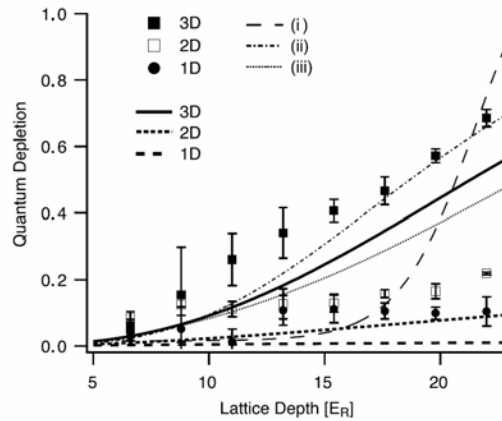


## Progress in year 2006

### 1. 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 Schrödinger 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 [1]. 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%.



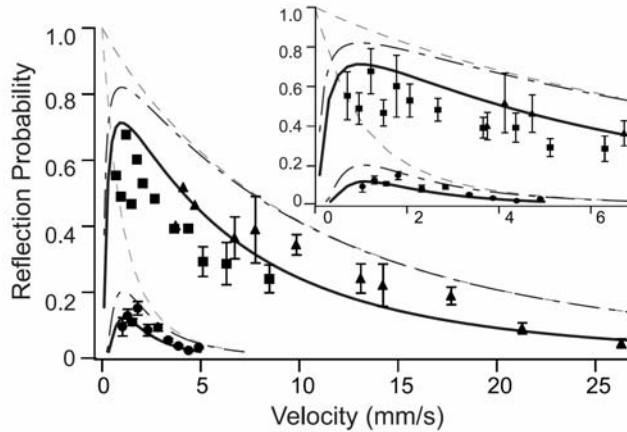
Quantum depletion of a sodium BEC confined in a one, two and three dimensional optical lattice: the data points are compared to the three thick curves which represent theoretical calculations using Bogoliubov theory and local density approximation. For comparison, also shown are (thin curves): (i) the (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)  $n = 7$

### 2. 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

~15% at low velocity [2]. A theoretical paper simulating quantum reflection of Bose-Einstein condensates could not explain the low reflectivity [3].

In this work, we have studied how inter-atomic interactions affect quantum reflection of Bose-Einstein condensates [4]. 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.

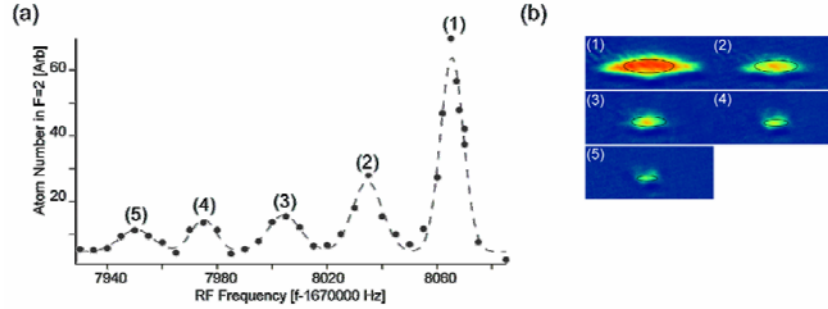


Reflection probability vs. incident velocity. Data are shown for a pillared (square) and solid (circle) Si surface. Single atom models give a monotonic rise to unity reflection. Our model which includes interactions (solid line) shows saturation of reflection at low velocity in qualitative agreement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

### 3. 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 [5]. 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 [6, 7] this feature has not been directly observed.

