

RLE PROGRESS REPORT 1999

COOLING AND TRAPPING NEUTRAL ATOMS

SUPPORT:

Office of Naval Research, Contract N00014-96-1-0485, AASERT N00014-98-1-0398
National Science Foundation, Contract PHY 95-01984
Army Research Office, Agreement DAAG55-98-1-0080, Contract DAAD19-99-1-0073
David and Lucile Packard Foundation, Grant 96-5158
NASA Grant NAG8-1435

PERSONNEL

FACULTY: Wolfgang Ketterle, David E. Pritchard

VISITING PROFESSOR: Tilman Pfau

POSTDOCTORAL ASSOCIATES: Axel Görlitz, Todd L. Gustavson, Roberto Onofrio,
Chandra S. Raman, Jörn Stenger, Johnny M. Vogels

GRADUATE STUDENTS: Jamil R. Abo-Shaeer, Ananth P. Chikkatur, Dallin S. Durfee, Subhadeep Gupta,
Zoran Hadzibabic, Shin Inouye, Christopher E. Kuklewicz, Aaron E. Leanhardt, Dan M. Stamper-Kurn,
Claudiu A. Stan

UNDERGRADUATE STUDENTS: Isaac M. Dinner, Jeffrey Gore, Till P. Rosenband

VISITING STUDENTS: Michael Köhl, Robert Löw

SUPPORT STAFF: Carol Costa

KEYWORDS:

Bose-Einstein condensation, ultracold atoms, magnetic trapping, optical trapping, evaporative cooling, quantum statistics, collective excitations

1. Introduction and overview

The observation of Bose-Einstein condensation (BEC) in dilute atomic gases [1-3] 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. Recent studies [4-6] have yielded first experimental evidence for the superfluid nature of Bose-Einstein condensates opening a new area for further experimental investigations. The coherent behavior of BEC is likely to find use in a variety of applications, e.g. atom interferometry, precision measurements and atom optics.

In early 1999 we achieved for the first time Bose-Einstein condensation in our second experimental apparatus which allowed us to extend the scientific agenda although our laboratories were shut down for two months due to a complete renovation. The main focus of our experimental work in 1999 were studies

involving the interaction of light with trapped Bose-Einstein condensates. We also continued our research on spinor Bose-Einstein condensates [7] extending studies we had begun in 1998.

Laser light can be used in various ways to probe and manipulate BEC. One intriguing aspect is that very far-off-resonance light is suited to create or shape a trapping potential for a condensate. In previous work we have used this to create a purely optical trap for BEC [8] which, for example, was used to study spinor condensates. In the second BEC apparatus we have combined magnetic and optical potentials, generated by an infrared laser beam to create a variety of trapping geometries. Thus, we were able to study surface excitations that are not accessible in a purely magnetic trap [9]. By using the repelling potential created by a green laser beam to stir a condensate we could produce evidence for the existence of a critical velocity for dissipation [4] which is related to the superfluid nature of a BEC.

Light can also be employed as spectroscopic tool for the study of the quasi-particle excitation spectrum of a condensate. We have used Bragg-scattering to determine the excitation spectrum of a condensate in the free-particle [10] as well as in the phonon regime [11]. During these studies we discovered a new form of superradiance in the interaction between coherent light and coherent atoms [12]. By combining Bragg scattering with this new phenomenon we were able to create a phase-coherent amplifier for matter waves [13].

2. Quantum tunneling across spin domains in a Bose-Einstein condensate

The observation of metastable spin domains in optically trapped $F=1$ spinor Bose-Einstein condensates of sodium (see RLE-Report 1998) [14] raised the question of how thermal equilibrium would ultimately be achieved. Besides thermally activated processes we observed quantum tunneling as equilibration process. For the study of this process, spinor condensates were prepared which consisted of only two spin domains in the $m_F=0$ and $m_F=+1$ states. Those domains are immiscible due to their antiferromagnetic interaction. When a field gradient was added which made it energetically favorable for the two domains to change sides, quantum tunneling was observed (Fig. 1). A mean-field description of the tunneling process was developed and agreed well with the measurements [7]. The analysis showed that the tunneling rates are a sensitive probe of the boundary between spin domains, and indicated an unpredicted spin structure in the boundary between spin domains which is prohibited in the bulk fluid.

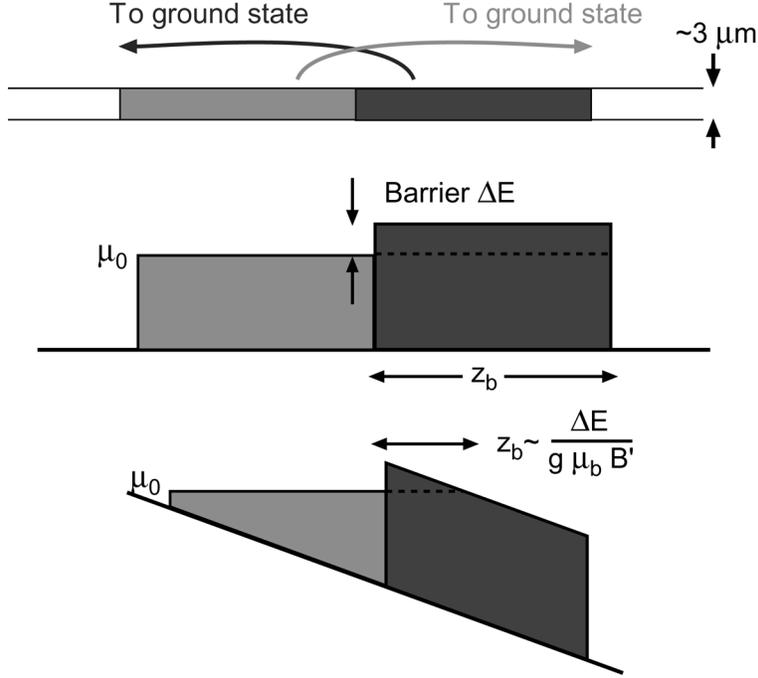


Figure 1: Study of quantum tunneling in a two-component Bose-Einstein condensate. The $m_F=1$ (grey) and $m_F=0$ atoms form two immiscible spin domains (upper figure) because the $m_F=1$ atoms experience an energy barrier due to the repulsive mean field interaction (middle figure). When a longitudinal magnetic field gradient is applied, the effective potential for the $m_F=1$ atoms changes to the lower figure, and the spin domains can rearrange themselves by quantum tunneling through each other.

