Cooling and Trapping Neutral Atoms

Academic and Research Staff
Professor Wolfgang Ketterle, Professor David E. Pritchard

Visiting Scientists and Research Affiliates
Kai Dieckmann, David Kielpinski, Takashi Mukaiyma, Dominik Schneble, Jeff Steinhauer, Yoshio Torii, Johnny M. Vogels

Graduate Students
Jamil R. Abo-Shaeer, Micah Boyd, Gretchen Campbell, Ananth P. Chikkatur, Jit-Kee Chin, Subhadeep Gupta, Zoran Hadzibabic, Aaron E. Leanhardt, Daniel Miller, Jongchul Mun, Tom Pasquini, Yong-Il Shin, Claudiu A. Stan, Erik W. Streed, Kaiwen Xu, Martin Zwierlein

Undergraduate Students
Pavel Gorelik, Christian Schunck, Edem Tsikata, James Xin Sun

Support Staff
Carol Costa

Sponsors:
National Science Foundation
Office of Naval Research
Army Research Office
David and Lucile Packard Foundation
NASA

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.

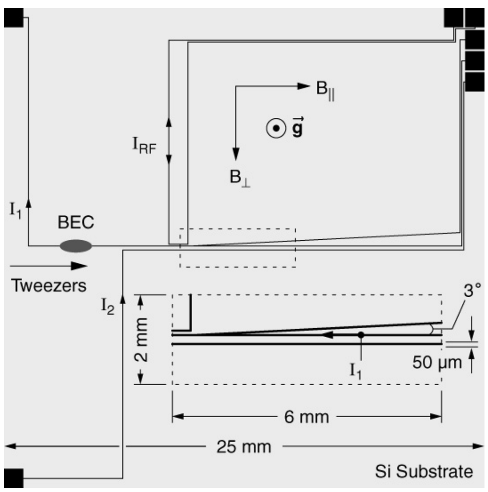
However, the most impactful work was in the area of "quantum engineering", realizing new capabilities of preparation and control of ultracold atoms. We are now one of the few groups worldwide who are working on two-component Fermi system with the goal of observing superfluidity by Cooper pairing. We 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.



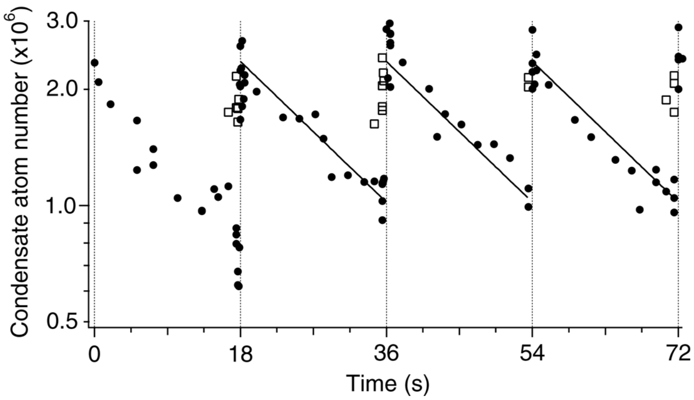
Microfabricated magnetic trap and waveguide. Optical tweezers loaded a Bose-Einstein condensate into the microtrap formed by currents $\mathbf{I}_1$ and $\mathbf{I}_2$ in conjunction with the magnetic bias field $B_{\square}$. Lowering $\mathbf{I}_2$ to zero released the condensate into a single-wire magnetic waveguide. Atom flow was from left to right. The condensate was trapped above the plane of the page and the gravitational acceleration, **g**, points out of the page. All microfabricated features are drawn to scale.

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.

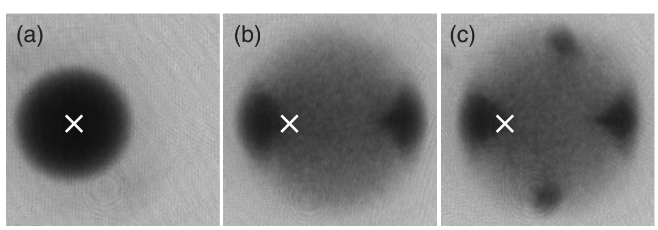
An interesting aspect of the continuous BEC is its phase. The freshly prepared condensates have a random phase relative to the condensate in the reservoir trap, and therefore, in the current experiment, the phase of the source after replenishment was random relative to the phase before the merger. In 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.