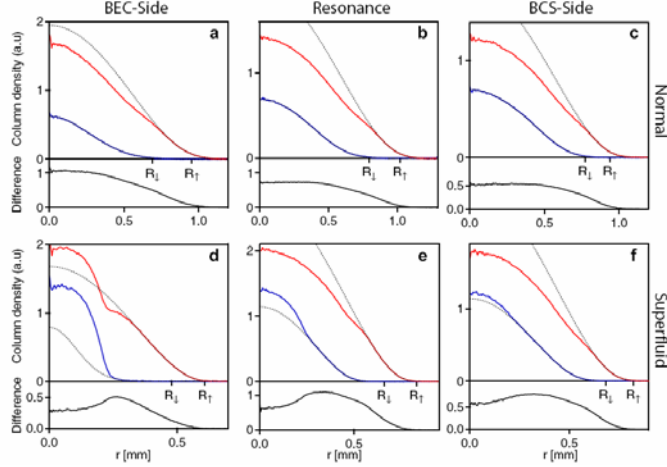
Recently we have used microwave spectroscopy to characterize the Superfluid – Mott insulator transition. Using the density dependent clock shift we were able to spectroscopically distinguish sites with different occupation numbers, and to directly image sites with occupation number  $n = 1$  to  $n = 5$ , revealing the shell structure of the Mott Insulator phase [8]. 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.

#### 4. 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 [9]. Furthermore, the non-interacting wings of excess atoms serve as a direct and reliable thermometer.

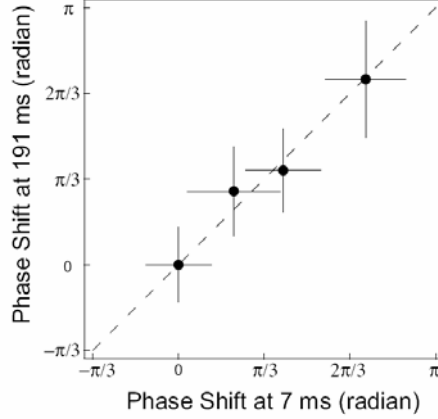


Direct observation of the phase transition in a strongly interacting two-state mixture of fermions with imbalanced spin populations. Top a-c and bottom d-f rows show observed column densities after expansion for the normal and the superfluid state, respectively. Panels a and d were obtained in the BEC-regime (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.

## 5. Long Phase Coherence Time and Number Squeezing of two Bose-Einstein Condensates on an Atom Chip

Precision measurements in atomic physics are usually done at low atomic densities to avoid collisional shifts and dephasing. This applies to both atomic clocks and atom interferometers. At high density, the atomic interaction energy results in so-called clock shifts and leads to phase diffusion in Bose-Einstein condensates. Operating an atom interferometer at low density severely limits the flux and therefore the achievable signal-to-noise ratio.

Here we show that we can operate a BEC interferometer at high density, with mean field energies exceeding  $\hbar$  5 kHz [10]. Using an radio frequency (RF) induced beam splitter we demonstrate that condensates can be split reproducibly, so that even after 200 ms, or more than one thousand cycles of the mean field evolution, the two condensates still have a controlled phase. The observed coherence time of 200 ms is ten times longer than the phase diffusion time for a coherent state, i.e., a state with perfectly defined relative phase at the time of splitting. Therefore, repulsive interactions during the beam splitting process have created a non-classical squeezed state with relative number fluctuations ten times smaller than for a Poissonian distribution



Long phase coherence of two separated condensates. Various phase shifts were applied on the condensates 2 ms after splitting by pulsing on an additional magnetic field. The shifts of the relative phase were measured at 7 ms and 191 ms, showing strong correlation. The dotted line denotes the ideal case of perfect phase coherence.

