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14. ABSTRACT

Major steps were taken to explore superfluidity in Fermi clouds. This created close links with condensed matter and many body physics.

During the funding period, major advances were done towards atom interferometry with Bose-Einstein condensates. The goal was to build matter wave sensors of unprecedented sensitivity due to the superior properties of condensates as atom sources.

We also demonstrated quantum simulation of magnetism using ultracold gases for the first time. We believe this system may provide answers to many open questions on magnetism in condensed matter systems.

15. SUBJECT TERMS
Fermi degeneracy, itinerant ferromagnetism, ultracold atoms, quantum simulation, S-wave superfluidity in fermions, observation of vortices in degenerate Fermi gases, ultracold fermions in optical lattices.

16. SECURITY CLASSIFICATION OF:

17. LIMITATION OF ABSTRACT

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a. REPORT

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Experiments with trapped neutral atoms

Final Technical Report

At the end of each grant period (generally three years) a final technical report is required. This report must be mailed to a list supplied to you at the beginning of the grant period. It is due no later than 90 days after the end of your grant. You can include it in a renewal proposal, if you are submitting one, to provide the background/progress part of your proposal. The format of this report has been changed, however! An outline of the required format follows:

1. Title of Grant: Experiments with trapped neutral atoms

2. Principal Investigator: Wolfgang Ketterle

3. R&T Code Grant No. N00014-06-1-0149

4. Funding profile:
Indicate the total grant amount and the amount of each yearly increment. If equipment was purchased, indicate the amount spent and a brief description of the equipment.

See institutional financial reports

5. Technical objective:
In bullet format indicate what the goals were of your project. Be concise. More than one objective is OK, but do not exceed three.

The proposal contained the following goals:

- S-wave superfluidity in fermions
- Observation of Vortices in degenerate Fermi gases
- Ultracold fermions in optical lattices

6. Published papers resulting from this support (numbers only):

a. Submitted but not published : 0
b. Published in refereed journals : 31
c. Published in non-refereed journals: 0

7. Number of technical reports submitted 0

8. Number of books written 0

9. Number of book chapters written 2

10. Patents as a result of this work
a. Number of applications filed none
b. Number of patents granted (include patent number and date of patent) none

11. Total number of presentations given ca. 150

List 1 - 3 of the most significant. Include forum, date, title, and a couple of sentences describing the significance of the presentation.

- *Superfluidity in a gas of strongly interacting fermions q*
  Plenary talk at LT 25, Amsterdam, 8/13/2008

The Low Temperature conferences take place every three years and feature major developments in quantum fluids, superconductors and other low temperature studies. Atomic gases have now a major presence at these meetings.

- *Superfluidity and BEC-BCS Crossover in an Ultracold Gas of Fermionic Atoms.*
  50 Years BCS Symposium, Brown University, Providence, RI, 4/12/07.

This symposium on 50 years of BCS theory featured atomic gases as the "newest kid on the block" which extended the studies of BCS pairing to the strong coupling limit.

- *Recent results at MIT on ultracold Fermi gases.*
  Bose-Einstein condensation 2007, San Feliu, Spain, 9/16/07

The biannual BEC conference is the most prestigious conference on atomic quantum gases.

12. Honors and awards received during the granting period:

List individually and include: Source, title, recipient, and date. Underline those that at least in part resulted from your ONR funding.

2006	
W. Ketterle	Fellow of the Optical Society of America
Yong-Il Shin	Finalist in the competition for the 2006 APS award for Outstanding Doctoral Thesis Research in Atomic, Molecular, or Optical Physics
Martin Zwierlein	Sofja Kovalevskaja-Prize and Fellowship of the Alexander von Humboldt Foundation (declined)
Gretchen Campbell	Deutsch Award for Excellence in Experimental Physics at MIT
2007	
Martin Zwierlein	Finalist in the competition for the 2007 APS award for Outstanding Doctoral Thesis Research in Atomic, Molecular, or Optical Physics
Martin Zwierlein	Otto-Klung-Weberbank-Preis
W. Ketterle	Honorary Ph.D. Degree from the University of Connecticut
W. Ketterle	Honorary Ph.D. Degree from Ohio State University
2009	
W. Ketterle	Humboldt Research Award
W. Ketterle	Leonie Wild Medal of the town of Eppelheim
W. Ketterle	James Joyce Award of the Literary & Historical Society of University College Dublin
Tony Hyun Kim	Joel Matthew Orloff Award - for outstanding scholarship in physics

	(MIT award for undergraduate student)
W. Ketterle	Honorary Membership in Deutscher Hochschulverband

All these prizes resulted at least in part from ONR funding.

13. Number of different post-docs supported at least 25% of the time for at least one calendar year:
Estimate total person-months of post-doc support under this grant: 0

14. Number of different graduate students supported at least 25% of the time for at least one calendar year:
Estimate total person-months of graduate student support under this grant: 54

15. List 2 - 5 of the most significant publications resulting from this work:

Include titles and full citations, as well as a few sentences indicating the significance of the publication.

- J.K. Chin, D.E. Miller, Y. Liu, C. Stan, W. Setiawan, C. Sanner, K. Xu, W. Ketterle:
  Fermionic superfluidity in a lattice,
  Nature **443** , 961-964 (2006).

This represents the first time the paired Fermi particles constituting a quantum fluid were nominally lodged within a crystal-like configuration of forces. This is a big step toward one of the big goals of research with ultracold fermi atoms, namely the ability to create an artificial crystalline superfluid or superconductor where the interaction parameters can be tuned at will.

- Y. Shin, C.H. Schunck, A. Schirotzek, and W. Ketterle:
  Phase diagram of a two-component Fermi gas with resonant interactions.
  Nature **451**, 689-693 (2008).

Using tomographic imaging, we determined the phase diagram of Fermi gases with population imbalance and settled a two-year long controversy about the so called Chandrasekhar-Clogston limit, the critical population imbalance which quenches the superfluid state.

- Gyu-Boong Jo, Ye-Ryoung Lee, Jae-Hoon Choi, Caleb A. Christensen, Tony H Kim, Joseph H. Thywissen, David E. Pritchard, Wolfgang Ketterle:
  Itinerant ferromagnetism in a strongly interacting Fermi gas of ultracold atoms,
  Science **325**, 1521-1524 (2009).

We demonstrated that a strongly interacting Fermi gas can manifest ferromagnetism. This study was the first of its kind addressing a Fermi gas with strong repulsive interactions.

16. Major accomplishments:

Here is the meat of what you did! In bullet format indicate the most significant accomplishments for the granting period.

