

## Cooling and Trapping Neutral Atoms

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### Sponsors:

National Science Foundation  
Office of Naval Research  
DARPA  
NASA

### Keywords:

Bose-Einstein condensation, ultracold atoms, magnetic trapping, optical trapping, quantum statistics, collective excitations, superfluidity, vortices, quantum gases, degenerate Fermi systems, atom-chips, atom interferometry

## Introduction and overview

Bose-Einstein condensation of atoms was achieved in 1995 and had a major impact of atomic physics. New techniques were developed to prepare atomic samples at nanokelvin temperature, to control their properties and to diagnose them with a variety of powerful techniques. Since then, the field has dramatically grown. The family of quantum-degenerate gases now includes metastable and fermionic atoms, and molecules. Such systems have become an ultralow-temperature laboratory for atom optics and collisional physics, and also for many-body physics that encompasses phenomena as phonons, superfluidity, quantized vortices, Josephson junctions, and quantum phase transitions.

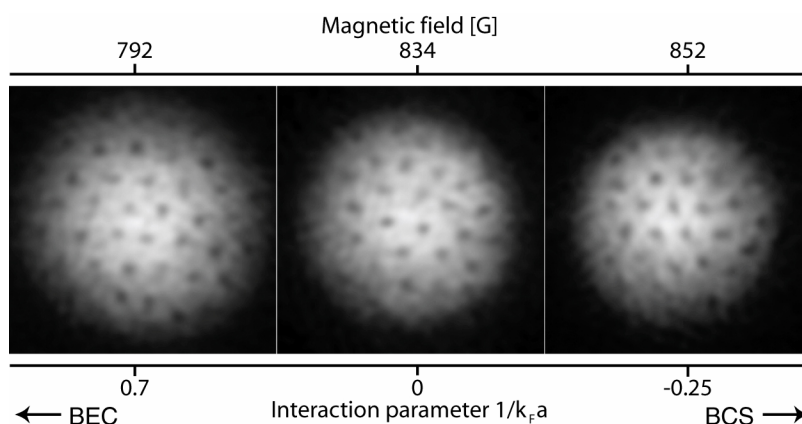
Most of our results in the past year reflect our focus on strongly interacting quantum gases. This has been pursued with bosons in optical lattices, and in our studies of fermionic superfluidity. A highlight of the past year was the first observation of a new form of high-temperature superfluidity in a gas of fermions. Major progress was also achieved in our program on atom interferometry where we study interference of two condensates either in an optical double-well potential or on an atom chip.

### 1. Vortices and Superfluidity in a Strongly Interacting Fermi Gas

Quantum-degenerate Fermi gases provide a remarkable opportunity to study strongly interacting fermions. In contrast to other Fermi systems, such as superconductors, neutron stars or the quark-gluon plasma, these gases have low densities and their interactions can be precisely controlled over an enormous range. By varying the pairing strength between two fermions near a Feshbach resonance, one

can explore the crossover from a Bose-Einstein condensate (BEC) of molecules to a Bardeen-Cooper-Schrieffer (BCS) superfluid of loosely bound pairs whose size is comparable to, or even larger than, the interparticle spacing. The crossover realizes a novel form of high- $T_C$  superfluidity and it may provide new insight for high- $T_C$  superconductors. Earlier experiments with Fermi gases have revealed condensation of fermion pairs [Greiner, 2003 #1476; Jochim, 2003 #1305; Zwierlein, 2003 #1303][Regal, 2004 #1306; Zwierlein, 2004 #1329], but not observed superfluidity. Our observation of vortex lattices directly displays superfluid flow in a strongly interacting, rotating Fermi gas [Zwierlein, 2005 #1480].

