Cooling and Trapping Neutral Atoms

RLE Groups
Atomic, Molecular and Optical Physics Group; MIT-Harvard Center for Ultracold Atoms

Academic and Research Staff
Professor Wolfgang Ketterle, Professor David E. Pritchard,

Visiting Scientists and Research Affiliates
Jae Hoon Choi, Ralf Gommers, Yingmei Liu, Yong-Il Shin, David Weld

Graduate Students
Jit-Kee Chin, Caleb Cristensen, Gyu-Boong Jo, David Hucul, Aviv Keshet, Ye-ryoung Lee, Patrick Medley, Daniel Miller, Hiro Miyake, Jongchul Mun, Tom Pasquini, Christian Sanner, Andre, Schirotzek, Christian Schunck, Edward Su

Undergraduate Students
Tony Kim

Support Staff
Joanna Keseberg

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Overview

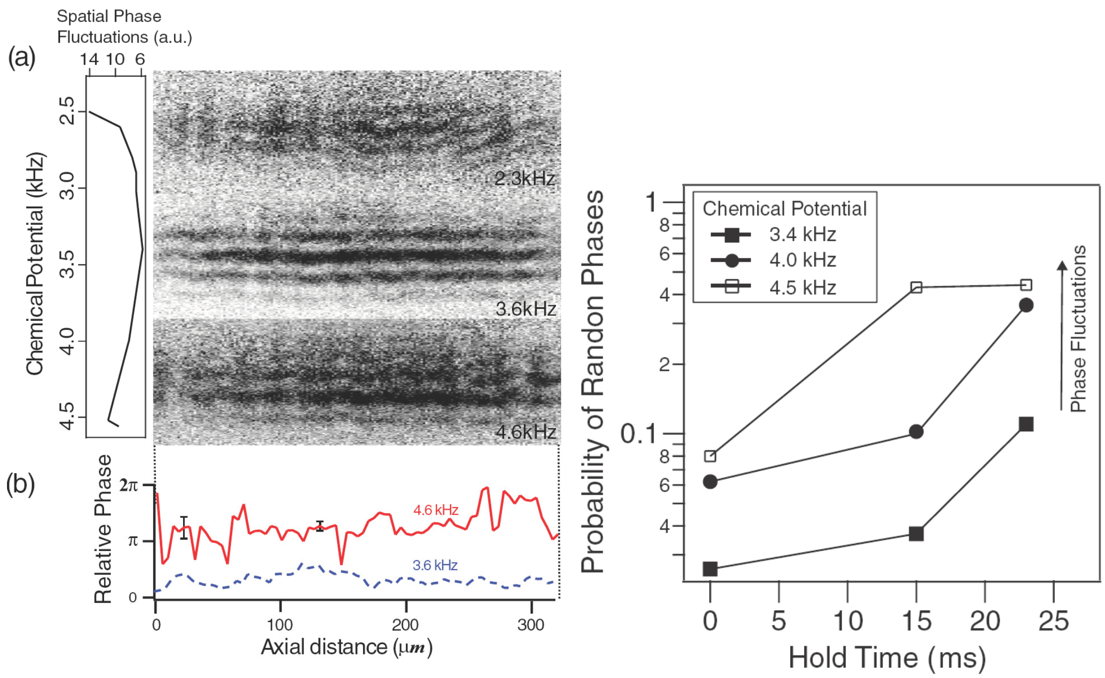
Most of our results in the past year reflect our focus on strongly interacting quantum gases. The highlight has been the study of fermionic superfluidity with variable interactions and population imbalance.

1. 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 [1].

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.



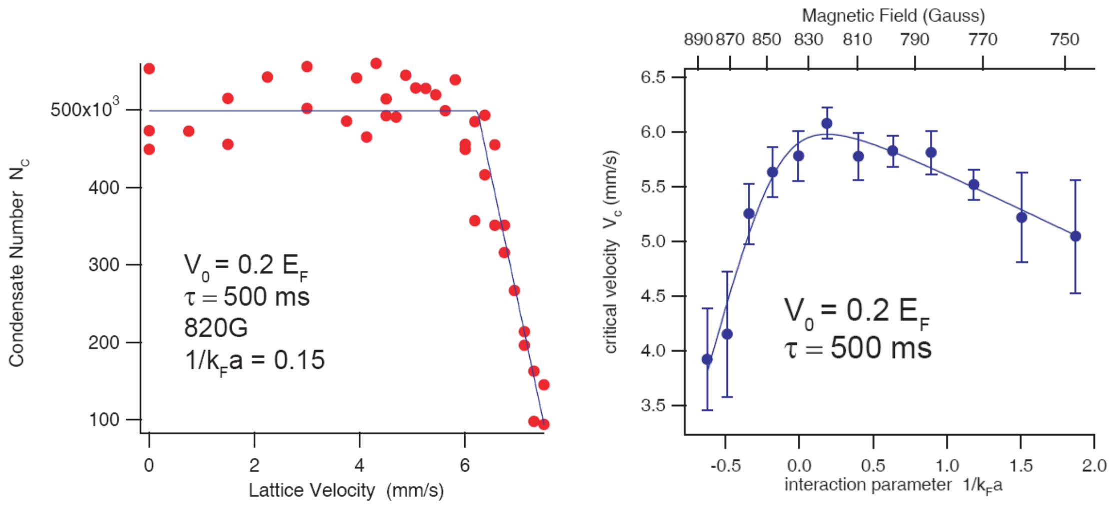
Effect of longitudinal phase fluctuations on the performance of the matter-wave interferometry.
(Left) Effect of spatial phase fluctuation on the waviness of interference fringes. Interference fringes obtained right after splitting a condensate in (a). For large spatial phase fluctuation (e.g., 4.6 kHz), 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.