3. Bragg spectroscopy of a Bose-Einstein condensate

The first evidence for Bose-Einstein condensation in dilute gases was obtained by a sudden narrowing of the velocity distribution as observed for ballistically expanding clouds of atoms. However, the dominant contribution to the observed momentum distribution of the expanding condensate was the released atomic interaction energy (mean-field energy) resulting in momentum distributions much broader than the zero-point motion of the ground state of the harmonic trapping potential. Since the size of a trapped condensate with repulsive interactions is larger than the trap ground state, the momentum distribution should be considerably narrower than in the trap ground state. We could measure the momentum distribution of a trapped condensate with Doppler velocimetry using two-photon Bragg scattering. We observed that the momentum distribution was Heisenberg uncertainty limited by its finite size, i.e. the coherence length of the condensate was equal to its size [10].

A shift of the narrow Bragg resonance was caused by the repulsive interactions within the condensate resulting in a spectroscopic measurement of the mean-field energy. More generally, we have established Bragg scattering as a spectroscopic technique to probe properties of the condensate. It can be used to map out the density fluctuations of the system and thus to measure directly the dynamic structure factor $S(q, \omega)$, which is the Fourier transform of the density-density correlation function and is central to the theoretical description of many-body systems.

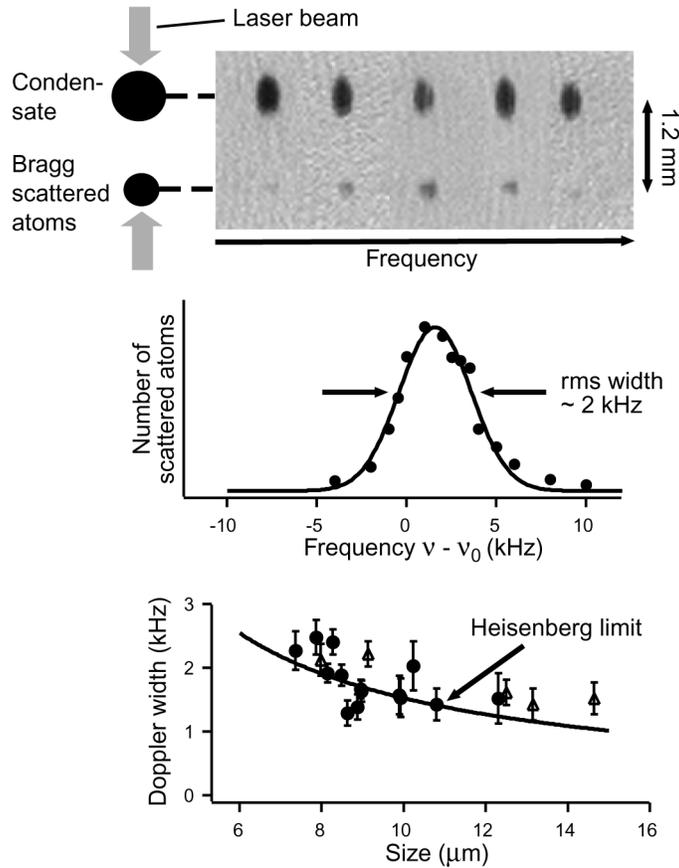


Figure 2: Bragg spectroscopy of a trapped condensate. A condensate was exposed to two counterpropagating laser beams and analyzed using time of flight absorption imaging (upper part). The number of Bragg scattered atoms showed a narrow resonance when the difference frequency between the two laser beams was varied (upper and middle part). The width of the resonance was studied for various radial sizes of the condensate. The solid line (lower part) compares the experimental results with the prediction for the momentum uncertainty due to the finite size.

4. Excitation of phonons in a Bose-Einstein condensate by light scattering

Light scattering imparts momentum to the condensate and creates an excitation (which can be a phonon or a free particle). A detailed study of the scattered light should therefore reveal a detailed picture of the Bose condensate similar to the case of superfluid helium where neutron scattering was used to obtain the spectrum of elementary excitations.

In the previous section, we showed how a condensate responds to a large momentum transfer which lead to particle-like excitations. Light scattering at small angles does not impart enough momentum to the condensate to create a recoiling atom. Instead, it creates a sound wave by “optically imprinting” phonons into the gas. A sound wave is a collective excitation of all the atoms in the system and therefore requires that the atoms don’t act as individual atoms, but show correlated motion. It has been predicted that this correlated motion results in much weaker light scattering than for free atoms. We found a significant decrease of the rate of light scattering in the phonon regime, providing dramatic evidence for the presence of correlated momentum excitations in the many-body condensate wavefunction [11]. For high-density condensates, even large-angle scattering is in the phonon regime. Therefore, this effect should turn a “pitch-black” condensate transparent since the collective nature of the condensate suppresses its ability to scatter light.

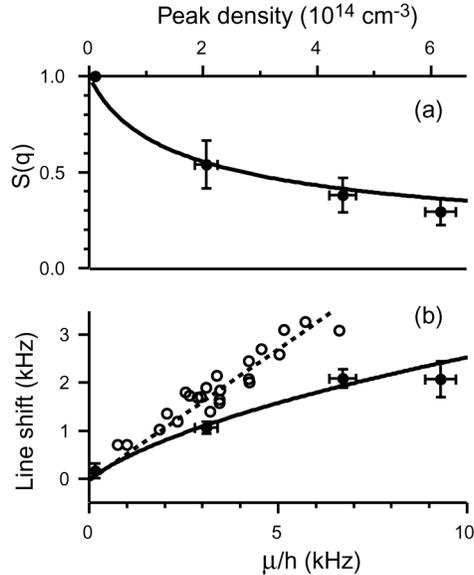


Figure 3: (a) Static structure factor $S(q)$ and (b) shift of the line center from the free particle resonance. $S(q)$ characterizes the strength of the scattering process during which momentum q is transferred to the condensate. As the density and the chemical potential μ increase, the structure factor is reduced, and the Bragg resonance is shifted upward in frequency. Solid lines are predictions of a local-density approximation. Dotted line indicates a mean-field shift of $4 \mu/7 h$ as measured in the free-particle regime (shown in open symbols).