A strongly interacting cloud of fermions was created by laser cooling, sympathetic cooling with sodium in a magnetic trap, followed by evaporative cooling in an optical trap [Zwierlein, 2003 #1303; Zwierlein, 2004 #1329]. The trapped cloud was rotated about its long axis using a blue detuned laser beam (wavelength 532 nm). A two-axis acoustooptic deflector generated a two-beam pattern that was rotated symmetrically around the cloud at a variable angular frequency. Vortex lattices were generated both above and below the Feshbach resonance at 834 Gauss.



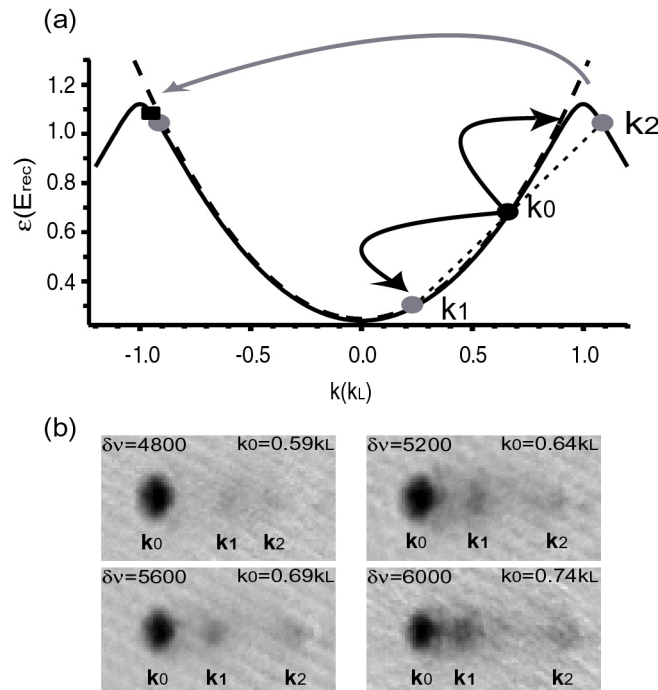
Vortex lattices in the BEC-BCS crossover. After a vortex lattice was created at 812 G, the field was ramped in 100 ms to 792 G (BEC-side), 833 G (resonance), and 853 G (BCS-side), where the cloud was held for 50 ms. After 2 ms of ballistic expansion, the magnetic field was ramped to 735 G for imaging. The field of view of each image is  $880 \mu\text{m} \times 880 \mu\text{m}$ .

## 2. Parametric scattering of Bose-Einstein condensates in a one dimensional optical lattice

If a condensate with positive scattering length is moving in free space, the condensate is stable: Atoms cannot elastically scatter into different momentum states and conserve energy and momentum due to the quadratic dispersion relation for free particles. In a one-dimensional optical lattice, even for small lattice depths the dispersion relation is no longer quadratic near the boundary of the first Brillouin zone. As a result, two atoms with certain values of the initial momentum  $k_0$  can elastically scatter, and a condensate moving through an optical lattice becomes unstable.

To demonstrate this, a  $^{87}\text{Rb}$  Bose-Einstein condensate was loaded into a moving optical lattice, i.e. the condensate had some adjustable quasi-momentum  $k_0$ . For values of  $k_0$  larger than  $\approx 0.55 k_L$ , where  $k_L$  is the wavevector of the optical lattice, the dispersion relation imposed by the Bloch structure of the lattice allows elastic scattering to occur into two distinct momentum states  $k_1$  and  $k_2$  as observed in the experiment.