Study of atomic condensates

- Observation of Strong Quantum Depletion in a Gaseous Bose-Einstein Condensate
- Continuous and Pulsed Quantum Zeno Effect

Atom chips

- Long Phase Coherence Time and Number Squeezing of two Bose-Einstein Condensates on an Atom Chip
- Phase Sensitive Recombination of Two Bose-Einstein Condensates on an Atom Chip
- Matter-Wave Interferometry with Phase Fluctuating Bose-Einstein Condensates

Atom optics

- The Role of Interactions in Quantum Reflection of Bose-Einstein Condensates Continuous measurement of the relative phase of two Bose-Einstein condensates using light scattering

Molecules consisting of bosonic atoms

- Dissociation and Decay of Ultracold Sodium Molecules
- Coherent Molecular Optics using Sodium Dimers

BEC-BCS crossover

- Direct Observation of the Superfluid Phase Transition in Ultracold Fermi Gases
- Observation of Phase Separation in a Strongly-Interacting Imbalanced Fermi Gas
- Pairing without superfluidity for ultracold fermionic atoms
- Tomographic RF Spectroscopy of a Trapped Fermi Gas at Unitarity
- Critical velocity for superfluid flow across the BEC-BCS crossover
- Phase diagram of a two-component Fermi gas with resonant interactions
- Determination of the fermion pair size in a resonantly interacting superfluid
- Realization of a strongly interacting Bose-Fermi mixture from a two-component Fermi gas
- Determination of the equation of state of a polarized Fermi gas at unitarity
- Determination of the Superfluid Gap in Atomic Fermi Gases by Quasiparticle Spectroscopy

Fermi gases in an optical lattice

- Superfluidity of ultracold fermions in an optical lattice

Bose-Einstein condensates in an optical lattice

- Imaging the Mott Insulator shells using atomic clock shifts
- Phase diagram for a Bose-Einstein condensate moving in an optical lattice

Itinerant ferromagnetism

- Observation of itinerant ferromagnetism in a strongly interacting Fermi gas of ultracold atoms

New techniques and systems

- Guiding atoms with a hollow core photonic crystal fiber
- Atom trapping with a thin magnetic film

17. Transitions:

Indicate any results from this grant that has attracted industrial or developmental interest. Indicate the source and form of interest. Give as much detail as possible. Example: SRC provided $100K in funding to determine if the etching process identified in our lab could be utilized by them in a manufacturing environment.

One aspect of our work is the ultimate control over the motion of atoms, at the quantum level. Such precise preparation of atoms might lead to better frequency standards, improved precision experiments and atom lithography with higher resolution. Our techniques are being used in several laboratories around the world, including national labs.

18. Summary of the overall impact of your work in this period.

Give a general statement of the impact of your work in relation to the objectives of the program. Also indicate if this work identified or stimulated a new research area.

In this funding period, major steps were taken to explore superfluidity in Fermi clouds. This created close links with condensed matter and many body physics.

During the funding period, major advances were done towards atom interferometry with Bose-Einstein condensates. The goal is to build matter wave sensors of unprecedented sensitivity due to the superior properties of condensates as atom sources.

We also demonstrated quantum simulation of magnetism using ultracold gases for the first time. We believe this system may provide answers to many open questions on magnetism in condensed matter systems.

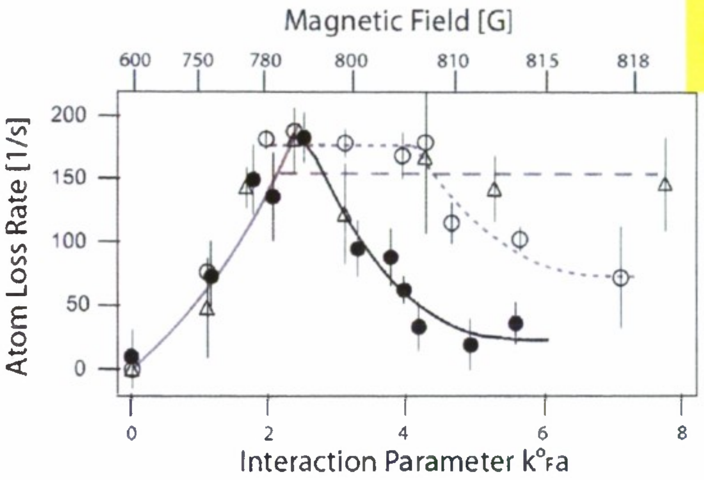
19. Four (4) key words/phrases describing your project.

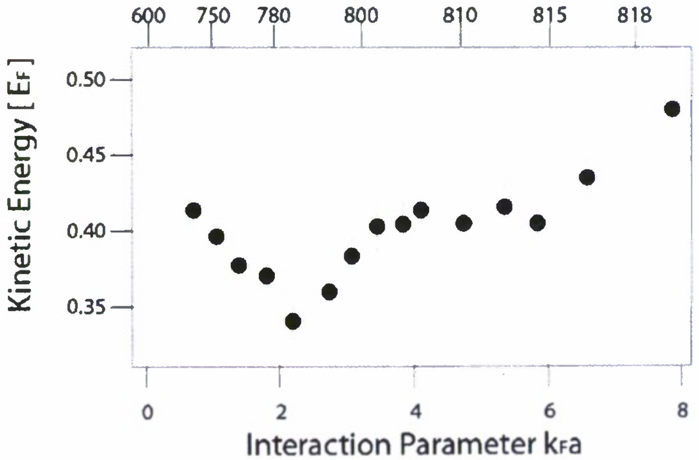
- Fermi degeneracy
- Itinerant ferromagnetism
- Ultracold atoms
- Quantum simulation

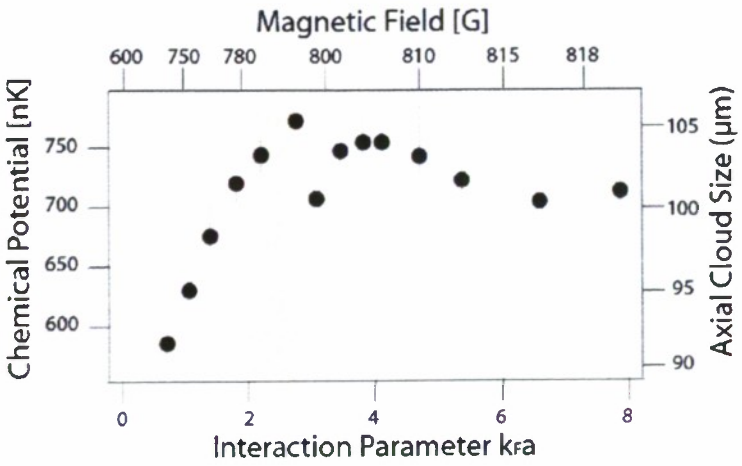
20. Provide three (3) viewgraphs highlighting the science and technology associated with the overall project.

see attached

Quantum magnetism with fermions







Three observations of non-monotonic behavior when approaching the Feshbach resonance

- Suggests that itinerant FM can occur for a free gas with short-range interactions
- First study of quantum magnetism in cold fermionic atoms
- Quantum simulation of a Hamiltonian for which even the existence of a phase transition is unknown