5. Superradiant Rayleigh scattering from a Bose-Einstein condensate

We have discovered a new phenomenon in the scattering of light by a condensate: highly directional, “superradiant” scattering of light and atoms [12]. This phenomenon is deeply rooted in the long coherence time of a condensate. When a condensate has scattered light, an imprint is left in the form of long-lived excitations. This “memory” accelerates the scattering of further photons into the same directions. It provides a gain mechanism for the generation of directed beams of atoms and light.

This phenomenon is fairly dramatic. When a condensate was illuminated with a single weak laser beam, it randomly scattered light into all directions (with the well-known dipolar pattern – this is ordinary Rayleigh scattering). However, above a certain threshold intensity, the condensate produced two highly directional beams of light. Such highly directional light scattering was accompanied by the production of highly directional beams of recoiling atoms (Fig. 4). These beams of atoms were shown to build up by matter wave amplification. The condensate acted as an amplifier for a recoiling atom and “amplified” it to about a million atoms. If one had collected the light in an optical cavity, one would have realized an optical laser. Therefore, the simultaneous superradiant emission of light and atoms emphasizes the symmetry between atom lasers and optical lasers.

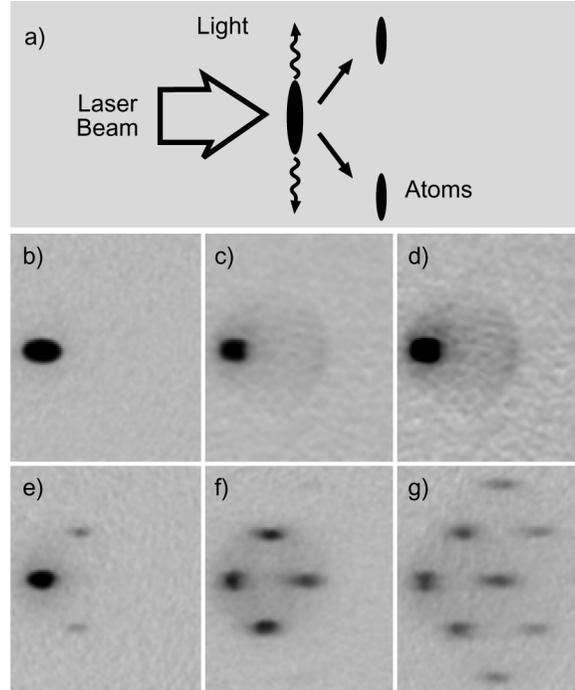


Figure 4: Observation of superradiant Rayleigh scattering. (a) A cigar-shaped condensate is illuminated with a single off-resonant laser beam. Collective scattering leads to photons scattered predominantly along the axial direction, and atoms at 45 degrees. (b-g) Absorption images after 20 ms time-of-flight show the atomic momentum distribution after exposure of the atoms to a laser pulse of variable duration. When the polarization is parallel to the long axis, superradiance is suppressed, and normal Rayleigh scattering was observed (b-d). For perpendicular polarization, directional superradiant scattering of atoms was observed (e-g), and evolved to repeated scattering for longer laser pulses (f,g). The pulse durations are 25 μs (b), 100 μs (c,d), 35 μs (e), 75 μs (f), 100 μs (g). The field of view of each image is 2.8 mm x 3.3 mm. The scattering angle appears to be larger than 45 degrees due to the angle of observation. All images use the same gray scale except for (d), which enhances the small signal of Rayleigh scattered atoms in (c).

6. Phase-coherent amplification of matter waves

Atom amplification differs from light amplification in one important aspect. Since the total number of atoms is conserved (in contrast to photons), the active medium of a matter wave amplifier has to include a reservoir of atoms. One also needs a coupling mechanism which transfers atoms from the reservoir to an input mode while conserving energy and momentum. We have used the superradiance discussed in the previous section to realize a matter wave amplifier [13] (see Fig. 5).

The gain process can be explained in a semiclassical picture. The input matter wave of wave vector \mathbf{K}_j interferes with the condensate at rest and forms a moving matter wave grating which diffracts the pump light with wave vector \mathbf{k}_0 into the momentum and energy conserving direction $\mathbf{k}_i = (\mathbf{k}_0 - \mathbf{K}_j)$. The momentum imparted by the photon scattering is absorbed by the matter wave grating by coherently transferring an atom from the condensate into the recoil mode, which is the input mode. The rate of scattering, which is given by the square of the grating amplitude, is proportional to the number of atoms in the input mode N_j , implying an exponential growth of N_j (as long as one can neglect the depletion of the condensate at rest).