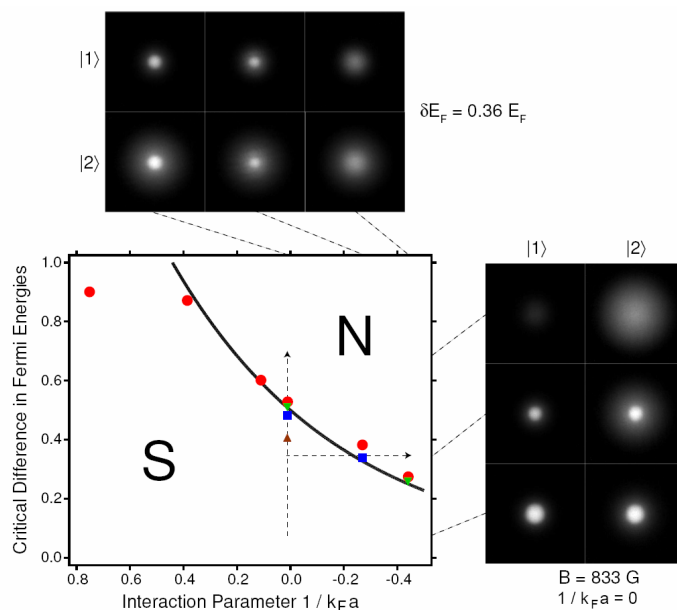
This process could be seeded. When a small fraction of atoms was first transferred to  $k_1$  before ramping on the lattice parametric amplification of scattered atoms into  $k_1$  and  $k_2$  was observed. These results can explain the dynamic instabilities shown in recent experiments with condensates in moving lattices [1,2].



(a) Band structure of the optical lattice. The dashed line shows the free-particle dispersion curve. The dispersion relation of the lattice allows two atoms with momentum  $k_0$  to elastically scatter into the final momentum states  $k_1$  and  $k_2$  and conserve both energy and momentum. (b) Absorption images for different initial condensate momenta  $k_0$ , showing parametric scattering.

### 3. Fermionic Superfluidity with Imbalanced Spin Populations

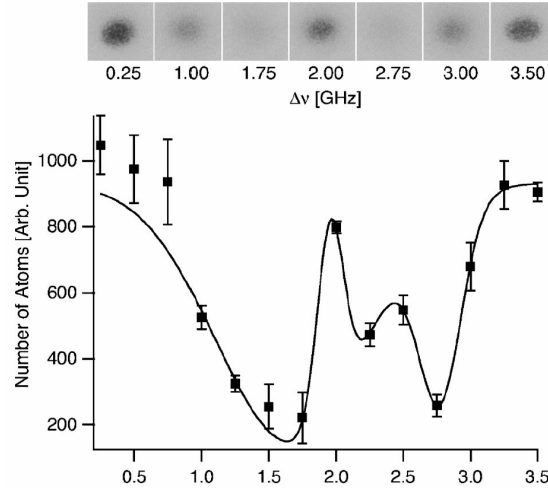
We have established superfluidity in a two-state mixture of ultracold fermionic atoms with imbalanced spin populations [1]. This study relates to the long-standing debate about the nature of the superfluid state in Fermi systems. Indicators for superfluidity were condensates of fermion pairs, and vortices in rotating clouds. For strong interactions, near a Feshbach resonance, superfluidity was observed for a broad range of population imbalances. We mapped out the superfluid regime as a function of interaction strength and population imbalance, and characterized the quantum phase transition to the normal state, known as the Pauli limit of superfluidity.



Phase diagram for interacting Fermi systems with adjustable interactions (horizontal axis) and adjustable spin populations (vertical axis, expressed by the difference in Fermi energies between the two spin states) showing the normal (N) and superfluid (S) regimes. Representative density profiles illustrate the quantum phase transition for fixed interaction (top, induced by varying the population imbalanced) and for fixed population imbalance (right) along the dashed lines. The bright spot in the center of the profiles is the pair condensate which indicates superfluidity.