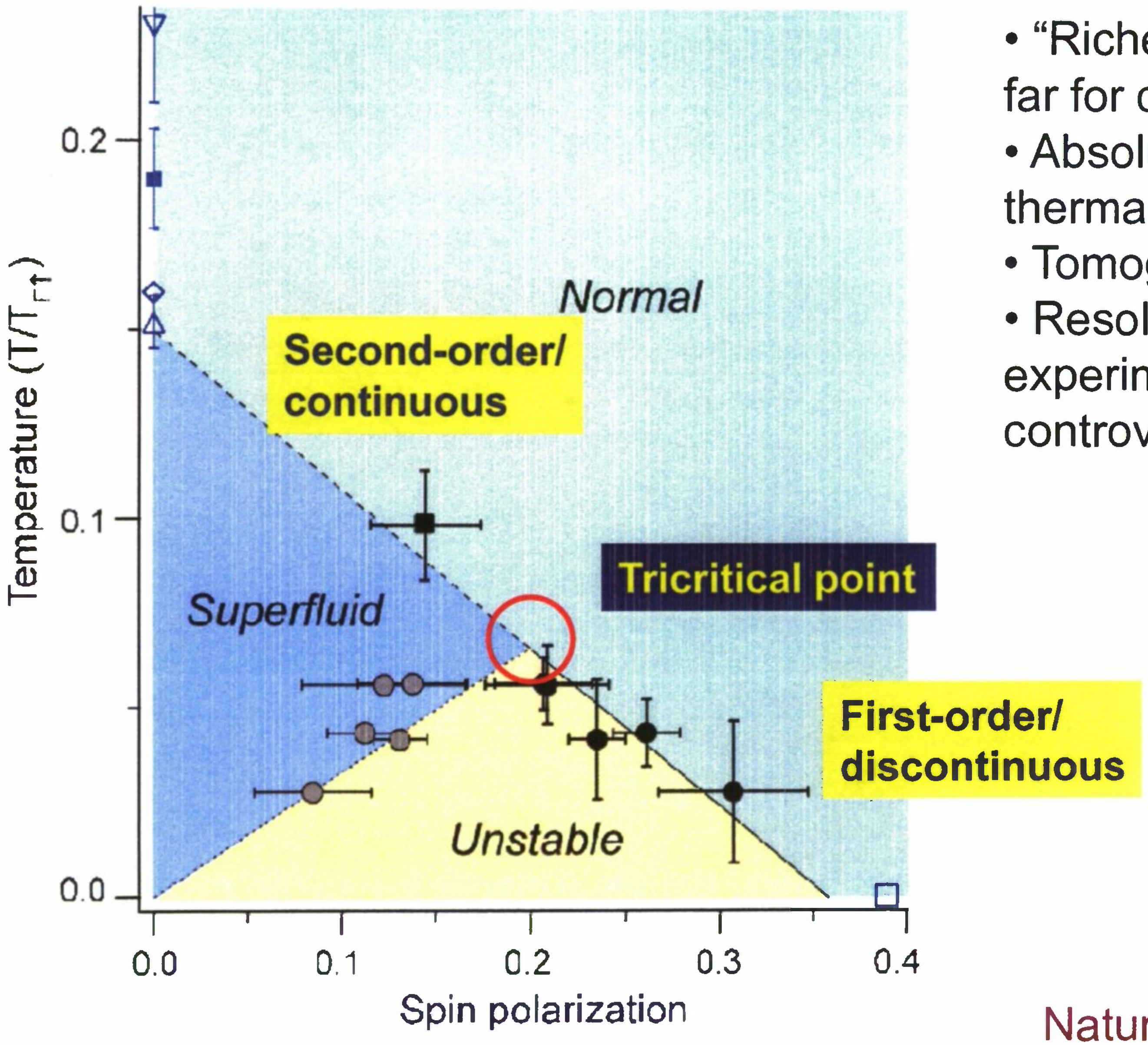
BUT:

- Magnetic domains not resolved
- Ferromagnetic fluctuations vs. ferromagnetic ground state

G.B. Jo, Y.R. Lee, J.H. Choi, C.A. Christensen, H. Kim, J. Thywissen, D.E. Pritchard, W.K., Science **325**, 1521-1524 (2009).

Phase Diagram of a Polarized Fermi Gas

Phase diagram for a homogeneous system



- “Richest” phase diagram so far for cold atoms
- Absolute thermometry using thermal wings
- Tomographic imaging
- Resolved long-standing experimental and theoretical controversy

Yong-il Shin
C.H. Schunck
A. Schirotzek, WK,
Nature 451, 689-693 (2008).

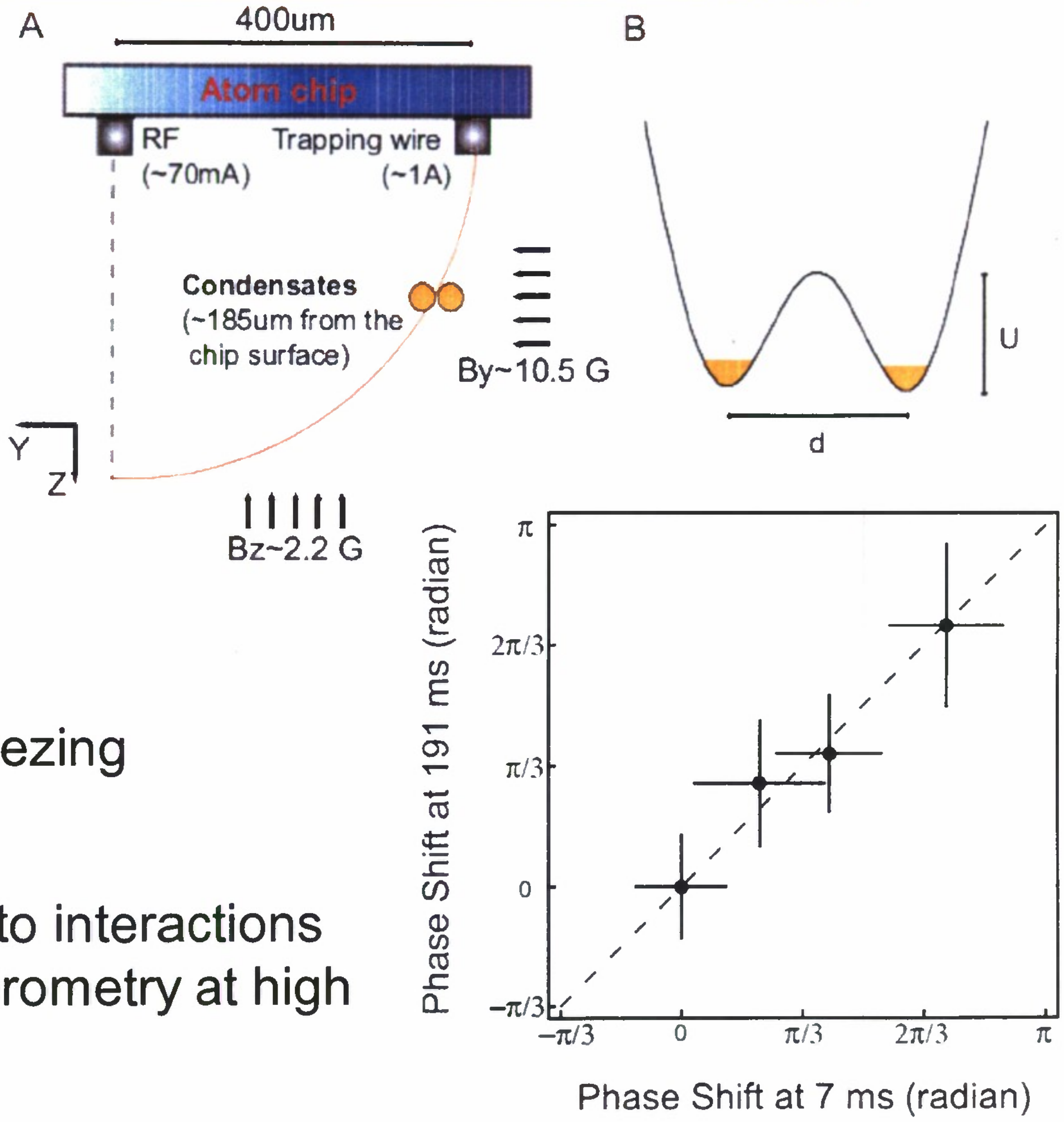
Matter wave interferometry on an atom chip

Objectives:
- Compact atom interferometer
- Study coherence time

Approach:
- Use atom chip with magnetic waveguide
- Use rf (dressed atom) beam splitter

Accomplishments:
- Long coherence time of 200 ms enhanced (x10) by number squeezing

Impact:
- Phase diffusion suppressed due to interactions
- Feasibility of on chip atom interferometry at high density



G.-B. Jo, Y. Shin, S. Will, T. A. Pasquini, M. Saba, M. Vengalattore, M. Prentiss, W. Ketterle, D. E. Pritchard, Long Phase Coherence Time and Number Squeezing of two Bose-Einstein Condensates on an Atom Chip, Phys. Rev. Lett. **98**, 030407 (2007).