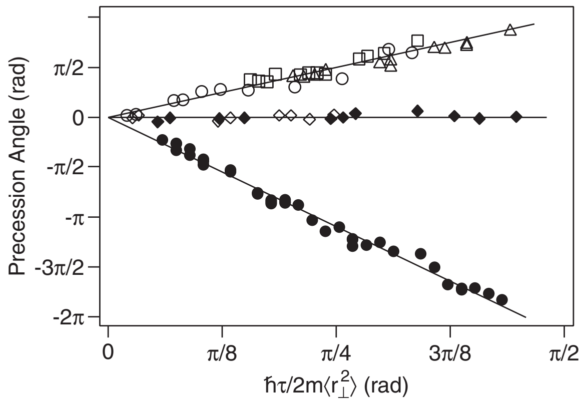


High-gain four wave mixing of matter waves. The wavepackets separated during 43 ms of ballistic expansion. (a) Only a 1% seed was present (barely visible), (b) only two source waves were created and no seed, (c) two source waves and the seed underwent the four-wave mixing process where the seed wave 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.

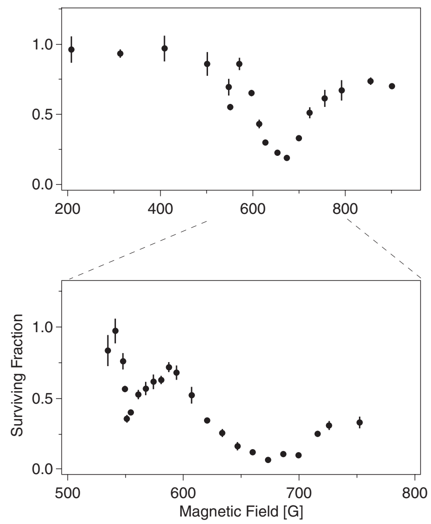


Surface wave spectroscopy. A quadrupolar deformation precessed with the rotating condensate. The graph shows the precession angle vs. normalized time in the presence of a vortex for condensates in the |1, -1> state measured after a delay of 0 ms (open circles), 5 ms (open squares), and 20 ms (open triangles) 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.

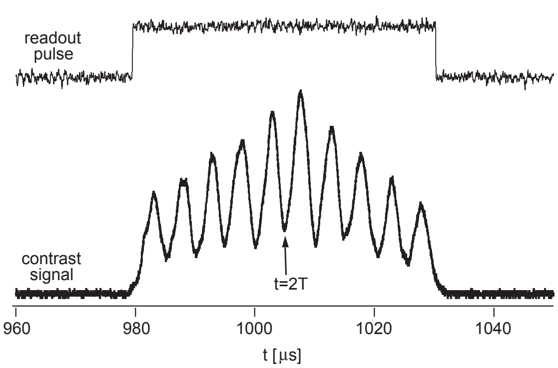


Magnetic field dependence of inelastic decay of lithium in a 50%-50% mixture of the lowest two hyperfine states. The fraction of the atoms remaining after a 500 ms magnetic field pulse is shown (upper graph). The two resonances are shown in more detail for 2 s magnetic field pulses (lower graph).

Contrast Interferometry using Bose-Einstein Condensates to Measure h/m and α

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 α.

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 µs readout.

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

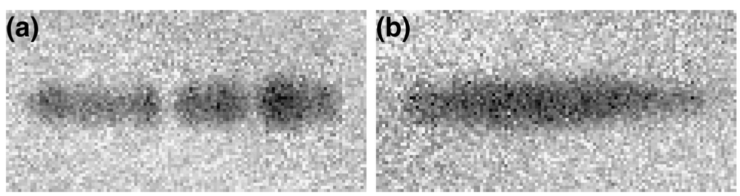
We have investigated the properties of Bose-Einstein condensates of sodium atoms in the upper hyperfine ground state in a purely optical trap [14]. Condensates in the high-field seeking |F=2, m_F=-2>

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.