#### 4. Sodium Bose-Einstein Condensates in an Optical Lattice

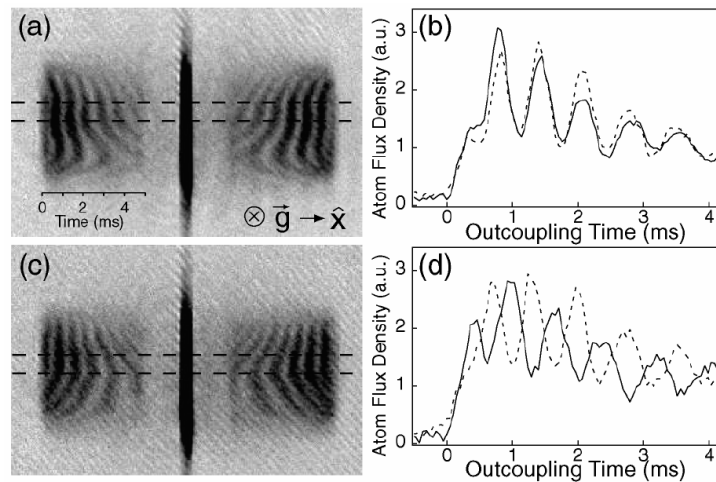
Optical lattices have become a powerful tool to enhance the effects of interaction in ultracold atomic systems to create strong correlations and probe many-body physics beyond the mean-field theory [2]. Simply through varying the depth of the lattice potential, one changes the tunneling rate as well as the on-site interaction energy by changing the confinement of the atoms. So far, most optical lattice experiments have been performed with relatively heavy atomic species (e.g. rubidium and potassium) for which the recoil frequencies are lower and lasers are readily available to achieve trap depths of several tens of recoil frequencies at a few tens of milliwatts. For  $^{23}\text{Na}$ , high power single-mode lasers are necessary for similar experiments. In this work, we chose to use a dye laser red-detuned by 5 nanometers from the D lines of sodium (589 nm). The spontaneous scattering rate limited the time window of the experiment to less than 50 ms, but was still sufficient to satisfy the adiabaticity condition to explore the quantum phase transition from a superfluid to a Mott insulator [3]. We also observed strong atom losses at various lattice laser detunings, which were interpreted as photoassociation transitions. The particular molecular states responsible for these transitions were identified through theoretical calculations and previous experimental data.



Photoassociation resonances: Atom loss from the optical lattice as a function of the lattice laser detuning. The top row of images shows the remaining atom cloud after the lattice was turned off and the cloud expanded for 30 ms. The lower graph shows the remaining number of atoms for these and additional frequency points. The zero of the  $x$  axis corresponds to a laser wavelength of 594.490 nm.

### 5. Optical Weak Link between Two Spatially Separate Bose-Einstein Condensates

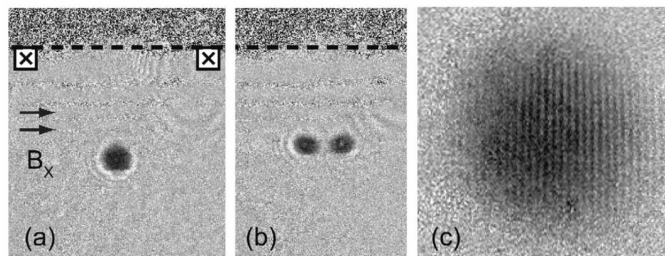
The concept of Josephson coupling can be extended to include two spatially separate quantum systems by using intermediate coupling systems. The phase of the coupling may be actively controlled by adjusting the coupling states of the intermediate systems. We have experimentally demonstrated phase-sensitive optical coupling of two spatially separate Bose-Einstein condensates using Bragg scattering [4]. We have studied two condensates in an optical double-well potential, irradiated by two pairs of Bragg beams which couple out beams of atoms propagating to the left or the right, respectively, and these unconfined propagating atoms constitute the intermediate coupling system in our scheme. Depending on the relative phases of the two condensates and the coupling states, we observe only one outcoupled beam propagating to one or the other side, or two identical beams propagating in opposite directions (see figure). This demonstrates phase control of currents and establishes a new scheme to realize Josephson effects with two non-overlapping condensates.