SUMMARY OF ACCOMPLISHMENTS

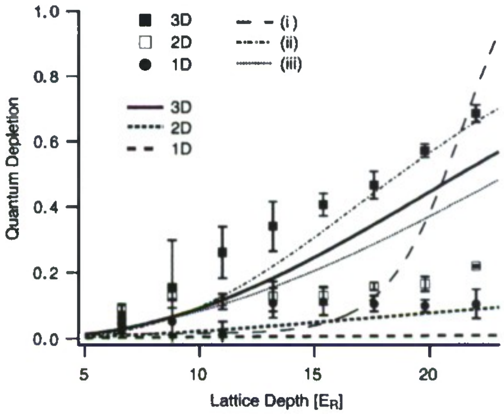
The past three years have been a period of enormous productivity for our group. The experiment on fermionic lithium was extremely successful in many directions. During the grant period, we studied BEC-BCS crossover, fermionic superfluidity in an optical lattice, and itinerant ferromagnetism in a Fermi gas. We also had some major results on BEC interferometry on an atom chip, but this part of our program has been terminated to make room for the research suggested by the current proposal.

This report contains a summary of the major results obtained during the last grant period (1/2006 – 8/2009). All these projects were at least partially supported by the ONR Grant No. N00014-06-1-0149.

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 bride 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%.

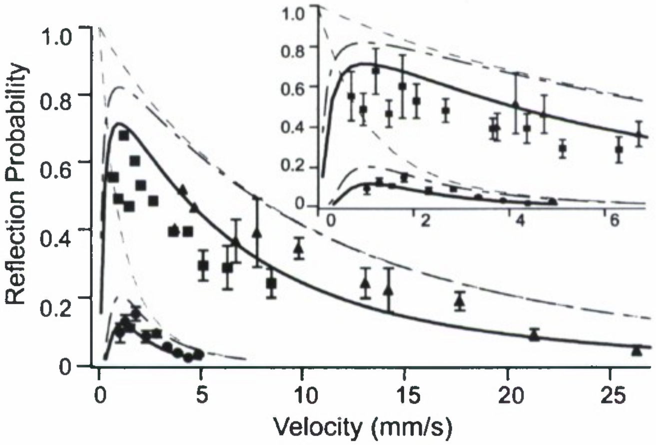


Quantum depletion of a sodium BEC confined in a one, two and three dimensional optical lattice: the data points are compared to the three thick curves which represent theoretical calculations using Bogoliubov theory and local density approximation. For comparison, also shown are (thin curves): (i) the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

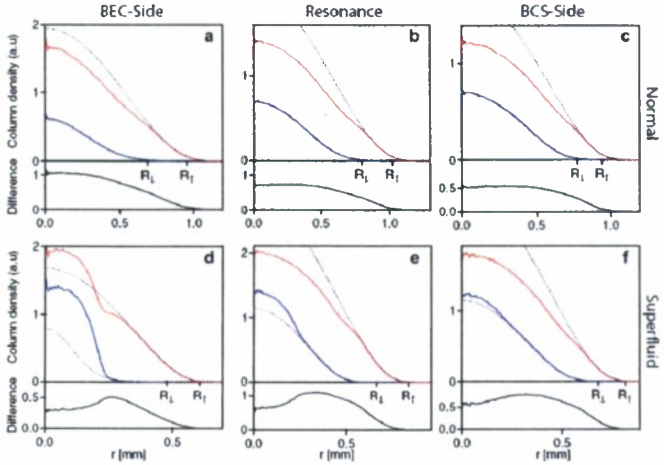


Reflection probability vs. incident velocity. Data are shown for a pillared (square) and solid (circle) Si surface. Single atom models give a monotonic rise to unity reflection. Our model which includes interactions (solid line) shows saturation of reflection at low velocity in qualitative agreement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

3. 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 [5]. Furthermore, the non-interacting wings of excess atoms serve as a direct and reliable thermometer.

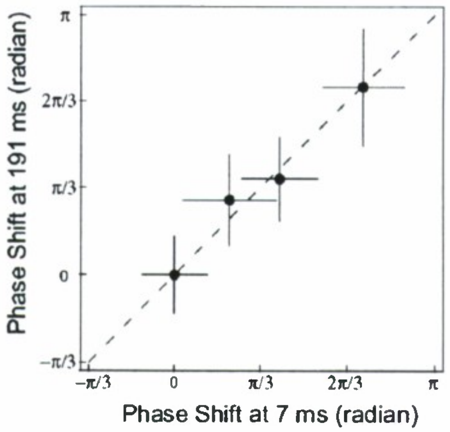


Direct observation of the phase transition in a strongly interacting two-state mixture of fermions with imbalanced spin populations. Top a-c and bottom d-f rows show observed column densities after expansion for the normal and the superfluid state, respectively. Panels a and d were obtained in the BEC-regime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

4. 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.

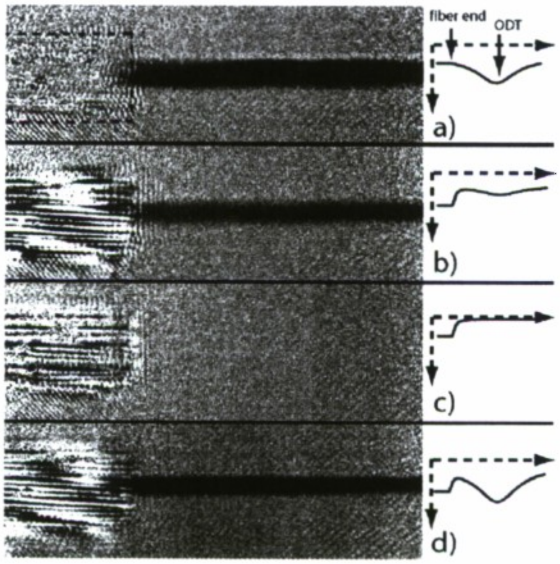
Here we show that we can operate a BEC interferometer at high density, with mean field energies exceeding h 5 kHz [6]. Using an radio frequency (RF) induced beam splitter we demonstrate that condensates can be split reproducibly, so that even after 200 ms, or more than one thousand cycles of the mean 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.

5. 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 condensates 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].