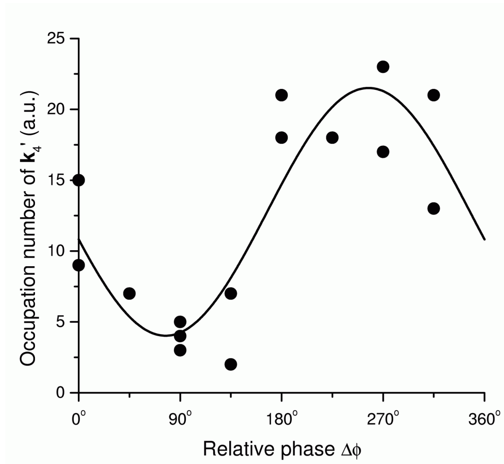


Fragmentation of Bose-Einstein condensates. Radial absorption images after 10 ms ballistic expansion of condensates containing $\approx 10^6$ atoms after holding at a distance of 85 μm from the microfabricated surface for 15 s in the (a) microfabricated magnetic trap and (b) optical dipole trap. Longitudinal 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.

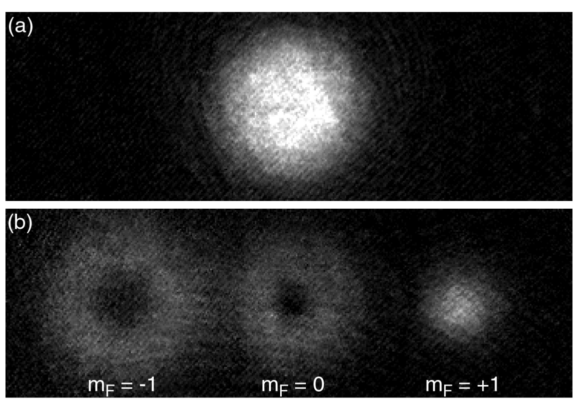


Coherence of the conjugate wave. Shown is the interference of the conjugate wave with a reference wave. The relative phase shift was introduced by shifting the phase of the rf-wave, which drove one of the acousto-optic modulators generating the Bragg beams.

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.

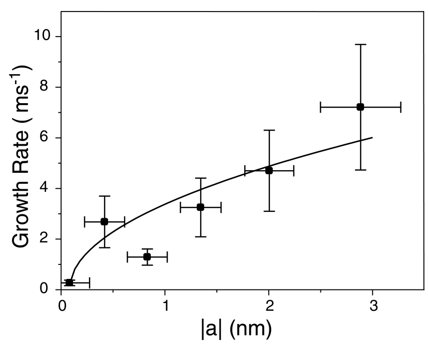


Coreless vortex formation in a spinor Bose-Einstein condensate. Coreless vortices were imprinted by slowly ramping the bias field to zero, and diagnosed by suddenly switching on a strong bias field, which decomposed the wavefunction into its m_F components with respect to a fixed axis. Axial absorption 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 μ was comparable to or less than the $\hbar\omega$ level spacing of the harmonic trapping potential. We have studied the collapse of large sodium condensates far in the Thomas-Fermi regime ($|\mu| >> \hbar\omega$), 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.

References

[1] T.L. Gustavson, A.P. Chikkatur, A.E. Leanhardt, A. Görlitz, S. Gupta, D.E. Pritchard, and W. Ketterle, Phys. Rev. Lett. **88**, 020401 (2002).
[2] A.E. Leanhardt, A.P. Chikkatur, D. Kielpinski, Y. Shin, T.L. Gustavson, W. Ketterle, and D.E. Pritchard, Phys. Rev. Lett. **89**, 040401 (2002).
[3] A.P. Chikkatur, Y. Shin, A.E. Leanhardt, D. Kielpinski, E. Tsikata, T.L. Gustavson, D.E. Pritchard, and W. Ketterle, Science **296**, 2193 (2002), published online in Science Express on May 16, 2002.
[4] S. Inouye, T. Pfau, S. Gupta, A.P. Chikkatur, A. Görlitz, D.E. Pritchard, and W. Ketterle, Nature **402**, 641 (1999).
[5] M. Kozuma, Y. Suzuki, Y. Torii, T. Sugiura, T. Kuga, E.W. Hagley, and L. Deng, Science **286**, 2309 (1999).
[6] J.M. Vogels, K. Xu, and W. Ketterle, Phys. Rev. Lett. **89**, 020401 (2002).
[7] T. Isoshima, M. Nakahara, T. Ohmi, and K. Machida, Phys. Rev. A **61**, 063610 (2000).
[8] A.E. Leanhardt, A. Görlitz, A.P. Chikkatur, D. Kielpinski, Y. Shin, D.E. Pritchard, and W. Ketterle, Phys. Rev. Lett. **89**, 190403 (2002).