Symmetric and antisymmetric correlation between outcoupled atom patterns. Two pairs of Bragg beams outcoupled atoms in either  $+x$  or  $-x$  direction. Absorption images were taken after 5 ms outcoupling and 2 ms additional ballistic expansion. The left outcoupled atom patterns were compared with the corresponding right patterns. Depending on the frequency of the Bragg beams, we observed symmetric correlation between the two patterns (top) or antisymmetric correlations (bottom). The field of view is 0.9 mm  $\times$  0.6 mm.

### 6. Interference of Bose-Einstein condensates split with an atom chip.

A major step towards compact matter wave sensors is an atom interferometer on an atom chip. We have used an atom chip to split a single Bose-Einstein condensate of sodium atoms into two spatially separated condensates [5]. Dynamical splitting was achieved by deforming the trap along the tightly confining direction into a purely magnetic double-well potential. We observed the matter wave interference pattern formed upon releasing the condensates from the microtraps. The intrinsic features of the quartic potential at the merge point, such as zero trap frequency and extremely high field-sensitivity, caused random variations of the relative phase between the two split condensates. Moreover, the perturbation from the abrupt change of the trapping potential during the splitting was observed to induce vortices.

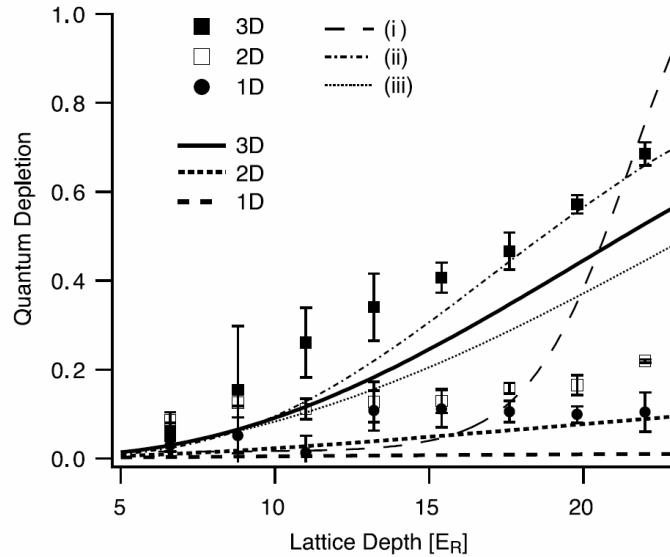


Splitting of condensates. (left) Condensates were initially loaded and prepared in the bottom well and (middle) split into two parts by increasing the external magnetic field. For clarity, two condensates were split by  $80\ \mu\text{m}$ . The dashed line indicates the chip surface position. (right) Two condensates were released from the magnetic double-well potential and the matter wave interference pattern of two condensates formed after time-of-flight.

### 7. Observation of Strong Quantum Depletion in a Gaseous Bose-Einstein Condensate

Gaseous condensates can be almost quantitatively described by a single macroscopic wave function shared by all atoms which is the solution of a non-linear Schrodinger equation. The fraction of the many-body wavefunction which cannot be represented by the macroscopic wavefunction is called the quantum depletion. In a homogenous BEC, it consists of admixtures of higher momentum states into the ground state of the system. For typical gas densities, the fraction of the quantum depletion is 0.2% whereas in liquid helium it is approximately 90 %.

To bridge the gap between Bose condensed gases and liquid helium, we have studied quantum depletion in an optical lattice, which enhanced the atomic interactions and modified the dispersion relation resulting in strong quantum depletion [6]. The depleted fraction was directly observed as a diffuse background in the time-of-flight images. Bogoliubov theory provided a semi-quantitative description for our observations of depleted fractions in excess of 50%.