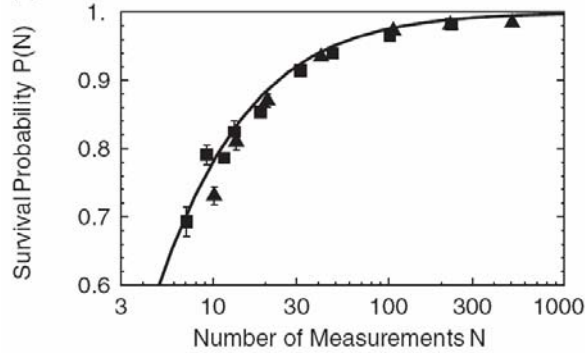
## 6. Guiding atoms with a hollow core photonic crystal fiber

In contrast to ordinary fibers, hollow core photonic crystal fibers guide light through vacuum. Red-detuned light in such a fiber can therefore act as a guide for ultracold atoms. We have done preliminary experiments where we loaded atoms into such a device. A sodium Bose-Einstein condensate was transported close to the fiber tip with optical tweezers, and was pulled into the fiber when the light through the fiber was ramped up, while the intensity of the tweezers beam was ramped down. Since the detection of atoms inside the fiber by direct imaging turned out to be infeasible, we retrieved some of the atoms by ramping up the light in the tweezers. Up to 5 % atoms re-appeared after having spent 30 ms in the hollow core fiber.

## 7. Continuous and Pulsed Quantum Zeno Effect

The quantum Zeno effect is the suppression of transitions between quantum states by frequent measurements and is a paradigm and test bed for quantum measurement theory. We have carried out a quantum Zeno experiment with Bose-Einstein condensed atoms [11]. The long coherence time and the high degree of control of the position and momentum of the atoms created a very clean system and allowed us to observe much stronger quantum Zeno suppression than before. Oscillations between two ground hyperfine states of a magnetically trapped condensate, externally driven at a transition rate  $\omega_R$  were suppressed by destructively measuring the population in one of the states with resonant light. We observed a suppression of the transition rate down to  $0.005 \omega_R$ .

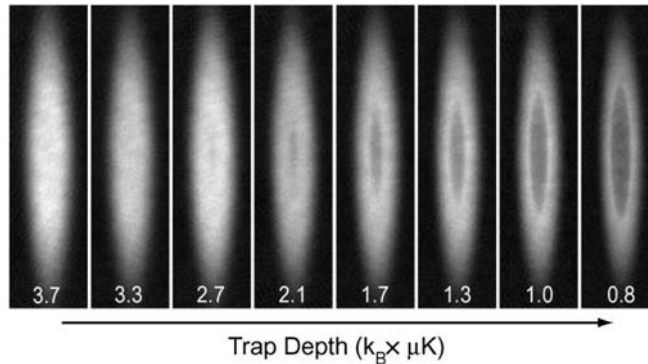
We compared the suppression of a continuous detection with scattering rate  $\gamma$  to a pulsed measurement with time interval  $\delta t$  between pulses and confirmed for the first time the predicted relation  $\gamma \delta t = 4$  for equal quantum Zeno suppression.



Demonstration of the quantum Zeno effect. The more measurements are performed, the longer the atoms stay in the initial state.

## 8. Observation of Phase Separation in a Strongly-Interacting Imbalanced Fermi Gas

At zero temperature, a BCS-type superfluid does not allow for unequal spin densities. The superfluid gap  $\Delta$  prevents unpaired fermions from entering the condensate. In a harmonic trap, this implies that an imbalanced Fermi mixture will phase separate into a central superfluid core of equal densities surrounded by a normal state at unequal densities. To test this hypothesis, we developed a novel phase contrast imaging technique that allows us to directly measure the density *difference* of the spin mixture [12]. This enabled us to observe the emergence of phase separation in situ (in the trap) as the Fermi mixture was cooled. At our lowest temperatures, the presence of a condensate was correlated with the presence of a core with equal densities of the two spin components.

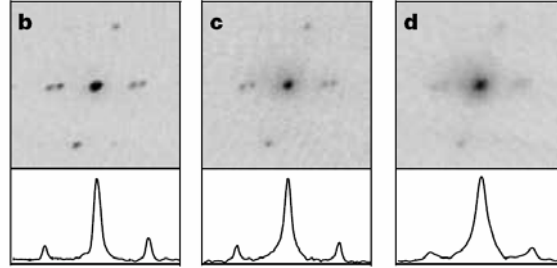


Observation of phase separation in strongly interacting, imbalanced Fermi mixtures. The images show the in-situ optical density *difference* between the two spin species. The emergence of a central region of equal spin densities is directly seen as the growth of a central, “hollow” core, surrounded by a cloud at unequal densities.