2. 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 [2]. 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 [3].

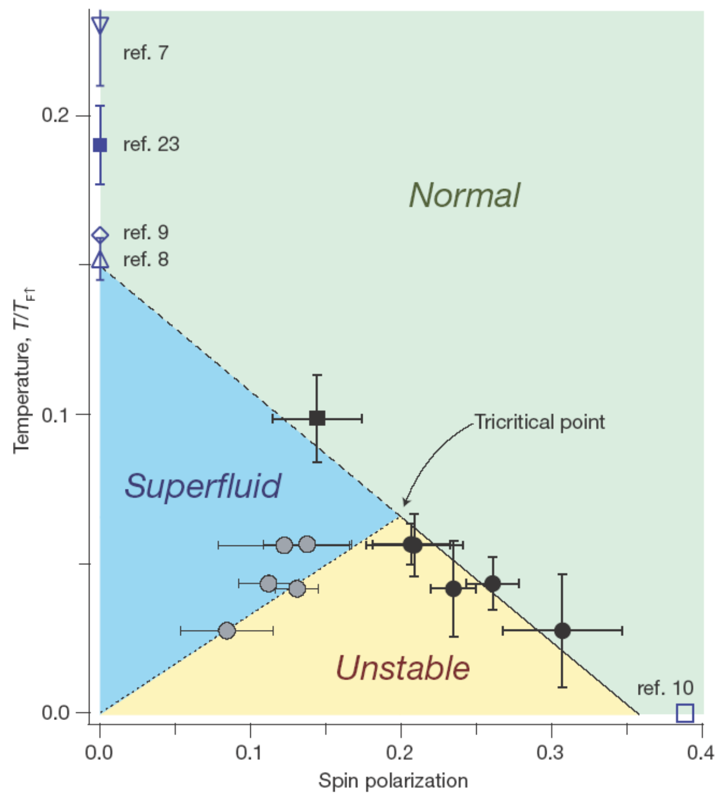
In good agreement with theoretical predictions we found a pronounced peak of the critical velocity at unitarity which confirms that superfluidity is most robust for resonant atomic interactions. The dependence of the critical velocity on lattice depth and on the inhomogeneous density profile was carefully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

3. 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 [4]. 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.



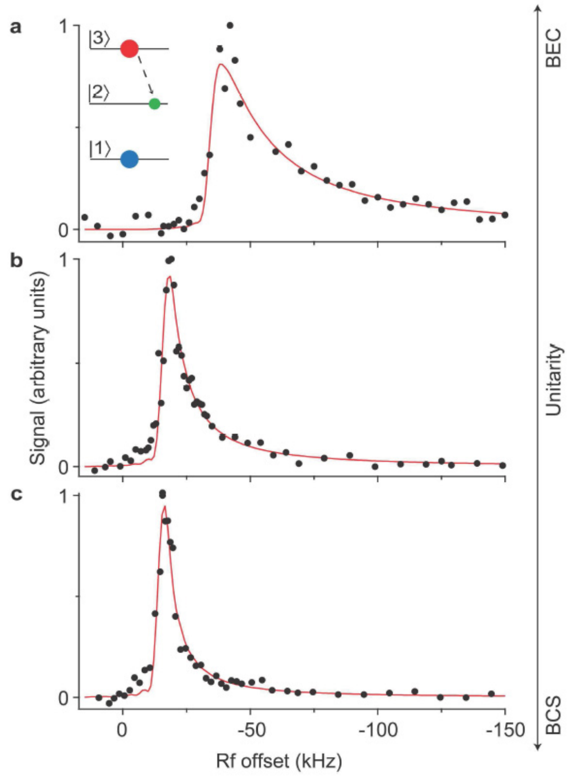
Phase diagram of a two-component Fermi gas with resonant interactions. The yellow area represents a thermodynamically unstable region, leading to phase separation between superfluid and normal. Above the tricritical point, the phase transition is continuous (second-order). The critical spin polarization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

4. 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 [5].