[9] K. Dieckmann, C.A. Stan, S. Gupta, Z. Hadzibabic, C. Schunck, and W. Ketterle, Phys. Rev. Lett. **89**, 203201 (2002).

[10] K.M. O'Hara, S.L. Hemmer, S.R. Granade, M.E. Gehm, J.E. Thomas, V.Venturi, E. Tiesinga, and C.J. Williams, Phys. Rev. A **66**, 041401(R) (2002).

[11] S. Gupta, K. Dieckmann, Z. Hadzibabic, and D.E. Pritchard, Phys. Rev. Lett. **89**, 140401 (2002).

[12] D.S. Weiss, B.C. Young, and S. Chu, Phys. Rev. Lett. **70**, 2706 (1993).

[13] S.B. Cahn, A. Kumarkrishnan, U. Shim, T. Sleator, P.R. Berman, and B. Dubetsky, Phys. Rev. Lett. **79**, 784 (1997).

[14] A. Görlitz, T.L. Gustavson, A.E. Leanhardt, R. Löw, A.P. Chikkatur, S. Gupta, S. Inouye, D.E. Pritchard, and W. Ketterle, preprint cond-mat/0208385.

[15] A.E. Leanhardt, Y. Shin, A.P. Chikkatur, D. Kielpinski, W. Ketterle, and D.E. Pritchard, preprint cond-mat/0211345.

[16] J.M. Vogels, J.K. Chin, and W. Ketterle, preprint cond-mat/0209067.

[17] A.E. Leanhardt, Y. Shin, D. Kielpinski, D.E. Pritchard, and W. Ketterle, preprint cond-mat/0212539.

[18] J.K. Chin, J.M. Vogels, and W. Ketterle, preprint cond-mat/0212568.

[19] V.A. Yurovsky, Phys. Rev. A **65**, 033605 (2002).

Publications

Papers (in refereed journals) and major book chapters

J.K. Chin, J.M. Vogels, and W. Ketterle:
Amplification of Local Instabilities in a Bose-Einstein Condensate with Attractive Interactions.
preprint, cond-mat/0212568.

A.E. Leanhardt, Y. Shin, D. Kielpinski, D.E. Pritchard, and W. Ketterle:
Coreless vortex formation in a spinor Bose-Einstein condensate.
preprint, cond-mat/0212539.

A.E. Leanhardt, Y. Shin, A.P. Chikkatur, D. Kielpinski, W. Ketterle, and D.E. Pritchard:
Bose-Einstein condensates near a microfabricated surface.
preprint, cond-mat/0211345.

J. M. Vogels, J. K. Chin, and W. Ketterle:
Coherent Collisions between Bose-Einstein Condensates.
Phys. Rev. Lett., in print; cond-mat/0209067.

A. Görlitz, T.L. Gustavson, A.E. Leanhardt, R. Löw, A.P. Chikkatur, S. Gupta, S. Inouye, D.E. Pritchard, and W. Ketterle:
Sodium Bose-Einstein Condensates in the F=2 State in a Large-volume Optical Trap.
preprint, cond-mat/0208385.

S. Gupta, K. Dieckmann, Z. Hadzibabic and D. E. Pritchard:
Contrast Interferometry using Bose-Einstein Condensates to Measure h/m and a
Phys. Rev. Lett. **89**, 140401 (2002).

W. Ketterle:
When atoms behave as waves: Bose-Einstein condensation and the atom laser.
in: Les Prix Nobel 2001 (The Nobel Foundation, Stockholm, 2002), pp. 118-154.
reprinted in: ChemPhysChem **3**, 736-753 (2002); Rev. Mod. Phys. **74**, 1131-1151 (2002).

K. Dieckmann, C. A. Stan, S. Gupta, Z. Hadzibabic, C. Schunck, and W. Ketterle:
Decay of ultracold fermionic lithium gas near a Feshbach resonance.
Phys. Rev. Lett. **89**, 203201 (2002).

W. Ketterle:
Superfluidity and Coherence in Bose-Einstein Condensates.
Physica Scripta **T102**, 36-38 (2002).

A.E. Leanhardt, A. Görlitz, A.P. Chikkatur, D. Kielpinski, Y. Shin, D.E. Pritchard, and W. Ketterle:
Imprinting vortices in a Bose-Einstein condensate using topological phases.
Phys. Rev. Lett. **89**, 190403 (2002).