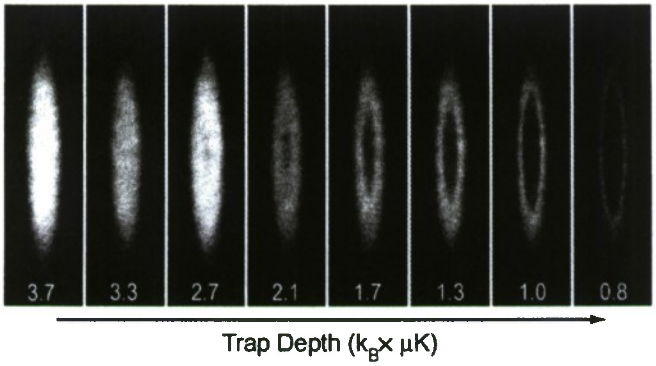


Images of atoms in the optical dipole trap (ODT) during the experiment. Also shown are sketches of the corresponding combined potential of the Hollow Core Fiber Trap (HCT) and ODT. (a) Atoms are held in the ODT near the fiber, with no light coupled into the fiber. The dashed line indicates the position of the 100 μm thick fiber. (b) Light is coupled to the fiber, and as the ODT intensity is ramped down, atoms are depleted from the ODT until

(c) no atoms remain outside the fiber when the ODT power reaches zero. (d) After ramping the ODT back up, atoms that were trapped in the HCT return to the ODT.

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

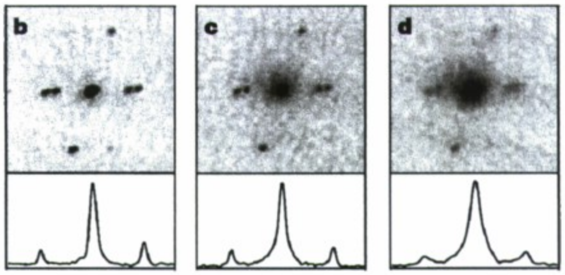
At zero temperature, a BCS-type superfluid does not allow for unequal spin densities. The superfluid gap Δ prevents unpaired fermions from entering the condensate. In a harmonic trap, this implies that an imbalanced Fermi mixture will phase separate into a central superfluid core of equal densities surrounded 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 [8]. 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.

7. 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 [9]. 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.

8. Superfluid Expansion of a Rotating Fermi Gas

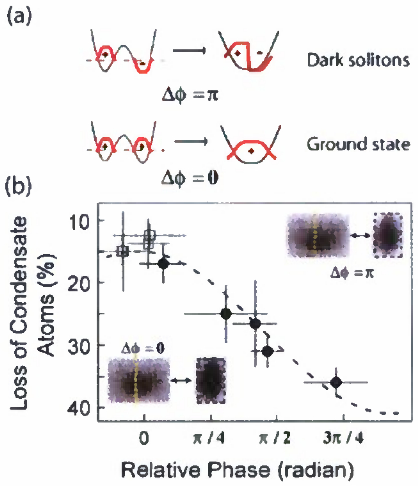
We have studied the expansion of a rotating, superfluid Fermi gas [10]. The presence and absence of vortices in the rotating gas are used to distinguish the superfluid and normal parts of the expanding cloud. Previous experiments have not been able to discriminate between superfluid and collisional hydrodynamics 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 $1{:}2\ \ 10^{11}$ 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.

9. 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 ~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 [11].

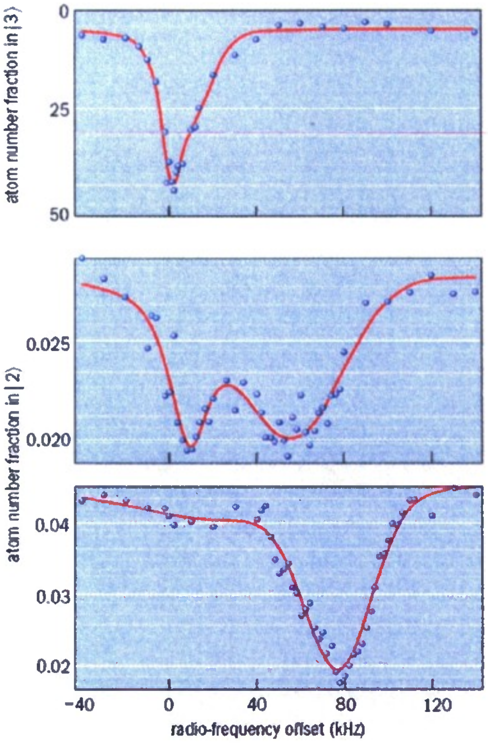


Concept and results on phase-sensitive recombination of two condensates. (a) The merged matter-wave functions are shown for the case of a sudden merger of interacting condensates leading to soliton formation for a relative phase of Pi. (b) The relative phase of two split condensates was monitored for 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.

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 [12]. 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.

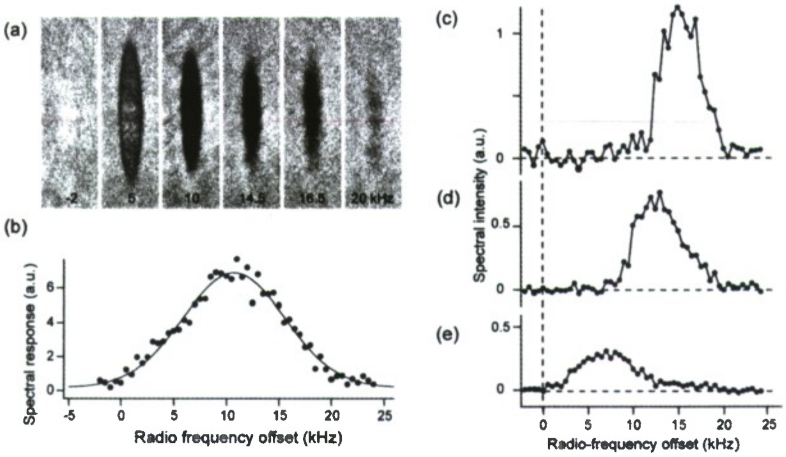


Radio-frequency spectroscopy was used to study pairing in the normal phase of a strongly interacting Fermi gas with highly imbalanced spin populations. At high temperatures (top) only a single atomic "peak" is present, indicating that no pairing has taken place. As the temperature is lowered (middle) 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 homogenous excitation spectrum of strongly interacting Fermi gases [13].

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.



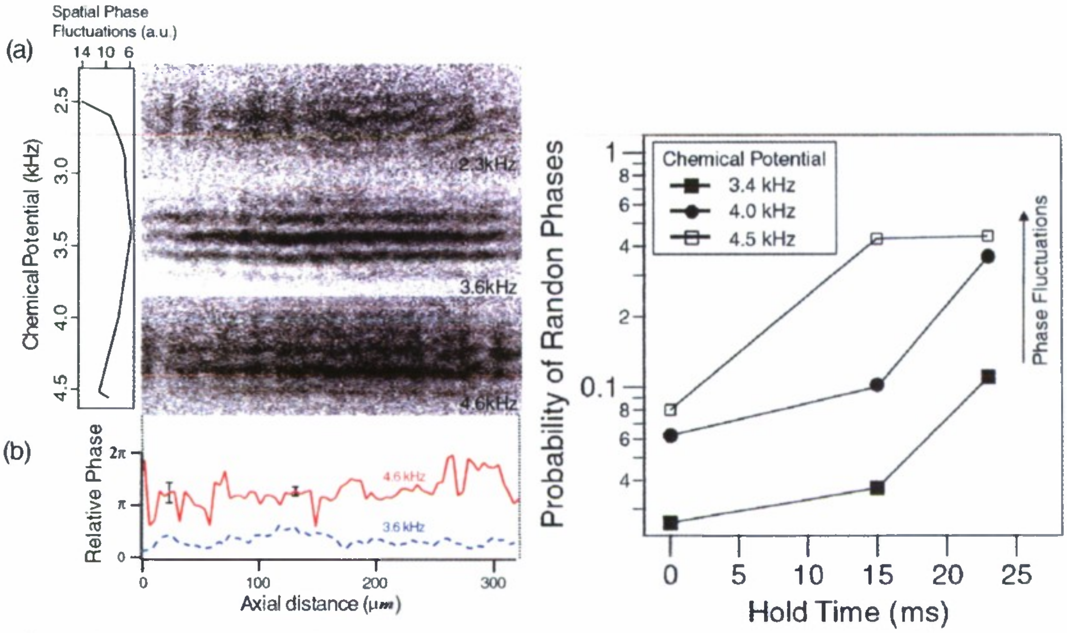
Tomographic radio-frequency (rf) spectroscopy of a trapped Fermi gas. (a) *in situ* phase-contrast images show the spatial structure of the spin excitation induced by an rf pulse, demonstrating the inhomogeneous density broadening effect in (b) the overall rf spectrum. Local rf spectra are tomographically 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).