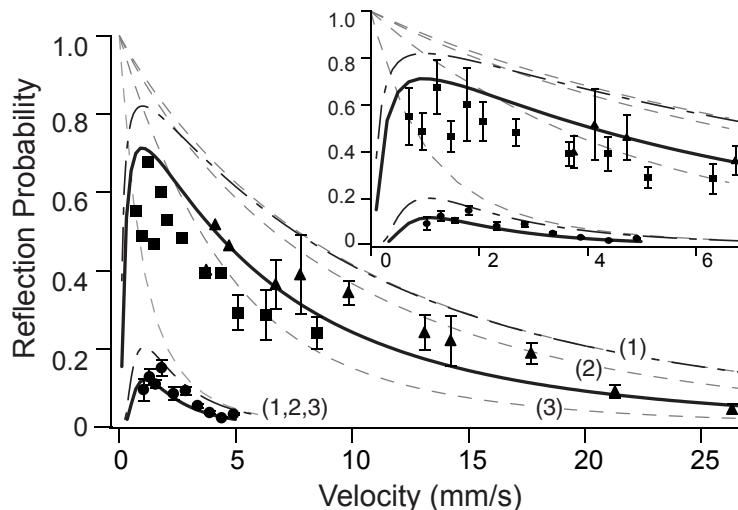


Quantum depletion of a sodium BEC confined in a one, two and three dimensional optical lattice: the data points are compared to the three thick curves which represent theoretical calculations using Bogoliubov theory and local density approximation. For comparison, also shown are (thin curves): (i) the (smoothed out) Mott-insulator fraction based on a mean-field theory; (ii) the calculated quantum depletion for a homogeneous system of per-site occupancy number  $n = 1$  and (iii)  $n = 7$

### 8. The Role of Interactions in Quantum Reflection of Bose-Einstein Condensates

Quantum reflection is the phenomena by which an atom is accelerated so abruptly by the Casimir-Polder potential that it reflects from the potential rather than being drawn into the surface. The usual model of quantum reflection treats the atom-surface interaction as a single atom in a potential. However, in a recent study of quantum reflection of Bose-Einstein condensates (BECs), the reflection probability was limited to  $\sim 15\%$  at low velocity [7]. A theoretical paper simulating quantum reflection of Bose-Einstein condensates could not explain the low reflectivity [8].

In this work, we have studied how inter-atomic interactions affect quantum reflection of Bose-Einstein condensates [9]. A silicon surface with a square array of pillars resulted in higher reflection probability than was previously observed with a solid silicon surface. For incident velocities greater than 2.5 mm/s, our observations agreed with single-particle theory. At velocities below 2.5 mm/s, the measured reflection probability saturated near 60% rather than increasing towards unity as predicted. We have extended the theory of quantum reflection to account for the mean-field interactions of a condensate which suppress quantum reflection at low velocity. Our model predicts improvements for longer healing lengths and how the corresponding reduction in condensate density sets a limit for the incident flux of atoms.



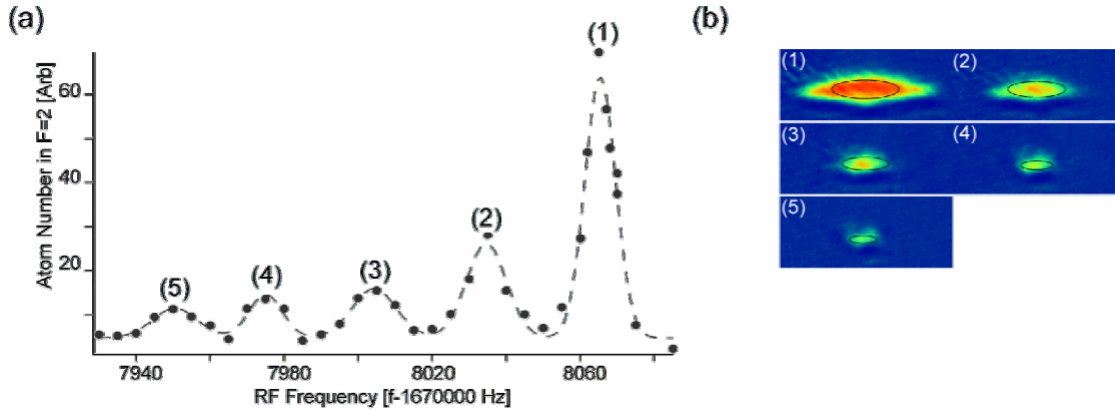
Reflection probability vs incident velocity. Data are shown for a pillared (square) and solid (circle) Si surface. Single atom models give a monotonic rise to unity reflection. Our model which includes interactions shows saturation of reflection at low velocity in qualitative agreement with our observations.

