

Cooling and Trapping Neutral Atoms

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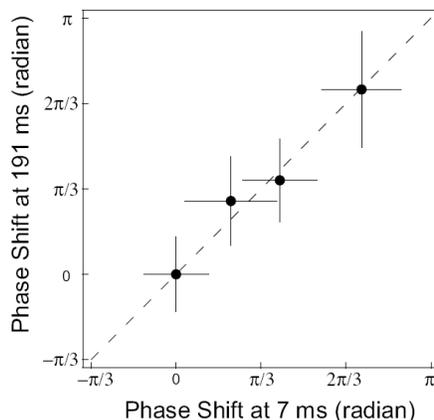
Overview

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 characterization of superfluid fermion systems with population imbalance and in an optical lattice. Major progress was also achieved in our program on atom interferometry where we study interference of two condensates on an atom chip.

1. 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 h 5 kHz [1]. 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.

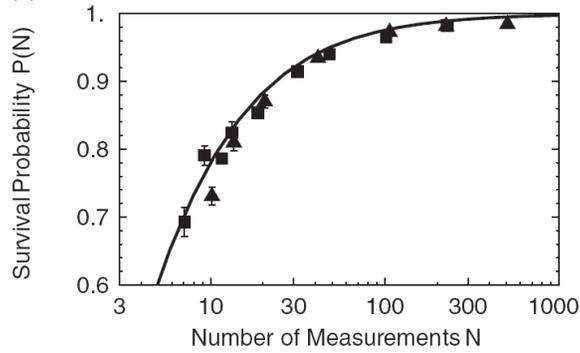
2. Guiding atoms with a hollow core photonic crystal fiber

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.

3. 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 [2]. 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 ω_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 $0.005 \omega_R$.

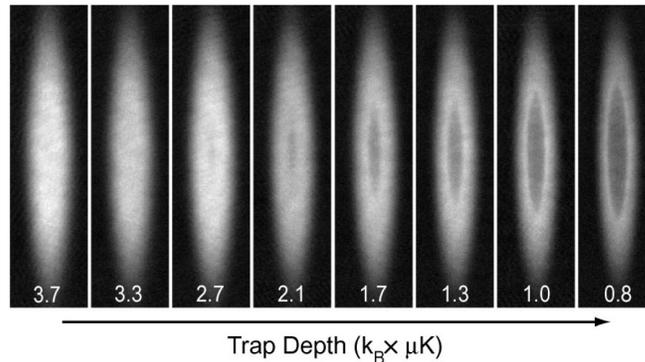
We compared the suppression of a continuous detection with scattering rate γ to a pulsed measurement with time interval δt between pulses and confirmed for the first time the predicted relation $\gamma \delta t = 4$ for equal quantum Zeno suppression.



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

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

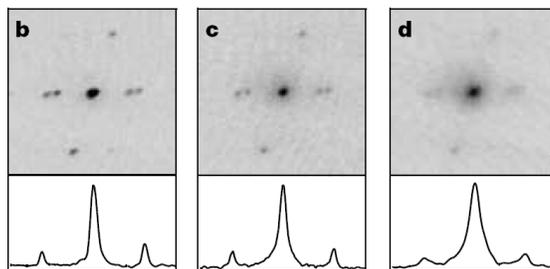
At zero temperature, a BCS-type superfluid does not allow for unequal spin densities. The superfluid gap Δ prevents unpaired fermions from entering the condensate. In a harmonic trap, this implies that an imbalanced Fermi mixture will phase separate into a central superfluid core of equal densities surrounded 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 [3]. 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.

5. Superfluidity of Ultracold Fermions in an Optical Lattice

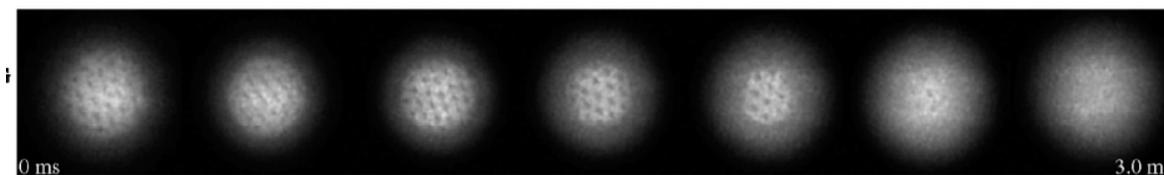
The study of superfluid fermion pairs in a crystalline potential has important ramifications for understanding superconductivity in many materials. By simulating such systems using cold atomic gases, various condensed matter models can be studied in a highly controllable environment. We have observed coherence and thus indirect evidence for superfluidity of interacting fermions in an optical lattice [4]. 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.