12. Matter-Wave Interferometry with Phase Fluctuating Bose-Einstein Condensates

A non-interacting zero-temperature Bose-Einstein condensate is the matter-wave analogue to the optical laser, and therefore the ideal atom source for matter-wave interferometry. However, at finite temperature elongated condensates (e.g. in wave guides) suffer from phase fluctuations.

We observed directly axial phase fluctuations and characterized their effect on the coherence time of the atom interferometer. We demonstrated that atom interferometry can be performed in the presence of phase fluctuations [14].

We found some degradation of the fringe contrast due to phase fluctuations. However, it appears that for our experimental conditions, this degradation is not due to the quantum limit of phase fluctuations, but is rather caused by asymmetries in the double-well potential leading to relative motion of the divided condensates.



Effect of longitudinal phase fluctuations on the performance of the matter-wave interferometry.

(Left) Effect of spatial phase fluctuation on the waviness of interference fringes. Interference fringes obtained right after splitting a condensate in (a). For large spatial phase fluctuation (e.g., 4.6 kHz), the fringe pattern shows more significant wiggles than for smaller phase fluctuations (e.g.,3.6 kHz). From the fringes for 3.6 kHz (dashed line) and 4.6 kHz (solid line) chemical potentials, relative phases are obtained along the axial direction in (b)

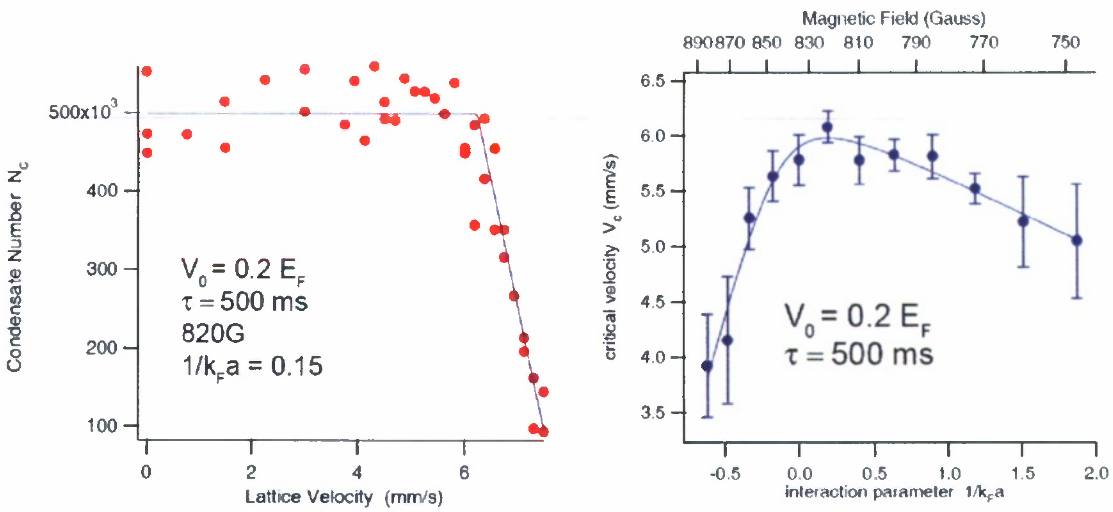
(Right) Effect of longitudinal phase fluctuations on the coherence time between the split condensates. The probability for a random phase for ten measurements of the relative phase is shown for three different amounts of the longitudinal phase fluctuations.

13. Critical velocity for superfluid flow across the BEC-BCS crossover

The recent realization of the BEC-BCS crossover in ultracold atomic gases allows one to study how bosonic superfluidity transforms into fermionic superfluidity. Many quantities, such as the speed of sound and the transition temperature, vary monotonously through the crossover. In contrast, the critical velocity for superfluid flow has been predicted to show a pronounced maximum [15]. This maximum occurs at the transition from a "bosonic" region where excitation of sound limits superfluid flow to a "fermionic" region where pair breaking dominates.

By crossing two tightly focused laser beams, we exposed only the central region to a 1D moving optical lattice and could observe the response of the superfluid at a well-defined density. In this way, critical velocities were obtained throughout the BEC-BCS crossover [16].

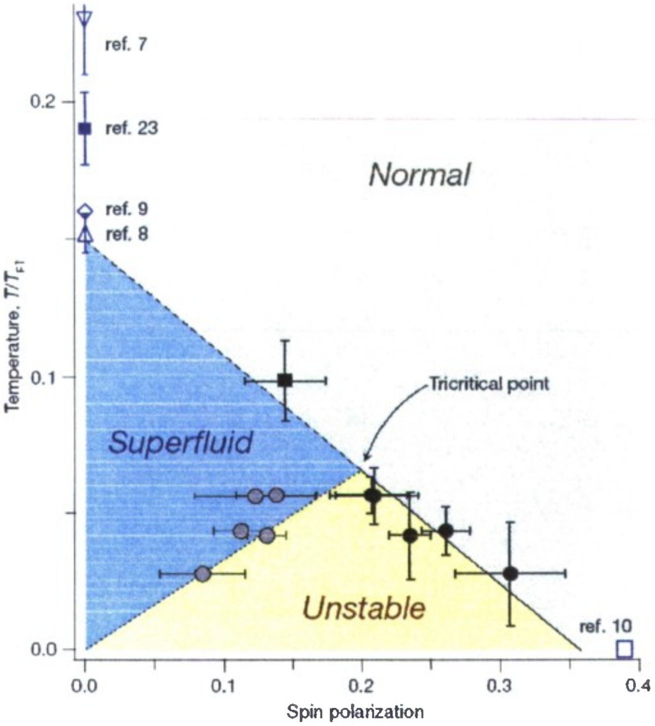
In good agreement with theoretical predictions we found a pronounced peak of the critical velocity at unitarity which confirms that superfluidity is most robust for resonant atomic interactions. The dependence of the critical velocity on lattice depth and on the inhomogeneous density profile was carefully studied.



(left) Onset of dissipation for superfluid fermions in a moving optical lattice. Shown is the number of fermion pairs which remained in the condensate after being subjected to a moving optical lattice at variable velocity. The abrupt onset of dissipation occurred at the critical velocity.
(right) Critical velocities throughout the BEC-BCS crossover. A pronounced maximum was found at resonance. Data are shown for a lattice with a depth of 0.2 E_F deep lattice. The solid line is a guide to the eye.