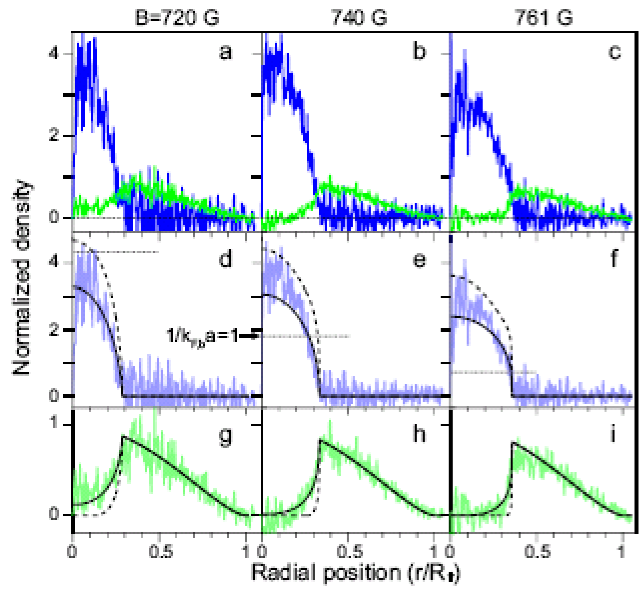
Rf dissociation spectra in the BEC-BCS crossover. Below, at, and above the Feshbach resonance, the spectrum shows the typical asymmetric lineshape of a pair dissociation spectrum and can be fitted with a line shape which has the fermion pair size as a fit parameter.

5. 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 [6]. 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.

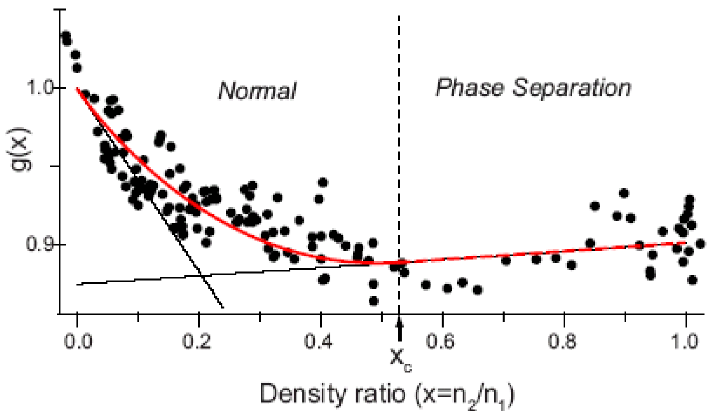


Strongly interacting Bose-Fermi mixtures. (a-c) Density profiles of bosonic dimmers (blue) and unpaired excess fermions (green) for various magnetic fields, beyond the critical coupling strength. Figures (d-f) and (g-i) compare experimental results to calculated density profiles for bosons and fermions,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

6. Determination of the equation of state of a polarized Fermi gas at unitarit

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 [7]. 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.

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Publications

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Realization of a strongly interacting Bose-Fermi mixture from a two-component Fermi gas:
Phys. Rev. Lett., in print; preprint, arXiv:0805.0623.

2. C.H. Schunck, Y. Shin, A. Schirotzek, and W. Ketterle:
Determination of the fermion pair size in a resonantly interacting superfluid.
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3. W. Ketterle and M. W. Zwierlein:
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4. 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).

5. D. E. Miller, J. K. Chin and C. A. Stan, Y. Liu, W. Setiawan, C. Sanner and W. Ketterle:
Critical velocity for superfluid flow across the BEC-BCS crossover.
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6. G.B. Jo, J.H. Choi, C.A. Christensen, Y.R. Lee, T.A. Pasquini, W. Ketterle, and D.E. Pritchard:
Matter-Wave Interferometry with Phase Fluctuating Bose-Einstein Condensates.
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1. W. Ketterle and G. Rempe:
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2. W. Ketterle:
Ganz große Fische fangen.
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Theses

Tom Pasquini, “Quantum Reflection of Bose-Einstein Condensates”, Ph.D. thesis, Department of Physics, MIT, 2007

Daniel E. Miller, “Studying Coherence in Ultra-Cold Atomic Gases”, Ph.D. thesis, Department of Physics, MIT, 2007

Jit Kee Chin, “Strongly-interacting Fermions in an Optical Lattice”, Ph.D. thesis, Department of Physics, MIT, 2007

Jongchul Mun, “Bose-Einstein Condensates in Optical Lattices: The Superfluid to Mott Insulator Phase Transition”, Ph.D. thesis, Department of Physics, MIT, 2008

Christian Schunck, “Pairing and Superfluidity in Strongly Interacting Fermi Gases”, Ph.D. thesis, Department of Physics, MIT, 2008