### 9. Imaging the Mott Insulator shells using atomic clock shifts

Bose-Einstein condensates in optical lattices are an ideal system for studying strongly-correlated many-body systems. The Mott Insulator transition is a paradigm of condensed matter physics and describes how electron correlations can lead to insulating behavior even for partially filled conduction bands. However, this behavior requires a commensurate ratio between electrons and sites. For neutral bosonic particles, the equivalent phenomenon is the transition from a superfluid to an insulator for commensurate densities. In inhomogeneous systems, as in atom traps, the condition of commensurability no longer applies: for sufficiently strong interparticle interactions, it is predicted that the system should separate into Mott insulator shells with different occupation number, separated by thin superfluid layers [10]. The most dramatic new feature of the Mott Insulator phase in ultracold atoms is this layered structure of the Mott shells, however in previous experiments [2, 11] this feature has not been directly observed.

Recently we have used microwave spectroscopy to characterize the Superfluid – Mott insulator transition. Using the density dependent clock shift we were able to spectroscopically distinguish sites with different occupation numbers, and to directly image sites with occupation number  $n=1$  to  $n=5$ , revealing the shell structure of the Mott Insulator phase [12]. We have also used this spectroscopy to determine the onsite interaction and lifetime for individual shells. Using atomic clock shifts to characterize the superfluid – Mott Insulator transition demonstrates the power of applying precision methods of atomic physics to problems in condensed matter physics.

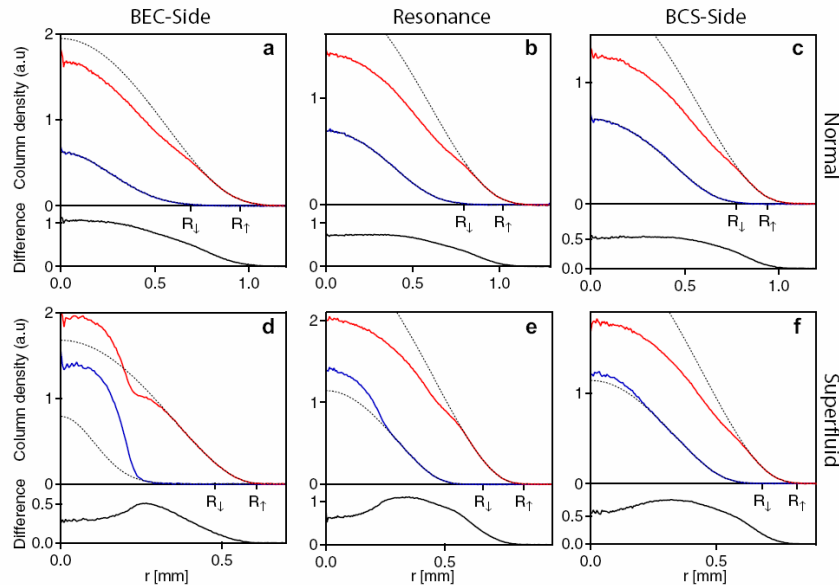




Imaging the shell structure of the Mott insulator. (a) Spectrum of the Mott insulator at a lattice depth of 35 recoil energies. (b) Absorption images for decreasing rf frequencies. Images 1, 2, 3, 4 and 5 were taken on resonance with the peaks shown in (a) and display the spatial distribution of the  $n=1-5$  shells. The solid lines shows the predicted contours of the shells.