14. Phase diagram of a two-component Fermi gas with resonant interactions

We have established the phase diagram of a spin-polarized Fermi gas of ^{6}Li atoms at unitarity. Using tomographic techniques, we determined the spatial structure of a trapped Fermi mixture, mapping out the superfluid phases versus temperature and density imbalance [17]. At low temperature, the sample shows spatial discontinuities in the spin polarization. This is the signature of a first-order superfluid-to-normal phase transition, which disappears at a tricritical point where the nature of the phase transition changes from first-order to second-order. We have confirmed that at zero temperature, there is a quantum phase transition from a fully paired superfluid to a partially polarized normal gas, resolving a major controversy about the Chandrasekhar-Clogston limit of superfluidity with resonant interactions. The phase diagram provides quantitative tests of theoretical calculations on the stability of fermionic superfluidity.



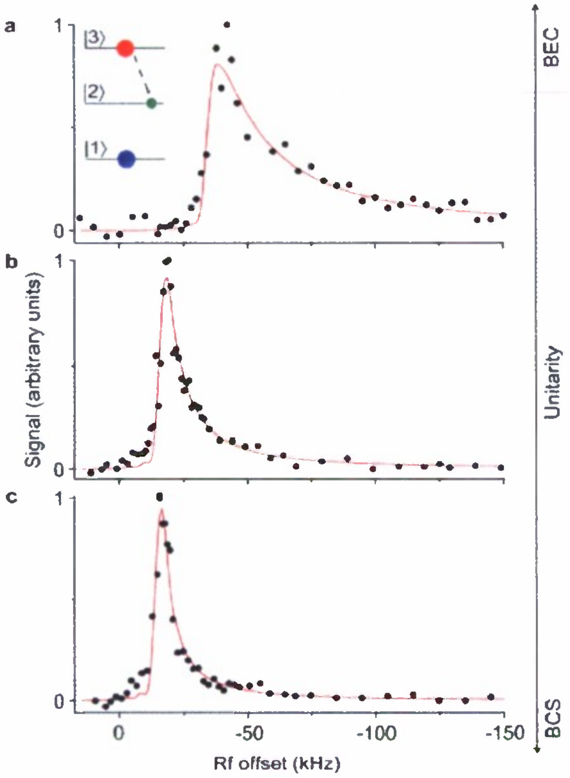
Phase diagram of a two-component Fermi gas with resonant interactions. The yellow area represents a thermodynamically unstable region, leading to phase separation between superfluid and normal. Above the tricritical point, the phase transition is continuous (second-order). The critical spin polarization at zero temperature is estimated to be ≈36%.

15. Determination of the fermion pair size in a resonantly interacting superfluid

Fermionic superfluidity requires the formation of pairs. The actual size of these fermion pairs varies by orders of magnitude from the femtometer scale in neutron stars and nuclei to the micrometer range in conventional superconductors. Many properties of the superfluid depend on the pair size relative to the interparticle spacing. For a given mass of the particles, there is a strong correlation between small pair size and high transition temperature. Even in high-temperature superconductors the reported values for the pair size are in the range of two to three interparticle spacings.

We have now been able to determine the pair size for resonantly interacting fermions, which were shown previously to have a very high transition temperature of 20 % of the Fermi temperature. The pair size was inferred from the RF dissociation spectrum of the pairs . Since an rf photon has negligible momentum, the allowed momenta for the fragments reflect the Fourier transform of the pair wavefunction, and the width of the RF spectrum is inversely proportional to the square of the pair size. In order to obtain "clean" RF spectra we had to realize resonant superfluidity in a new system, a spin mixture of lithium atoms where the final state after RF excitation has only weak interactions.

The pair size of the fermionic superfluid on resonance was determined to be 80 % of the interparticle spacing, the smallest pairs found so far for fermionic superfluids [18].



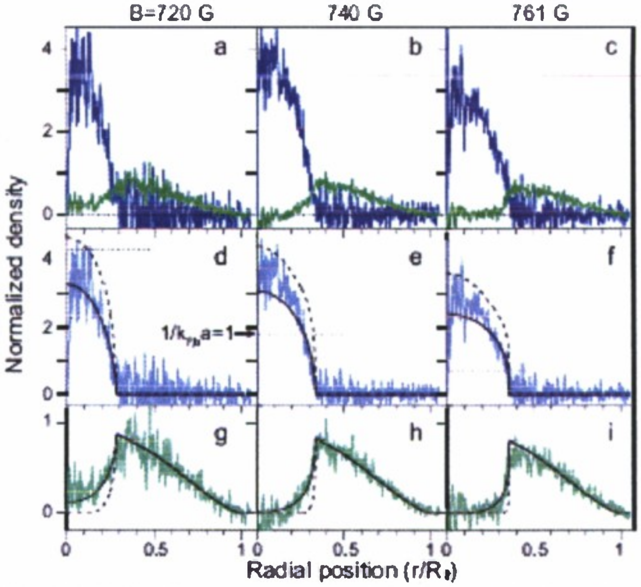
Rf dissociation spectra in the BEC-BCS crossover. Below, at, and above the Feshbach resonance, the spectrum shows the typical asymmetric lineshape of a pair dissociation spectrum and can be fitted with a line shape which has the fermion pair size as a fit parameter.

16. Realization of a strongly interacting Bose-Fermi mixture from a two-component Fermi gas

Fermions are the fundamental building blocks of matter, whereas bosons emerge as composite particles. The simplest physical system to study the emergence of bosonic behavior is a two-component fermion mixture, where the composite boson is a dimer of the two different fermions.

By analyzing in situ density profiles of ^{6}Li atoms in the BEC-BCS crossover regime, we have identified a critical coupling strength, beyond which all minority atoms pair up with majority atoms, and form a Bose condensate [19]. This is the regime where the system can be effectively described as a boson-fermion mixture. We have also determined the dimer-fermion scattering length, consistent with the exact value which has been predicted over 50 years ago but has never been experimentally confirmed.

Below the critical coupling strength, the composite nature of the boson becomes essential and the degeneracy pressure from excess unpaired fermions affects the structure of the composite boson, resulting in a zero-temperature quantum phase transition to a normal state where Bose-Einstein condensation is quenched.

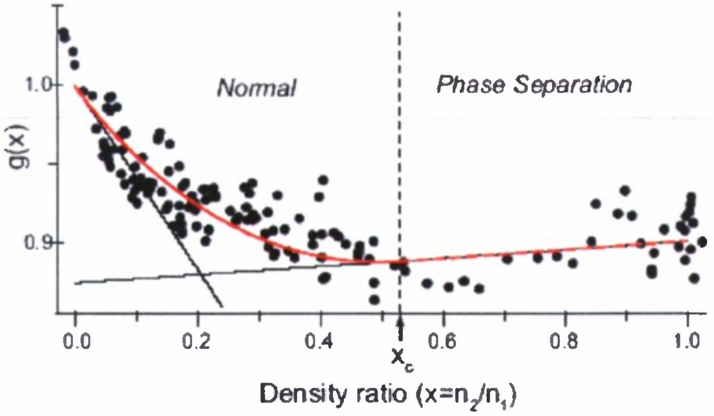


Strongly interacting Bose-Fermi mixtures. (a-c) Density profiles of bosonic dimers (blue) and unpaired excess fermions (green) for various magnetic fields, beyond the critical coupling strength. Figures (d-f) and (g-i) compare experimental results to calculated density profiles for bosons and fermions, respectively, confirming the validity of a boson-fermion description.