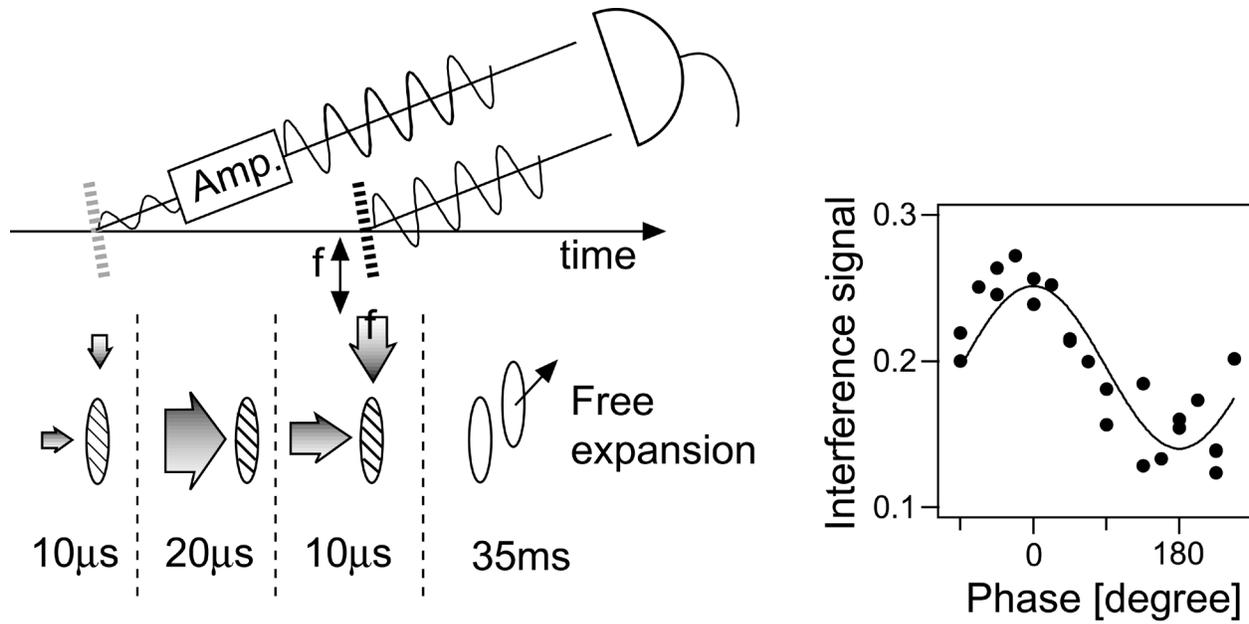


Figure 5: Experimental scheme for observing phase coherent matter wave amplification. A small-amplitude matter wave was split off the condensate by applying a pulse of two off-resonant laser beams (Bragg pulse). This input matter wave was amplified by passing it through the condensate pumped by a laser beam. The coherence of the amplified wave was verified by observing its interference with a reference matter wave, which was produced by applying a second (reference) Bragg pulse to the condensate. The interference signal was observed after 35 ms of ballistic expansion. The fringes on the right side show the interference between the amplified input and the reference matter wave. Figure taken from ref. [13].

Input matter waves with a well defined momentum were generated by using Bragg scattering to transfer a small part of the condensate into a recoil mode. The input matter wave was amplified by applying an intense radial pump pulse for 20 μs . The number of atoms in the recoil mode was then determined by suddenly switching off the trap and observing the ballistically expanding atoms after 35 ms of time-of-flight using resonant absorption imaging. After the expansion, the condensate and the recoiling atoms were fully separated (Fig. 6). Phase-coherence of the matter-wave amplifier was demonstrated with an interferometric technique (Fig. 5).

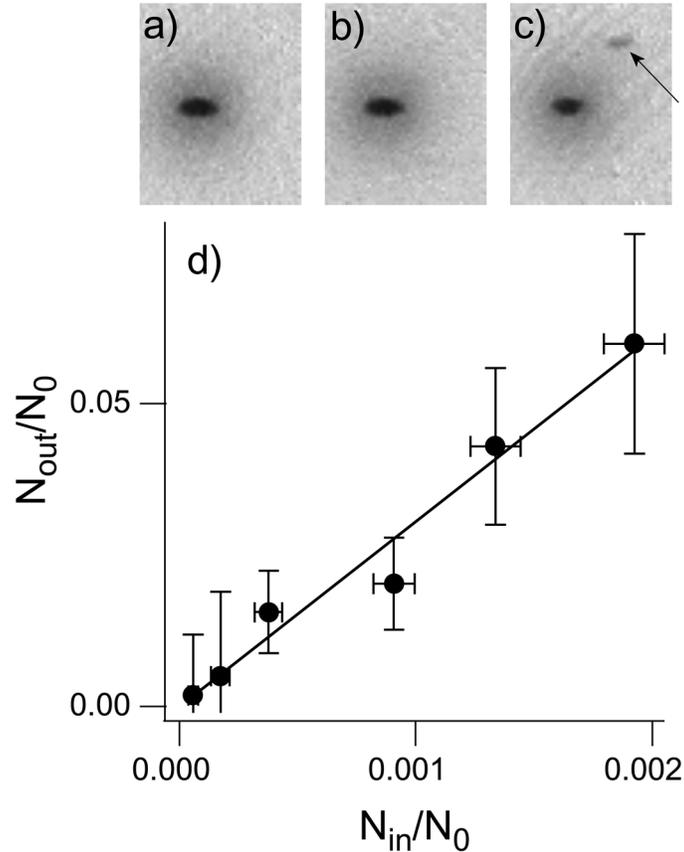


Figure 6: Input-output characteristic of the matter-wave amplifier. (a-c) Typical time-of-flight absorption images demonstrating matter wave amplification. The output of the seeded amplifier (c) is clearly visible, whereas no recoiling atoms are discernible in the case without amplification (a) or amplification without the input (b). The size of the images is 2.8 mm x 2.3 mm. (d) Output of the amplifier as a function of the number of atoms at the input. A straight line fit shows a number gain of 30. Figure taken from ref. [13].

Our experiment can be regarded as a demonstration of an active atom interferometer. It realizes a two-pulse atom interferometer with phase-coherent amplification in one of the arms. Such active interferometers may be advantageous for precise measurements of phase shifts in highly absorptive media, e.g. for measurements of the index of (matter wave) refraction when a condensate passes through a gas of atoms or molecules [15]. Since the most accurate optical gyroscopes are active interferometers [16], atom amplification might also play a role in future matter-wave gyroscopes [17]. In an independent effort a Japanese group [18] has achieved similar results on the amplification of matter waves.

7. A second generation BEC experiment

BEC in atomic gases has many intriguing aspects. Since our group wants to explore several aspects, we started in 1997 with the construction of a second BEC apparatus. The new design includes an intense slow atomic beam, a glass cell with high optical quality as the trapping chamber and a tightly confining magnetic trap. In January '99, the first condensates were produced with about five million atoms in the condensate.