### 10. Direct Observation of the Superfluid Phase Transition in Ultracold Fermi Gases

The hallmark of Bose-Einstein condensation (BEC) and superfluidity in trapped, weakly interacting Bose gases is the sudden appearance of a dense central core inside a thermal cloud. In strongly interacting gases, such as the recently observed fermionic superfluids, this clear separation between the superfluid and the normal parts of the cloud is no longer given and the phase transition could be detected only using magnetic field sweeps into the weakly interacting regime. Here we demonstrate that the superfluid phase transition can be directly observed by sudden changes in the shape of the clouds, in complete analogy to the case of weakly interacting Bose gases. By preparing unequal mixtures of the two spin components involved in the pairing, we greatly enhance the contrast between the superfluid core and the normal component [13]. Furthermore, the non-interacting wings of excess atoms serve as a direct and reliable thermometer.



Direct observation of the phase transition in a strongly interacting two-state mixture of fermions with imbalanced spin populations. Top a-c and bottom d-f rows show observed column densities after expansion for the normal and the superfluid state, respectively. Panels a and d were obtained in the BEC-regime (at 781 G), b,e on resonance ( $B = 834$  G) and c,f on the BCS-side of the Feshbach resonance (at 853 G). The appearance of a dense central feature in the

smaller component marks the onset of condensation. The dashed lines show Thomas-Fermi fits to the wings of the column density.

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## Publications

### Papers (in refereed journals) and major book chapters

1. G.K. Campbell, J. Mun, M. Boyd, P. Medley, A.E. Leanhardt, L. Marcassa, D.E. Pritchard, and W. Ketterle:  
*Imaging the Mott Insulator Shells using Atomic Clock Shifts.*  
to be published.
2. T. A. Pasquini, M. Saba, G. Jo, Y. Shin, W. Ketterle, D. E. Pritchard, T. A. Savas, N. Mulders:  
*Low velocity quantum reflection of Bose-Einstein condensates.*  
cond-mat/0603463.
3. M.W. Zwierlein, C.H. Schunck, A. Schirotzek, W. Ketterle:  
*Direct Observation of the Superfluid Phase Transition in Ultracold Fermi Gases.*  
Nature, in print; cond-mat/0605258.
4. Vitaly V. Kocharovskiy, Vladimir V. Kocharovskiy, Martin Holthaus, C.H. Raymond Ooi, Anatoly A. Svidzinsky, Wolfgang Ketterle, Marlan O. Scully:  
*Fluctuations in Ideal and Interacting Bose-Einstein Condensates: From the laser phase transition analogy to squeezed states and Bogoliubov quasiparticles.*  
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5. K. Xu, Y. Liu, D.E. Miller, J.K. Chin, W. Setiawan, and W. Ketterle:  
*Observation of Strong Quantum Depletion in a Gaseous Bose-Einstein Condensate.*  
Phys. Rev. Lett. **96**, 180405 (2006).
6. M.W. Zwierlein, A. Schirotzek, C.H. Schunck, and W. Ketterle:  
*Fermionic Superfluidity with Imbalanced Spin Populations.*  
Science **311**, 492-496 (2006); published online on Dec. 22, 2005.
7. G.K. Campbell, J. Mun, M. Boyd, E.W. Streed, W. Ketterle, and D.E. Pritchard:  
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1. M. Zwierlein, A. Schirotzek, C. Schunck, W. Ketterle.  
*Superfluid Expansion of a Rotating Fermi Gas.*  
DAMOP (APS Division of Atomic, Molecular, and Optical Physics), Knoxville, TN, 2006, 5/16-5/20/2006, Abstract Z3 10; Bull. Am. Phys. Soc. **51**, 165 (2006).
2. M. Zwierlein, A. Schirotzek, C. Schunck, W. Ketterle  
*Direct Observation of Resonance Condensation in Imbalanced Fermi Mixtures.*  
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