17. Determination of the equation of state of a polarized Fermi gas at unitarity

At unitarity, i.e. when the scattering length for the free fermions diverges, the behavior of the system becomes universal, being independent of the nature of the interactions. We have determined the universal equation of state of a two-component Fermi gas with resonant interactions by analyzing the in situ density distributions of a population-imbalanced Fermi mixture confined in a harmonic trap [20]. Since the variation of the external trapping potential across the sample scans the chemical potential, the density information of a single sample, in principle, contains the whole information on the equation of state. We have presented a method to determine the equation of state directly from the shape of the trapped cloud.

We have found that the behavior of a partially polarized normal gas can be well described by a normal Fermi liquid picture, which includes the binding energy of a single minority atom resonantly interacting with a majority Fermi sea, the effective mass of the quasiparticles, and its correction.



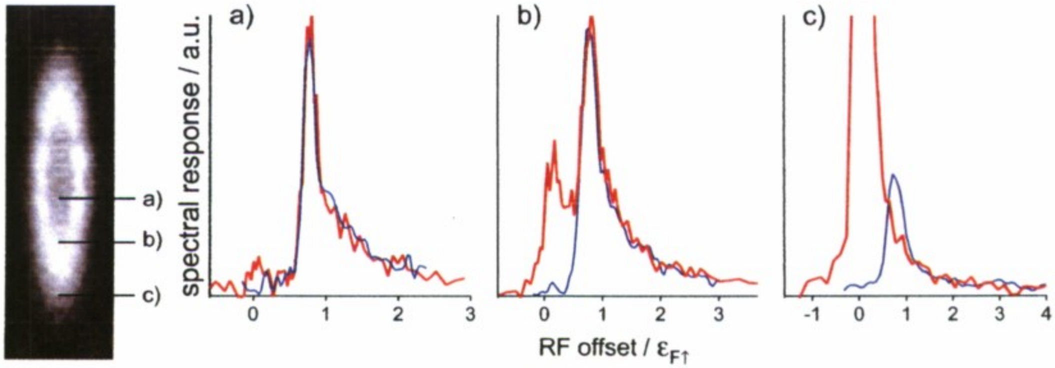
Thermodynamic potential of a two-component Fermi gas with resonant interactions. The universal function g(x) for the energy density $E(n_1,n_2)$ is defined as $E(n_1,n_2)=E_0(n_1)\ g(x)^{5/3}$, where n_1 and n_2 are the densities of component 1 and 2, respectively, E_0 is the energy density of a single-component Fermi gas, and $x=n_2/n_1$ is the density ratio. x_c is the critical density ratio for the normal-to-superfluid phase transition. The red solid line is a model fit to the normal region ($x<x_c$), using a normal Fermi liquid description.

18. Determination of the Superfluid Gap in Atomic Fermi Gases by Quasiparticle Spectroscopy

Using RF spectroscopy, we have studied pairing correlations in imbalanced Fermi gases and addressed the question what happens if we have fewer spin down than spin up fermions. Do the spin down fermions form pairs, leading to bimodal distribution of paired and unpaired majority atoms, or do minority fermions interact with the majority Fermi sea as a polarizable medium?

In a superfluid phase described by BCS theory, the excess particles can be accommodated only as thermally excited quasiparticles. A double-peaked spectrum reflects the co-existence of pairs and unpaired particles. In the BCS limit, the splitting between the two peaks is the superfluid gap parameter. Therefore, RF spectroscopy of quasiparticles is a direct way to observe the superfluid gap in close analogy with tunneling experiments in superconductors. We determined the superfluid gap Δ to be 0.44 times the (majority) Fermi energy [21].

In the normal phase, at large spin polarization, the limit of a single minority particle immersed into a Fermi sea is approached, which can be identified as a polaron. We find that these different kinds of pairing correlations are smoothly connected across the critical density imbalance, also called the Clogston- Chandrasekhar limit of superfluidity.



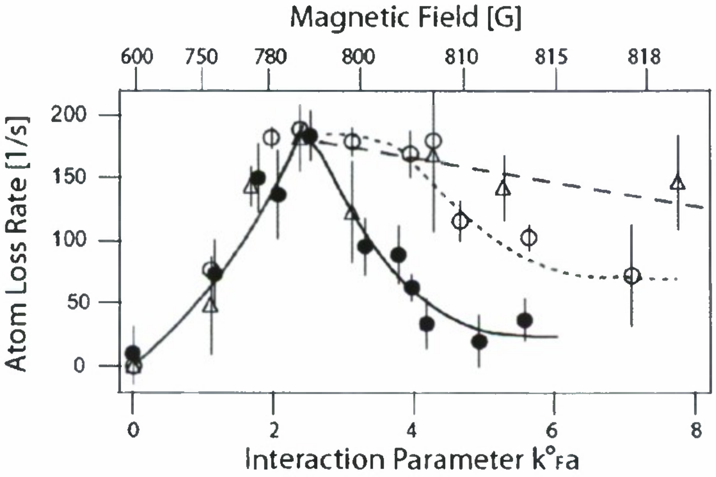
Tomographic RF spectroscopy of strongly interacting Fermi mixtures. A trapped, inhomogeneous sample has various phases in spatially different regions. The spectra of each region (red: majority, blue: minority) reveals the nature of pairing correlation of the corresponding phase. (a) Balanced superfluid. (b) Polarized superfluid. The additional peak in the majority spectrum is the contribution of the excess fermions, which can be identified as fermionic quasiparticles in a superfluid. From the separation of the two peaks, the pairing gap energy of a resonantly interacting superfluid has been determined. (c) Highly polarized normal gas. The minority peak no longer overlaps with the majority spectrum, indicating the transition to polaronic correlations.

19. Observation of itinerant ferromagnetism in a strongly interacting Fermi gas of ultracold atoms

Ferromagnetism of delocalized (itinerant) fermions occurs due to repulsive interactions and the exchange energy which reduces the interaction energy for spin polarized domains due to the Pauli exclusion principle. At a critical interaction, given by the so-called Stoner criterion [22], they system spontaneously develops domains and becomes ferromagnetic. This, together with a suitable band structure in a periodic lattice, explains why certain metals, like iron and nickel, are ferromagnetic. The simplest models for ferromagnetism assume a gas of fermions with repulsive interactions, and predict, in mean-field approximation, the onset of ferromagnetism. However, there has been no proof or experimental observation for ferromagnetism in a Fermi gas.

Here we study a gas of ultracold fermionic lithium atoms and increase the strength of repulsive interactions by tuning an external magnetic field close to a Feshbach resonance. We observe non-monotonic behavior of lifetime, kinetic energy and size. This provides strong evidence for the Stoner instability, i.e. a phase-transition to a ferromagnetic state. [23]

This experiment can be regarded as a quantum simulation of a simple Hamiltonian (the hard core Fermi gas), for which even the existence of a phase transitions has not been proven.



Atom loss rate as a probe for local spin polarization, for different temperatures. (a) T/T_F = 0:55 (dashed curve), (b) T/T_F = 0:22 (dotted curve), and T/T_F = 0:12 (solid black curve). The atom loss rate (due to molecule formation) increases for increasing strength of interactions, until the two components of the Fermi gas separate in domains, suppressing the loss. The maximum of the loss rate occurs close to the onset of ferromagnetism. Higher temperatures appear to suppress ferromagnetism.

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