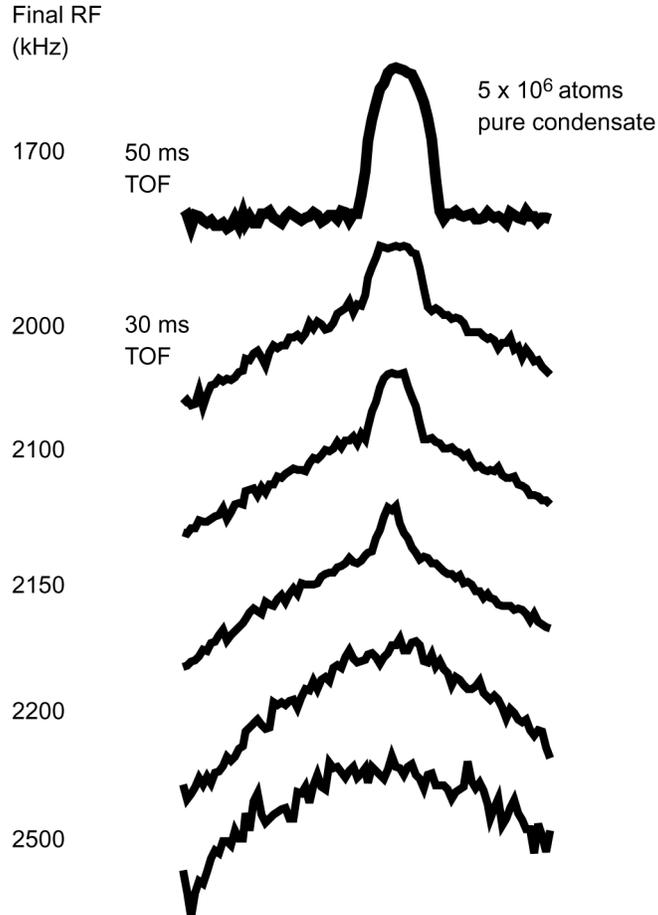


Figure 7: Evidence for Bose-Einstein condensation in our new experiment. As the temperature of the cloud is reduced, the profiles of the ballistically expanding cloud show the sudden appearance of a narrow peak – the condensate. Further cooling produces almost pure condensates. The temperature is almost linearly related to the final rf frequency.

8. Surface Excitations in a Bose-Einstein Condensate

Collective modes which have no radial nodes and are localized close to the surface of the condensate are called surface modes. In a semiclassical picture these excitations can be considered the mesoscopic counterpart to tidal waves at the macroscopic level. Those excitations are of special interest since they show a crossover between collective and single-particle behavior, which is crucial for the existence of a critical rotational velocity. Furthermore, they probe the surface region of the condensate where the density of the thermal cloud is peaked, and should be sensitive to the interactions between condensed and non-condensed atoms [19].

Since these modes don't have cylindrical symmetry, they cannot be excited by modulating currents in the coils of a dc magnetic trap. We have therefore developed a method to create perturbations with high spatial and temporal control [9]. Excitations were driven by the optical dipole force of a far-off-resonant focused laser beam which was controlled by a two-axis acousto-optical deflector. A rapid scan created a pattern of two or four points which had the correct symmetry to excite quadrupolar or hexadecapolar surface oscillations. A temporal modulation of the intensity or a rotation of the whole pattern resulted in standing and rotating waves, respectively (Fig. 8).

This novel method should be useful for exciting even higher-lying excitations, and to impart angular momentum to the whole condensate which should result in vortex formation.

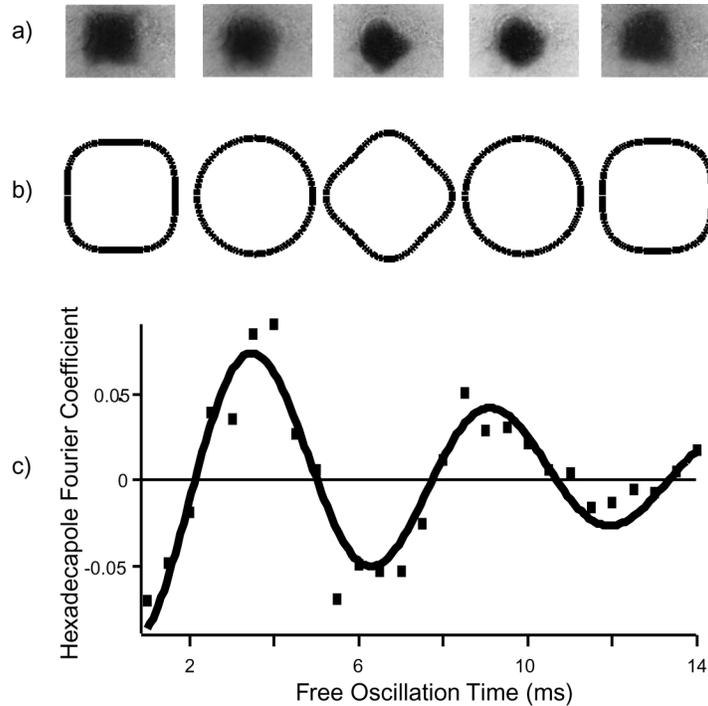


Figure 8: Observation of a standing hexadecapolar excitation of a Bose-Einstein condensate. Absorption images of a condensate driven to excite the $m=4$ mode for various hold times (1, 2, 3.5, 4.5 and 6.5 ms from left to right) in the magnetic trap (a). The shape oscillations of a pure $m=4$ mode are schematically depicted in (b) for one cycle. The contours of images like those in Fig. a were Fourier analyzed. Fig. c shows the oscillation of the $m=4$ Fourier coefficient.

9. Evidence for a Critical Velocity in a Bose-Einstein-Condensate

The existence of a macroscopic order parameter implies superfluidity of gaseous condensates. Observing frictionless flow is a challenge given the small size of the system and its metastability. We have taken a step towards this goal by studying dissipation when an object was moved through the condensate [4]. This is in direct analogy with the well-known argument by Landau [20] and the vibrating wire experiments in superfluid helium [21]. Instead of dragging a massive macroscopic object through the condensate we used a blue detuned laser beam which repelled atoms from its focus to create a moving boundary condition.