6. Superfluid Expansion of a Rotating Fermi Gas

We have studied the expansion of a rotating, superfluid Fermi gas [5]. 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.

7. Atom trapping with a thin magnetic film

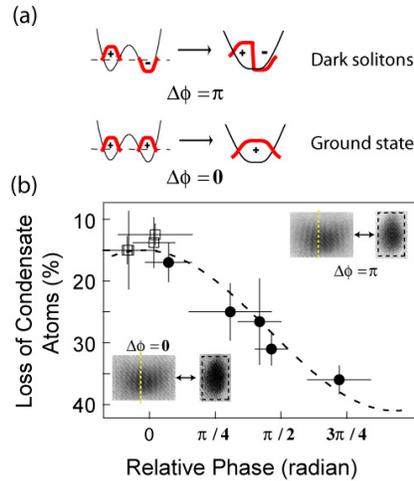
In this work we have investigated atom trapping with a thin magnetic film; specifically that of a hard disk platter written with a periodic pattern [6]. This exploratory work was assessing thin magnetic films as an alternative to atom chips using permanent magnets or current-carrying conductors. We were 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.

8. Phase Sensitive Recombination of Two Bose-Einstein Condensates on an Atom Chip

Most experiments in atom interferometry use freely propagating atom clouds. Alternative geometries are confined-atom interferometers where atoms are guided or confined in trapping potentials, often realized by using atom chips. Many discussions of confined-atom interferometers proposed a readout by merging the two separated atomic clouds, but it was also shown that the

recombination process is very sensitive to atomic interactions which can lead to exponential growth of unstable modes.

The present work demonstrates that interactions between atoms and collective excitations are not necessarily deleterious to direct recombination of separated trapped condensates that have acquired a relative phase in atom interferometry. We show that in-trap recombination leads indeed to heating of the atomic cloud. However, this heating is phase dependent and can be used as a robust and sensitive readout of the atom interferometer. The resulting oscillations of the condensate atom number are dramatic (typically $\sim 25\%$ contrast), occur over a wide range of recombination rates, and permit high signal to noise ratios since they simply require a measurement of the total number of condensate atoms in the trap [7].

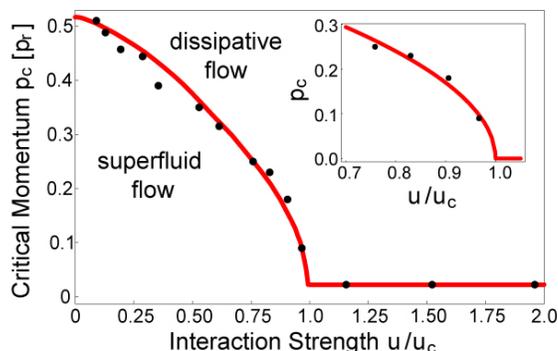


Concept and results on phase-sensitive recombination of two condensates. (a) The merged matter-wave functions are shown for the case of a sudden merger of interacting condensates leading to soliton formation for a relative phase of π . (b) The relative phase of two split condensates was monitored for various hold time after splitting by suddenly releasing the two condensates and observing interference. The heating during recombination (observed through the loss of condensate atoms) was correlated with the relative phase and can be used as in situ read out the atom interferometer.

9. Phase diagram for a Bose-Einstein condensate moving in an optical lattice

Mott insulator (MI) physics is an important paradigm for the suppression of transport by particle correlations. So far, with ultracold atoms, the superfluid to MI transition has been studied mostly in a stationary system. In this work, we study the stability of superfluid currents in a moving optical lattice, as suggested in ref. [8], and extend previous studies in two regards. First, superfluidity near the MI transition has only been indirectly inferred from coherence measurements, whereas in this work, we characterize the superfluid regime by observing a critical current for superfluid flow. Second, previous studies were not able to precisely locate the phase transition partially due to the inhomogeneous density, while the sudden onset of dissipation provides a clear distinction between the two quantum phases.

We observed that superfluid current became unstable if the momentum exceeded a critical momentum, and the critical momentum varied from 0.5 recoil momentum in a very weak lattice to zero in the Mott insulator phase. We study the phase diagram for the stability of superfluid current as a function of momentum and lattice depth. Our phase boundary extrapolates to the critical lattice depth for the SF-to-MI transition, which was measured with high precision to be $13.5 (+/- 0.2)$ recoil energy [9].

