $|1, -1>$ (open diamonds) and $|2, 2>$ (filled diamonds) condensates, and in the presence of a vortex for $|2, 2>$ condensates measured immediately upon the completion of the inversion of the axial bias field (filled circles).

Decay of an ultracold fermionic lithium gas near a Feshbach resonance

The interactions between atoms can be strongly modified by tuning magnetic fields to Feshbach resonances where a molecular state has the same energy as the colliding atoms. For degenerate Fermi gases, such control over the interaction strength is crucial in the search for a superfluid phase transition. Otherwise, the phase transition temperatures are too low to be experimentally accessible. Near Feshbach resonances, the enhancement of the scattering length is usually accompanied by enhanced inelastic collisions, which lead to rapid trap loss. We have performed the first study of inelastic collisions in a fermionic system near a Feshbach resonance. We have observed resonant magnetic field dependent inelastic decay of an ultracold, optically trapped spin mixture of $^6$Li [9].

The spin mixture of the two lowest hyperfine states showed two decay resonances at 550 G and 680 G. The feature near 680 G may be related to the long-predicted Feshbach resonance around 800 G. The resonance at 550G was unexpected, but new theoretical calculations have now identified it as an additional Feshbach resonance [10], which was not found in previous calculations. Even on resonance, the observed decay happened on a time scale longer than the trap oscillation time, the time for elastic collisions, and the expected sub-millisecond time needed for the formation of Cooper pairs.
Contrast Interferometry using Bose-Einstein Condensates to Measure $h/m$ and $\alpha$

We have demonstrated a new atom interferometer scheme, which shows promise for a high precision measurement of the recoil energy of an atom [11]. A precise measurement of the recoil frequency will lead to a more precise determination of $h/m$ and of the fine structure constant $\alpha$.

Our interferometer extends previous schemes used at Stanford [12] and New York [13], and combines their advantages. Optical standing wave pulses were used to create a symmetric three-path interferometer. This configuration encodes the photon recoil phase in the contrast of the interference fringes, rather than in their phase. Because it is insensitive to the fringe phase, the method is not sensitive to vibrations, accelerations, or rotations. The symmetry also suppresses errors from magnetic field gradients, and our use of only one internal state suppresses errors arising from differences in the ac Stark shifts between different internal states. A crucial aspect of this new interferometer is the use of atomic samples with sub-recoil momentum distribution. We use a Bose-Einstein condensate (BEC) as a bright sub-recoil atom source. This allows the contrast oscillations to persist for many cycles, permitting precise determination of the recoil phase in a single “shot.”

Typical single-shot signal from the contrast interferometer. The contrast signal is the intensity of a laser beam reflected by the interfering atomic matter waves. It represents the beat note between two simple interference patterns. Ten oscillations with 60 % are observed during the 50 $\mu$s readout.

Sodium Bose-Einstein Condensates in the F=2 State in a Large-volume Optical Trap

We have investigated the properties of Bose-Einstein condensates of sodium atoms in the upper hyperfine ground state in a purely optical trap [14]. Condensates in the high-field seeking $|F=2, m_F=-2>$
state were created from initially prepared $|F=1, m_F=-1>$ condensates using a one-photon microwave transition at 1.77 GHz. The condensates were stored in a large-volume optical trap created by a single laser beam with an elliptical focus. This resulted in lower densities and longer lifetimes of the condensates. We found condensates in the stretched state $|F=2, m_F=-2>$ to be stable for several seconds at densities in the range of $10^{14}$ atoms/cm$^3$. In addition, we studied the clock transition $|F=1, m_F=0> \rightarrow |F=2, m_F=0>$ which is to lowest order insensitive to stray magnetic fields and determined a density-dependent frequency shift (the so-called clock shift).

**Bose-Einstein condensates near a microfabricated surface**

Microfabricated chips with current-carrying wires can confine ultracold atoms more tightly and in more complex geometries. However, previous experiments revealed unexpected phenomena when ultracold atoms were trapped very close to microfabricated surfaces: Fragmentation of the cloud, and shortening of the lifetime were observed. In this study, we compared magnetically and optically confined Bose-Einstein condensates near a microfabricated surface [15]. Since the two traps operate on different principles, this study provided a unique examination of the interaction between Bose-Einstein condensates and a microfabricated surface.