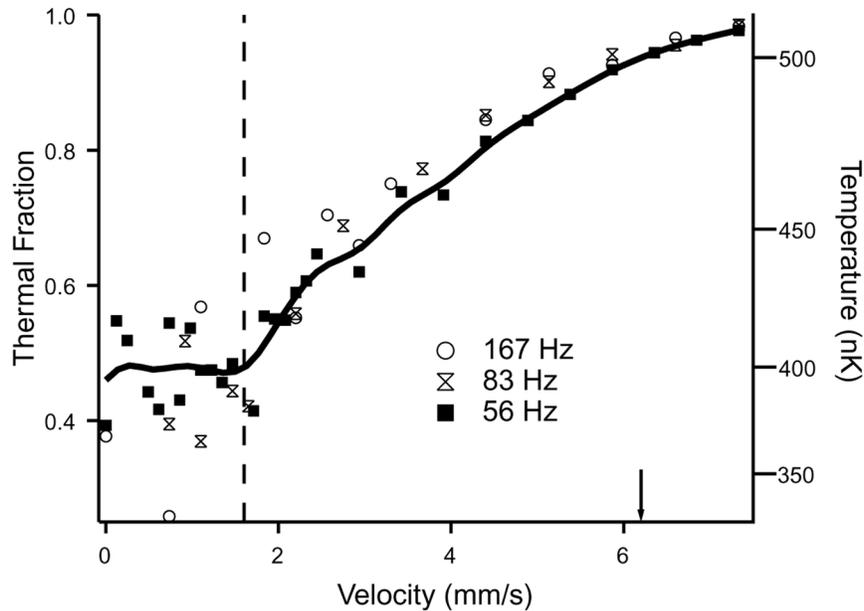


Figure 9: Evidence for a critical velocity. Shown is the final temperature after a laser beam was scanned through the condensate at variable velocity for 900 ms using different scan frequencies. The dashed line separates the regimes of low and high dissipation. The peak sound velocity is marked by an arrow. The data series for 83 and 167 Hz showed large shot-to-shot fluctuations at velocities below 2 mm/sec. The solid line is a smoothing spline fit to the 56 Hz data set to guide the eye. Figure taken from ref. [4].

The beam created a “hole” with a diameter of 13 μm which was scanned back and forth along the long axis of the cigar-shaped condensate (Thomas-Fermi diameters of 45 and 150 μm in the radial and axial directions, respectively). After exposing the condensate to the scanning laser beam for about one second, the final temperature was determined. As a function of the velocity of the scanning beam, we could distinguish two regimes of heating separated by a critical velocity. For low velocities, no or little dissipation was observed, and the condensate appeared immune to the presence of the scanning laser beam. For higher velocities, the heating increased, until at a velocity of about 6 mm/s the condensate was almost completely depleted after the stirring. The cross-over between these two regimes was quite pronounced and occurred at a critical velocity of about 1.6 mm/s which was a factor of roughly four smaller than the speed of sound at the peak density of the condensate (Fig. 9).

These observations are in qualitative agreement with numerical calculations based on the non-linear Schrödinger equation which predict that heating at subsonic velocities is due to the onset of vortex nucleation [22-24]. Because of surface effects and the non-zero temperature, we expect additional corrections leading to dissipation at even lower velocities and a smooth crossover between low and high dissipation. More precise measurements of the heating should allow us to study these finite-size and finite-temperature effects.

10. References

1. M.H. Anderson, J.R. Ensher, M.R. Matthews, C.E. Wieman, and E.A. Cornell, *Science* **269**, 198 (1995).
2. K.B. Davis, M.-O. Mewes, M.R. Andrews, N.J. van Druten, D.S. Durfee, D.M. Kurn, and W. Ketterle, *Phys. Rev. Lett.* **75**, 3969 (1995).
3. C.C. Bradley, C.A. Sackett, and R.G. Hulet, *Phys. Rev. Lett.* **78**, 985 (1997).
4. C. Raman, M. Köhl, R. Onofrio, D.S. Durfee, C.E. Kulewicz, Z. Hadzibabic, and W. Ketterle, *Phys. Rev. Lett.* **83**, 2502 (1999).

5. M.R. Matthews, B.P. Anderson, P.C. Haljan, D.S. Hall, C.E. Wieman, and E.A. Cornell, Phys. Rev. Lett. **83**, 2498 (1999).
6. K.W. Madison, F. Chevy, W. Wohlleben, and J. Dalibard, Phys. Rev. Lett. **84**, 806 (2000).
7. D.M. Stamper-Kurn, H.-J. Miesner, A.P. Chikkatur, S. Inouye, J. Stenger, and W. Ketterle, Phys. Rev. Lett. **83**, 661 (1999).
8. D.M. Stamper-Kurn, M.R. Andrews, A.P. Chikkatur, S. Inouye, H.-J. Miesner, J. Stenger, and W. Ketterle, Phys. Rev. Lett. **80**, 2027 (1998).
9. R. Onofrio, D.S. Durfee, C. Raman, M. Köhl, C.E. Kuklewicz, and W. Ketterle, Phys. Rev. Lett. **84**, 810 (2000).
10. J. Stenger, S. Inouye, A.P. Chikkatur, D.M. Stamper-Kurn, D.E. Pritchard, and W. Ketterle, Phys. Rev. Lett. **82**, 4569 (1999).
11. D.M. Stamper-Kurn, A.P. Chikkatur, A. Görlitz, S. Inouye, S. Gupta, D.E. Pritchard, and W. Ketterle, Phys. Rev. Lett. **83**, 2876 (1999).
12. S. Inouye, A.P. Chikkatur, D.M. Stamper-Kurn, J. Stenger, D.E. Pritchard, and W. Ketterle, Science **285**, 571 (1999).
13. S. Inouye, T. Pfau, S. Gupta, A.P. Chikkatur, A. Görlitz, D.E. Pritchard, and W. Ketterle, Nature **402**, 641 (1999).
14. H.-J. Miesner, D.M. Stamper-Kurn, J. Stenger, S. Inouye, A.P. Chikkatur, and W. Ketterle, Phys. Rev. Lett. **82**, 2228 (1999).
15. J. Schmiedmayer, M.S. Chapman, C.R. Ekstrom, T.D. Hammond, S. Wehinger, and D.E. Pritchard, Phys. Rev. Lett. **74**, 1043 (1995).
16. G.E. Stedman, Rep. Prog. Phys. **60**, 615 (1997).
17. T.L. Gustavson, P. Bouyer, and M.A. Kasevich, Phys. Rev. Lett. **78**, 2046 (1997).
18. M. Kozuma, Y. Suzuki, Y. Torii, T. Sugiura, T. Kuga, E.W. Hagley, and L. Deng, Science **286**, 2309 (1999).
19. F. Dalfovo, S. Giorgini, M. Guilleumas, L.P. Pitaevskii, and S. Stringari, Phys. Rev. A **56**, 3840 (1997).
20. K. Huang, *Statistical Mechanics*, second edition (Wiley, New York, 1987).
21. C.A.M. Castelijns, K.F. Coates, A.M. Guénault, S.G. Mussett, and G.R. Pickett, Phys. Rev. Lett. **56**, 69 (1985).
22. T. Frisch, Y. Pomeau, and S. Rica, Phys. Rev. Lett. **69**, 1644 (1992).
23. C. Huepe and M.-E. Brachet, C.R. Acad. Sci. Paris Série II **325**, 195 (1997).
24. T. Winiecki, J.F. McCann, and C.S. Adams, Phys. Rev. Lett. **82**, 5186 (1999).