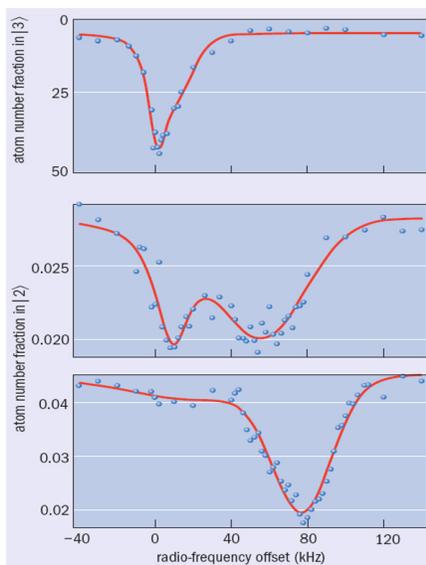


Critical momentum for a condensate in a three-dimensional moving lattice. The solid line shows the theoretical prediction for the superfluid region. The horizontal solid line is a fit to the data points in the MI phase. (Inset) Fit of critical momenta near the SF-MI phase transition.

10. Pairing without superfluidity for ultracold fermionic atoms

We have used radio-frequency spectroscopy to study pairing in the normal and superfluid phases of a strongly interacting Fermi gas with imbalanced spin populations. At high spin imbalances, above the so-called Chandrasekhar-Clogston limit of superfluidity, the system does not become superfluid even at zero temperature. In this normal phase pairing of the minority atoms is observed: While isolated atoms show a narrow peak in the radio-frequency spectrum, those that are bound in pairs produce a second peak at a higher frequency due to the extra energy required to break the bond. At the lowest temperature we found almost complete pairing of the minority atoms, indicated by the remaining frequency-shifted peak [10]. Since the system is beyond the Chandrasekhar-Clogston limit, this normal state consists of fermion pairs that do not undergo condensation and form a superfluid even at the lowest temperature: pairing can occur without superfluidity.

We have also studied whether radio frequency spectroscopy can reveal the onset of superfluidity. As we crossed the phase transition by varying population imbalance and temperature we found almost identical spectra, suggesting that radio-frequency spectroscopy cannot distinguish between the two phases.

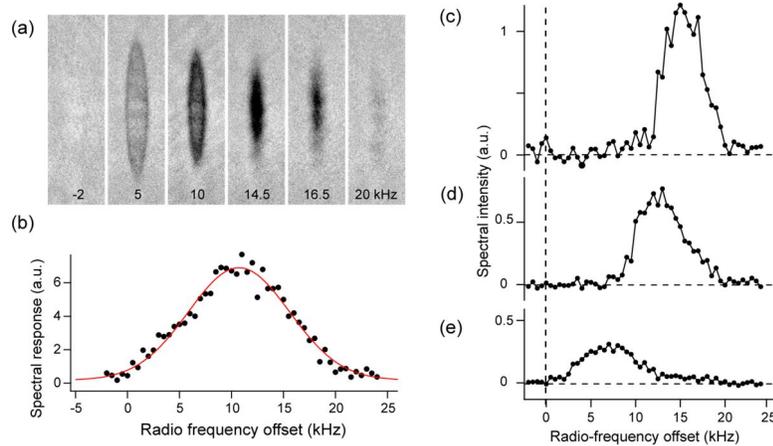


Radio-frequency spectroscopy was used to study pairing in the normal phase of a strongly interacting Fermi gas with highly imbalanced spin populations. At high temperatures (top) only a single atomic “peak” is present, indicating that no pairing has taken place. As the temperature is lowered (middle) a second peak emerges, reflecting the existence of pairs that require additional excitation energy. At sufficiently low temperatures (bottom) only the pairing peak remains, demonstrating that full pairing develops in the absence of superfluidity.

11. Tomographic RF Spectroscopy of a Trapped Fermi Gas at Unitarity

Experiments on trapped ultracold atoms deal with samples with inhomogeneous density, leading to a broadening of spectral features and a smear-out of phase transitions. We show here that spatial imaging and tomographic reconstruction can eliminate inhomogeneous broadening and observe the homogeneous excitation spectrum of strongly interacting Fermi gases [11].

The spatial distribution of the rf-induced excited region in the trapped gas was recorded with *in situ* phase-contrast imaging and the local rf spectra were tomographically compiled after 3D image reconstruction. In contrast to the inhomogeneous rf spectrum, the homogeneous local rf spectrum shows a clear spectral gap with an asymmetric line shape.



Tomographic radio-frequency (rf) spectroscopy of a trapped Fermi gas. (a) *in situ* phase-contrast images show the spatial structure of the spin excitation induced by an rf pulse, demonstrating the inhomogeneous density broadening effect in (b) the overall rf spectrum. Local rf spectra are tomographically reconstructed from the images. Local spectra at (c) $r=0$ R, (d) $r=0.4$ R, and (e) $r=0.7$ R (R: the radius of the cloud).

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