## 9. Superfluidity of Ultracold Fermions in an Optical Lattice

The study of superfluid fermion pairs in a crystalline potential has important ramifications for understanding superconductivity in many materials. By simulating such systems using cold atomic gases, various condensed matter models can be studied in a highly controllable environment. We have observed coherence and thus indirect evidence for superfluidity of interacting fermions in an optical lattice [13]. The observation of

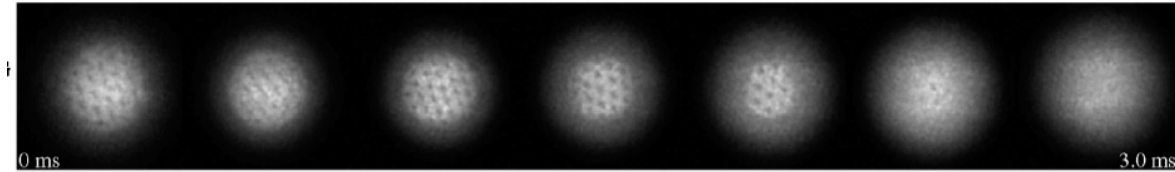
distinct interference peaks when a condensate of fermionic atom pairs was released from an optical lattice (see figure), implies long-range order, a characteristic property of a superfluid. Conceptually, this means that s-wave pairing and coherence of fermion pairs have now been established in a lattice potential, in which the transport of atoms occurs by quantum mechanical tunneling and not by simple propagation. These observations were made for interactions on both sides of a Feshbach resonance.



Observation of high-contrast interference of fermion pairs released from an optical lattice below and above the Feshbach resonance. Those interference patterns show coherence and indirectly superfluidity of fermions in an optical lattice.

### 10. Superfluid Expansion of a Rotating Fermi Gas

We have studied the expansion of a rotating, superfluid Fermi gas [14]. The presence and absence of vortices in the rotating gas are used to distinguish the superfluid and normal parts of the expanding cloud. Previous experiments have not been able to discriminate between superfluid and collisional hydrodynamics in expansion. Since BCS type pairing is a many-body phenomenon requiring high density, the superfluid pairs should “break” during expansion. Here we show that superfluid pairing survives during the initial phase of the expansion. We have observed superfluid flow up to 5 ms of expansion, when the peak density had dropped by a factor of 17 compared to the in-trap values. This extends the range where fermionic superfluidity has been studied to densities of  $1:2 \cdot 10^{11} \text{ cm}^3$ , about an order of magnitude lower than any previous study.



Superfluid expansion of a strongly interacting rotating Fermi gas. Shown are absorption images for different expansion times on the BCS side of the Feshbach resonance at 960 G (0.0, 0.5, 1.0, 1.5, 2.0, 2.5, and 3 ms), before the magnetic field was ramped to the BEC side for further expansion. The vortices served as markers for the superfluid parts of the cloud. Superfluidity survived the expansion for several milliseconds and was gradually lost from the low density edges of the cloud towards its center.

### 11. Atom trapping with a thin magnetic film

In this work we have investigated atom trapping with a thin magnetic film; specifically that of a hard disk platter written with a periodic pattern [15]. This exploratory work was

assessing thin magnetic films as an alternative to atom chips using permanent magnets or current-carrying conductors. We were able to load cold atoms from an optical dipole trap and cool them to BEC on the surface with radiofrequency evaporation. Fragmentation of the atomic cloud due to imperfections in the magnetic structure was observed at distances closer than 40  $\mu\text{m}$  from the surface. Attempts to use the disk as an atom mirror showed dispersive effects after reflection.

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