RECENT PUBLICATIONS

I. Papers (in refereed journals) and major book chapters

1. S. Inouye, T. Pfau, S. Gupta, A. P. Chikkatur, A. Görlitz, D.E. Pritchard, and W. Ketterle: *Observation of phase-coherent amplification of atomic matter waves.* Nature **402**, 641-644 (1999).
2. R. Onofrio, D.S. Durfee, C. Raman, M. Köhl, C.E. Kuklewicz, and W. Ketterle: *Surface excitations in a Bose-Einstein condensate.* Phys. Rev. Lett. **84**, 810-813 (2000).

3. W. Ketterle:
Bose-Einstein condensation in dilute atomic gases: atomic physics meets condensed matter physics.
Proceedings of the 22nd International Conference on Low Temperature Physics (LT 22).
Physica B, in print.
4. C. Raman, M. Köhl, R. Onofrio, D.S. Durfee, C.E. Kuklewicz, Z. Hadzibabic, and W. Ketterle:
Evidence for a critical velocity in a Bose-Einstein condensed gas.
Phys. Rev. Lett. **83**, 2502-2505 (1999).
5. J. Stenger, S. Inouye, D.M. Stamper-Kurn, A.P. Chikkatur, D.E. Pritchard, and W. Ketterle:
Bragg spectroscopy and superradiant Rayleigh scattering in a Bose-Einstein condensate.
Appl. Phys. B **69**, 347-352 (1999).
6. D.M. Stamper-Kurn, A.P. Chikkatur, A. Görlitz, S. Inouye, S. Gupta, D.E. Pritchard, and W. Ketterle:
Excitation of phonons in a Bose-Einstein condensate by light scattering.
Phys. Rev. Lett. **83**, 2876-2879 (1999).
7. S. Inouye, A.P. Chikkatur, D.M. Stamper-Kurn, J. Stenger, D.E. Pritchard, and W. Ketterle:
Superradiant Rayleigh scattering from a Bose-Einstein condensate.
Science **285**, 571-574 (1999).
8. D.M. Stamper-Kurn, H.-J. Miesner, A.P. Chikkatur, S. Inouye, J. Stenger, and W. Ketterle:
Quantum tunneling across spin domains in a Bose-Einstein condensate.
Phys. Rev. Lett. **83**, 661-665 (1999).
9. W. Ketterle, D.S. Durfee, and D.M. Stamper-Kurn:
Making, probing and understanding Bose-Einstein condensates.
In *Bose-Einstein condensation in atomic gases*, Proceedings of the International School of Physics
"Enrico Fermi", Course CXL, edited by M. Inguscio, S. Stringari and C.E. Wieman (IOS Press,
Amsterdam, 1999) pp. 67-176.
10. J. Stenger, S. Inouye, A.P. Chikkatur, D.M. Stamper-Kurn, D.E. Pritchard, and W. Ketterle:
Bragg spectroscopy of a Bose-Einstein condensate.
Phys. Rev. Lett. **82**, 4569-4573 (1999).
11. H.-J. Miesner, D.M. Stamper-Kurn, J. Stenger, S. Inouye, A.P. Chikkatur, and W. Ketterle:
Observation of metastable states in spinor Bose-Einstein condensates.
Phys. Rev. Lett. **82**, 2228-2231 (1999).
12. J. Stenger, S. Inouye, M.R. Andrews, H.-J. Miesner, D.M. Stamper-Kurn, and W. Ketterle:
Strongly enhanced inelastic collisions in a Bose-Einstein condensate near Feshbach resonances.
Phys. Rev. Lett. **82**, 2422-2425 (1999).

II. Articles in Proceedings

1. W. Ketterle:
Experimental studies of Bose-Einstein condensates in sodium.
in: *Bose Einstein Condensates and Atom Lasers*, Proceedings of the International School of
Quantum Electronics, 27th Course, Erice, 1999 (Kluwer Academic, London, in print).
2. D.M. Stamper-Kurn, A.P. Chikkatur, A. Görlitz, S. Gupta, S. Inouye, J. Stenger, D.E. Pritchard, and W.
Ketterle:
Probing Bose-Einstein condensates with optical Bragg scattering
Proceedings of the Tenth Conference on Many-Body Physics (MBX), Seattle, Sept. 1999, in print.
3. J. Stenger, S. Inouye, D.M. Stamper-Kurn, A.P. Chikkatur, D.E. Pritchard, and W. Ketterle:
Bragg spectroscopy and superradiant Rayleigh scattering in a Bose-Einstein condensate.
(Article is identical to the Appl. Phys. B paper).
Proceedings of the Intern. Conf. on Laser Spectroscopy (ICOLS), Innsbruck, eds. D. Leibfried, J.
Eschner, F. Schmidt-Kaler, and R. Blatt, World Scientific (1999), in print.
4. W. Ketterle and C. Raman:
Collisions at nanokelvin temperatures in Bose-Einstein condensates.
Proceedings of the International Conference on the Physics of Electronic and Atomic Collisions (XXI
ICPEAC) July 1999, Sendai, Japan, in print.