A. P. Chikkatur, Y. Shin, A. E. Leanhardt, D. Kielpinski, E. Tsikata, T. L. Gustavson, D. E. Pritchard, and W. Ketterle:
A Continuous Source of Bose-Einstein Condensed Atoms.
Science **296**, 2193-2195 (2002); published online in Science Express on May 16, 2002.

J.M. Vogels, K. Xu, and W. Ketterle:
Generation of macroscopic pair-correlated atomic beams by four-wave mixing in Bose-Einstein condensates.
Phys. Rev. Lett. **89**, 020401 (2002).

A.E. Leanhardt, A.P. Chikkatur, D. Kielpinski, Y. Shin, T.L. Gustavson, W. Ketterle, and D.E. Pritchard:
Propagation of Bose-Einstein condensates in a magnetic waveguide.
Phys. Rev. Lett. **89**, 040401 (2002).

J.R. Anglin and W. Ketterle:
Bose-Einstein condensation of atomic gases.
Nature **416**, 211-218 (2002).

Z. Hadzibabic, C.A. Stan, K. Dieckmann, S. Gupta, M.W. Zwierlein, A. Görlitz, and W. Ketterle:
Two species mixture of quantum degenerate Bose and Fermi gases.
Phys. Rev. Lett. **88**, 160401(2002).

J.M. Vogels, K. Xu, C. Raman, J.R. Abo-Shaeer, and W. Ketterle:
Experimental observation of the Bogoliubov transformation for a Bose-Einstein condensed gas.
Phys. Rev. Lett. **88**, 060402 (2002).

T.L.Gustavson, A.P.Chikkatur, A.E.Leanhardt, A.Görlitz, S.Gupta, D.E.Pritchard, and W.Ketterle:
Transport of Bose-Einstein Condensates with Optical Tweezers.
Phys. Rev. Lett. **88**, 020401 (2002).

J.R. Abo-Shaeer, C. Raman, and W. Ketterle:
Formation and Decay of Vortex Lattices in Bose-Einstein Condensates at Finite Temperatures.
Phys. Rev. Lett. **88**, 070409 (2002).

Articles in Proceedings

Wolfgang Ketterle:
The Bose-Einstein Condensate- a Superfluid Gas of Coherent Atoms.
Proceedings of the International Conference on Atomic Physics (ICAP) 2002, in print.

S. Inouye, J.R. Abo-Shaeer,.P. Chikkatur, A. Görlitz, S. Gupta, T.L. Gustavson, A.E. Leanhardt, C. Raman, T. Rosenband, J.M. Vogels, K. Xu, D.E. Pritchard, and W. Ketterle:
Vortex Excitations in a Bose-Einstein Condensate.
Proceedings of the 7th International Symposium on Foundations of Quantum Mechanics in the Light of New Technology (ISQM-Tokyo '01), Hatoyama, Japan, August 27-30, 2001 (World Scientific, Singapore, 2002), pp. 122-127.

Conference contributions with published abstracts

S. Gupta, K. Dieckmann, Z. Hadzibabic, and D. Pritchard:
Contrast Interferometry with Bose-Einstein Condensates to Measure h/m and α.
OSA Annual meeting 9/29 – 10/3/2002, Orlando, Florida, Conference Program, TuB2.

S. Gupta, K. Dieckmann, Z. Hadzibabic and D.E. Pritchard:
Contrast Interferometry with Bose-Einstein Condensates to Measure h/m and α*.*
18th International Conference on Atomic Physics, 7/28-8/2/2002, Cambridge, MA, Book of Abstracts, p. 191.

S. Gupta, K. Dieckmann, Z. Hadzibabic and D.E. Pritchard:
Contrast Interferometry with Bose-Einstein Condensates to Measure h/m and α*.*
18th International Conference on Atomic Physics, 7/28-8/2/2002, Cambridge, MA, Book of Abstracts, p. 191.

Z. Hadzibabic, K. Dieckmann, A Görlitz, S. Gupta, C.H. Schunck, C.A. Stan, M.W. Zwierlein, and W. Ketterle:
Quantum degenerate mixture of Bose and Fermi atomic gases.
OSA Annual meeting 9/29 – 10/3/2002, Orlando, Florida, Conference Program, MB3.

A.E. Leanhardt, A.P. Chikkatur, D. Kielpinski, Y. Shin, W. Ketterle, and D. .E Pritchard:
Science with Bose-Einstein condensates in an auxiliary vacuum chamber.
OSA Annual meeting 9/29 – 10/3/2002, Orlando, Florida, Conference Program, TuB5.