Condensate fragmentation observed in microfabricated magnetic traps was not observed in optical dipole traps at the same location. Therefore, the corrugated potential was created by the current carrying wires. The measured condensate lifetime was $>20$ s and independent of the atom-surface separation under both magnetic and optical confinement. The much shorter lifetimes observed elsewhere were probably due to technical noise. Radio-frequency spin-flip transitions driven by technical noise were directly observed for optically confined condensates and could limit the condensate lifetime in microfabricated magnetic traps.

![Fragmentation of Bose-Einstein condensates](image)

Fragmentation of Bose-Einstein condensates. Radial absorption images after 10 ms ballistic expansion of condensates containing $\approx 10^6$ atoms after holding at a distance of 85 $\mu$m from the microfabricated surface for 15 s in the (a) microfabricated magnetic trap and (b) optical dipole trap. Longitudinal fragmentation occurred for condensates held in the microfabricated magnetic trap, but not for those confined optically at the same location with the microfabricated magnetic trap off. The field of view is 0.5 mm x 1.0 mm.

**Coherent Collisions between Bose-Einstein Condensates**

Four-wave mixing of atoms was implemented by colliding two condensates and seeding them with a third wave. Amplification of the third wave and generation of a fourth conjugate wave was observed. The coherence of the amplified waves was shown by observing high contrast interference with a reference wave and by reversing the amplification process [16]. This demonstrates the coherent nature of elastic collisions.

Since our experiments also placed limits on all known sources of decoherence, we inferred that relative number squeezing is most likely present between the amplified modes.
Coherence of the conjugate wave. Shown is the interference of the conjugate wave with a reference wave. The relative phase shift was introduced by shifting the phase of the rf-wave, which drove one of the acousto-optic modulators generating the Bragg beams.

Coreless vortex formation in a spinor Bose-Einstein condensate

Topological defects vary between superfluid systems described by scalar and vector order parameters. In spin-less or spin-polarized condensates, line defects such as vortices have cores where the density of condensed particles is necessarily zero to keep the order parameter single-valued. However, in condensates with an internal, spin degree-of-freedom, coreless vortices exist as spin textures.

We have phase-imprinted coreless vortices in a spinor Bose-Einstein condensate [17] following a recent theoretical suggestion [7]. The three-component order parameter of $F = 1$ sodium condensates held in a magnetic trap was manipulated by adiabatically reducing the magnetic bias field along the trap axis to zero. The remaining field was a radial quadrupole field. This distributed the condensate population across its three spin states and created a spin texture. Each spin state acquired a different phase winding which caused the spin components to separate radially.

Coreless vortex formation in a spinor Bose-Einstein condensate. Coreless vortices were imprinted by slowly ramping the bias field to zero, and diagnosed by suddenly switching on a strong bias field, which decomposed the wavefunction into its $m_F$ components with respect to a fixed axis. Axial absorption images display the optical density of condensates after 20 ms of ballistic expansion (a) without and (b) with a magnetic field gradient applied to separate the three different spin states. The ring-shaped
structures for the $m_F = -1$ and 0 states are evidence for the non-zero winding number (or angular momentum). The field of view is 1.0 mm × 3.0 mm.

Amplification of Local Instabilities in a Bose-Einstein Condensate with Attractive Interactions

Our current understanding of the collapse of Bose-Einstein condensates (BECs) with attractive interactions is incomplete. Previous experiment studied very small condensates where the attractive mean field energy $\mu$ was comparable to or less than the $\omega$ level spacing of the harmonic trapping potential. We have studied the collapse of large sodium condensates far in the Thomas-Fermi regime ($|\mu| >> \omega$), where the spatial profile of the condensate is relatively homogeneous [18]. Much of the dynamics of such a system is then described by local phenomena. When the interactions become attractive, Yurovsky predicted that local instabilities with momentum on the order of the (imaginary) speed of sound will undergo exponential growth [19].

By seeding the condensate with phonons (using optical imprinting) we observed the exponential growth of such excitations when the scattering length was suddenly switched negative. The scattering length could be varied by changing the magnetic field near a Feshbach resonance. For our parameters, this quantum evaporation process becomes comparable or faster than the global collapse even without seeding.

![Growth rate of excitations in a BEC with scattering length $a < 0$. The rate increases with the magnitude of the negative scattering length $|a|$. The solid line shows a best fit to the theoretical prediction.](image)

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