5. J. Stenger:
Bragg spectroscopy and superradiant Rayleigh scattering in a Bose-Einstein condensate.
 (Article is identical to the Appl. Phys. B paper).
 in: Laser Spectroscopy XIV, eds. R. Blatt, J. Eschner, D. Leibfried, F. Schmidt-Kaler (World Scientific, Singapore, 1999), pp. 90-99.

III. Popular articles

1. W. Ketterle:
 Experimental studies of Bose-Einstein condensation.
 Physics Today, December 1999, pp. 30-35.
2. W. Ketterle:
 What does a Bose-Einstein condensate look like?
 Optics&Photonics News, December 1999, p. 38.
3. W. Ketterle:
 Bose-Einstein condensation.
 McGraw-Hill Encyclopedia of Science & Technology, 9th Edition, in print.

IV. Conference contributions with published abstracts

1. W. Ketterle:
Spectroscopy of a Bose-Einstein condensate.
 Inspired by Herzberg: Spectroscopy for the Year 2000, Symposium in memory of Gerhard Herzberg, Cornwall, Ontario, Canada, 10/30 – 11/3, 1999, Book of Abstracts, p. 5.
2. W. Ketterle:
What does a Bose-Einstein condensate look like?
 International School of Quantum Electronics, 27th Course, Bose-Einstein condensates and Atom Lasers, Erice, Sicily, 10/19-24/1999, Book of Abstracts, p.3
3. S. Inouye, J. Stenger, A. Chikkatur, D. Stamper-Kurn, D. Pritchard, and W. Ketterle:
Collective amplified emission of light and atoms from a BEC.
 OSA 1999 annual meeting/ILS-XV, Book of Abstracts.
4. W. Ketterle:
Recent Advances in Bose-Einstein Condensation.
 EPS-11: Trends in Physics, 9/6-10/1999, London, Abstract Book, p.5.
5. W. Ketterle:
Bose-Einstein condensation in dilute atomic gases – atomic physics meets condensed matter physics.
 XXII International Conference on Low Temperature Physics, 8/4-11/1999, Espoo, Finland, Book of Abstracts, p. 28.
6. W. Ketterle:
Recent Results on BEC: Quantum Tunneling, Bragg Spectroscopy and Superradiance.
 1999 NASA/JPL International Conference on Fundamental Physics in Space.
 Washington DC, 4/29-5/1/1999, Book of Abstracts, p.2.
7. J. Stenger, S. Inouye, A. Chikkatur, D. Stamper-Kurn, D. Pritchard, and W. Ketterle:
Bragg spectroscopy of a Bose-Einstein condensate.
 Bull. Am. Phys. Soc. **44**, 1008 (1999).
8. D.M. Stamper-Kurn, J. Stenger, H.-J. Miesner, S. Inouye, A.P. Chikkatur, and W. Ketterle:
Putting a spin on BEC: Ground states, metastability, and tunneling.
 Bull. Am. Phys. Soc. **44**, 1007 (1999).

9. J. Stenger, D.M. Stamper-Kurn, S. Inouye, H. Miesner, A.P. Chikkatur und W. Ketterle:
Spinor-Bose-Einstein-Kondensate und optische Auskoppler.
Verhandl. DPG, 519 (1999).
10. W. Ketterle:
Keeping the focus on Bose-Einstein condensates.
Fysica '99, Nederlandse Natuurkundige Vereniging, Delft, Netherlands, 4/14/1999.
11. W. Ketterle:
The Physics of Cold Atoms at Millikelvin, Mikrokelvin and Nanokelvin Temperatures.
Tutorial at the APS Centennial Meeting, Atlanta, 3/21-3/26/1999.
Program on Short Courses, Tutorials and Workshops.
12. W. Ketterle:
Spinor condensates and Bragg spectroscopy
Workshop on Bose-Einstein condensation and degenerate Fermi gases, JILA, Boulder, 2/10-2/12/1999, Book of Abstracts.
13. C. Raman:
New optical tools to study BEC.
Conference on Macroscopic Quantum Coherence Phenomena, Trieste, 7/5-9/1999, Book of Abstracts.
14. S. Inouye:
Spinor condensates and Bragg spectroscopy.
Symposium on "Quantum phenomena of ultracold atoms and their applications", Spring meeting of the Physical Society of Japan, Hiroshima, 3/29/1999, Book of Abstracts.
15. D.M. Stamper-Kurn:
Probing Bose-Einstein condensates with light.
Tenth Conference on Many-Body Physics (MBX), Seattle, Sept. 1999, abstract.
16. R. Onofrio:
Recent Experiments in Bose-Einstein condensation: Superradiance and critical velocities.
1999 Fundamental Problems in Quantum Theory Workshop, 8/8-13/99, Baltimore, Program, p. 22.
17. S. Inouye:
Elastic and inelastic collisions in a Bose-Einstein condensate near Feshbach resonances.
ITAMP workshop on Fragmentation and Recombination in Novel 3- and 4-Body Systems, Cambridge, MA, 11/4-6/1999, Book of Abstracts, p. 14.
18. J. Stenger:
Spectroscopy and Superradiance in a Sodium BEC
ICOLS, Innsbruck, June 7 - 11, 1999, Book of Abstracts, p. 5-2

V. THESES

Dallin S. Durfee:

Dynamic Properties of Dilute Bose-Einstein Condensates

Ph.D. diss., Dept. of Physics, MIT, 1999.

Dan M. Stamper-Kurn:

Peeking and poking at a new quantum fluid:

Studies of gaseous Bose-Einstein condensates in magnetic and optical traps

Ph.D. diss., Dept. of Physics, MIT, 1999.