K. Xu, J. Vogels, J. Abo-Shaeer, J.K. Chin, and W. Ketterle:
Generation of macroscopic pair-correlated atomic bea s by four-wave mixing in Bose-Eisntein condensates.
OSA Annual meeting 9/29 – 10/3/2002, Orlando, Florida, Conference Program, TuB4.

S. Gupta, Z. Hadzibabic, K. Dieckmann, C. Stan, C. Schunck, and W. Ketterle:
Investigation of Feshbach resonance in a degenerate fermionic gas.
OSA Annual meeting 9/29 – 10/3/2002, Orlando, Florida, Conference Program, MC1.

D. Schneble, Y. Torii, M. Boyd, E. Streed, G. Campbell, P. Gorelik, D.E. Pritchard, and W. Ketterle:
Superradiance in a Bose-Einstein condensate in the short-pulse regime.
OSA Annual meeting 9/29 – 10/3/2002, Orlando, Florida, Conference Program, TuB6.

W. Ketterle:
A continuous BEC source and other recent work on quantum degenerate alkali gases at MIT.
7th workshop on Atom Optics and Interferometry, 9/28 – 10/2/2002, Lunteren, The Netherlands, Book of Abstracts.

K. Dieckmann, C.A. Stan, S. Gupta, Z. Hadzibabic, C. Schunck, and W. Ketterle:
Decay of an Ultracold Fermionic Lithium Gas near a Feshbach Resonance.
7th workshop on Atom Optics and Interferometry, 9/28 – 10/2/2002, Lunteren, The Netherlands, Book of Abstracts, I-23.

D. Kielpinski, A.E. Leanhardt, A.P. Chikkatur, Y. Shin, T.L. Gustavson, W. Ketterle, and D.E. Pritchard:
Propagation of Bose-Einstein Condensates in a Magnetic Waveguide
7th workshop on Atom Optics and Interferometry, 9/28 – 10/2/2002, Lunteren, The Netherlands, Book of Abstracts, I-44.

A.E. Leanhardt, A.P. Chikkatur, D. Kielpinski, Y. Shin, T.L. Gustavson, E. Tsikata, W. Ketterle and D.E. Pritchard:
Bose-Einstein condensates on a microchip.
18th International Conference on Atomic Physics, 7/28-8/2/2002, Cambridge, MA, Book of Abstracts, p. 84.

J.M. Vogels, K. Xu and W. Ketterle:
Generation of macroscopic pair-correlated atomic beams by four-wave mixing in Bose-Einstein condensates.
18th International Conference on Atomic Physics, 7/28-8/2/2002, Cambridge, MA, Book of Abstracts, p. 87.

Z. Hadzibabic, C.A. Stan, K. Dieckmann, S. Gupta, C. Schunck, M.W. Zwierlein, A. Görlitz and W. Ketterle:
Two-Species Mixture of Quantum Degenerate Bose and Fermi Gases.
18th International Conference on Atomic Physics, 7/28-8/2/2002, Cambridge, MA, Book of Abstracts, p. 96.

J.G.E. Harris, R.A. Michniak, S. Nguyen, N. Brahms, B. Zygelman, W. Ketterle and J.M. Doyle:
Progress towards buffer-gas cooling and magnetic trapping of sodium
18th International Conference on Atomic Physics, 7/28-8/2/2002, Cambridge, MA, Book of Abstracts, p. 172.

A.P. Chikkatur, Y. Shin, A.E. Leanhardt, D. Kielpinski, E. Tsikata, T.L. Gustavson, D.E. Pritchard, and W. Ketterle:
A Continuous Source of Bose-Einstein Condensed Atoms
18th International Conference on Atomic Physics, 7/28-8/2/2002, Cambridge, MA, Book of Abstracts, p. 208.

M. Boyd, E. Streed, G. Campbell, P. Gorelik, D. Schneble, Y. Torii, D.E. Pritchard, and W. Ketterle:
High-Performance Apparatus for Making Bose-Einstein Condensates of Rubidium.
18th International Conference on Atomic Physics, 7/28-8/2/2002, Cambridge, MA, Book of Abstracts, p. 212.

W. Ketterle:
Recent Work on Quantum-Degenerate Alkali Gases At MIT.
Workshop on recent developments in the physics of cold atomic gases, Trento, 7/15-7/18/2002, Book of Abstracts, p. 19.

A.P. Chikkatur, A.E. Leanhardt, Y. Shin, D. Kielpinski, E. Tsikata, T.L. Gustavson, D.E. Pritchard and W. Ketterle:
Exploring Physic Using Transported Bose-Einstein Condensates
Workshop on recent developments in the physics of cold atomic gases, Trento, 7/15-7/18/2002, Book of Abstracts, p. 33.

S. Gupta, K. Dieckmann, Z. Hadzibabic, W. Ketterle, and D.E. Pritchard:
Measuring the Photon Recoil Frequency using Interferometry with Bose-Einstein Condensates.
Bull. Am. Phys. Soc. **47**, 117 (2002).

A. Chikkatur, A. Leanhardt, D. Kielpinski, Y.-I. Shin, D. Pritchard, and W. Ketterle:
Waveguide physics using Bose-Einstein condensates.
Bull. Am. Phys. Soc. **47**, 92 (2002).

T. Gustavson, A. Chikkatur, A. Leanhardt, A. Görlitz, S. Gupta, D. Pritchard, and W. Ketterle:
Transport of Bose-Einstein Condensates with Optical Tweezers.
Bull. Am. Phys. Soc. **47**, 92 (2002).

D. Schneble, Y. Torii, E. Streed, M. Boyd, P. Gorelik, G. Campbell, D. Pritchard, and W. Ketterle:
Superradiance in a Bose-Einstein condensate in the short-pulse regime.
Bull. Am. Phys. Soc. **47**, 93 (2002).

J. Vogels, K. Xu, and W. Ketterle:
Collisional matter wave amplification and squeezing.
Bull. Am. Phys. Soc. **47**, 46 (2002).

Z. Hadzibabic, C.A. Stan, K. Dieckmann, S. Gupta, M.W. Zwierlein, A. Görlitz, and W. Ketterle:
Two-Species Mixture of Quantum Degenerate Fermi and Bose Gases.
Bull. Am. Phys. Soc. **47**, 47 (2002).

Y. Torii, E. Streed, M. Boyd, D. Schneble, P. Gorelik, G. Campbell, D. Pritchard, and W. Ketterle:
High-performance Apparatus for Bose-Einstein Condensation of Rubidium Atoms.
Bull. Am. Phys. Soc. **47**, 32 (2002).

W. Ketterle:
Gaseous Bose-Einstein condensates – A nanokelvin laboratory for quantum physics.
Bull. Am. Phys. Soc. **47**, 10 (2002).

A.E. Leanhardt, A.P. Chikkatur, D. Kielpinski, Y. Shin, D.E. Pritchard, and W. Ketterle:
Topological vortex formation in a Bose-Einstein condensate.
QELS 2002, Postdeadline Paper, QPD9.

W. Ketterle:
Bose-Einstein condensates – superfluid gases.
QELS 2002 Technical Digest, JWA4.

J.M. Vogels, K. Xu, C. Raman, J.R. Abo-Shaeer, and W. Ketterle:
Experimental observation of the Bogoliubov transformation for a Bose-Einstein condensed gas.
QELS 2002 Technical Digest, QWC2.

T. Gustavson, A. Chikkatur, AE. Leanhardt, A. Görlitz, S. Gupta, D.E. Pritchard, and W. Ketterle:
Transport of Bose-Einstein Condensates Using Optical Tweezers.
QELS 2002 Technical Digest, QWF4.

W. Ketterle:
The Bose-Einstein condensate: A superfluid gas of coherent atoms.
Bull. Am. Phys. Soc. **47**, 482 (2002).

W. Ketterle:
Bose-Einstein condensates: Matter made of matter waves.
American Association for the Advancement of Science, Annual Meeting, Boston, February 14-19, 2002, Program, page A3.

Theses

Pavel Vladimir Gorelik:
Rubidium Bose Einstein Condensates and Snubber Circuits for High Current Inductive Loads.
B.S. thesis.

Edem Tsikata:
The Characterization of Bose-Einstein Condensates on an Atom Chip.
B.S. thesis.

Ananth Chikkatur:
Colliding and Moving Bose-Einstein Condensates: Studies of superfluidity and optical tweezers for condensate transport.
Ph.D. thesis.

Christian Schunck:
Study of an ultracold cloud of fermionic ^{6}Li atoms near a Feshbach resonance.
Diploma thesis, University of Heidelberg, Germany.