Cooling and Trapping Neutral Atoms

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Overview

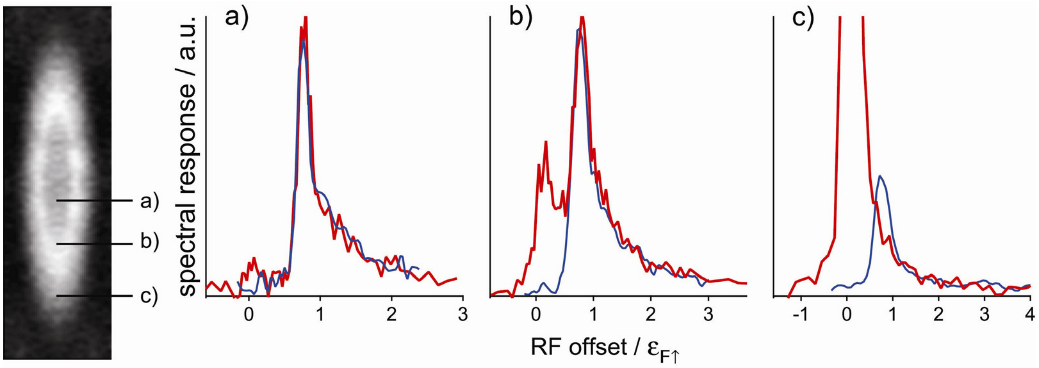
All our results in the past year reflect our focus on strongly interacting quantum gases. Although we published only two papers, both were major accomplishments. The superfluid gap is the most important parameter characterizing the superfluid state, and we were able to observe it for the first time. Our experiment on ferromagnetism is the first example of quantum magnetism in ultracold fermions and hopefully the beginning of many more exciting results.

1. 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 [1].

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.



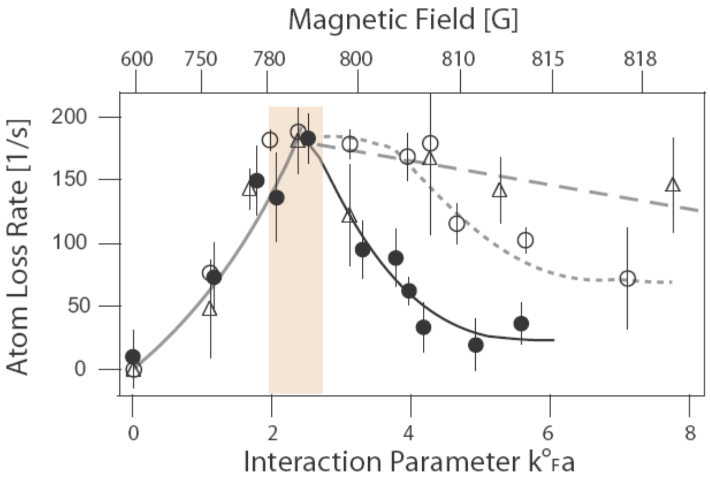
Tomographic RF spectroscopy of strongly interacting Fermi mixtures. A trapped, inhomogeneous sample has various phases in spatially different regions. The spectra of each region (red: majority, blue: minority) reveals the nature of pairing correlation of the corresponding phase. (a) Balanced superfluid. (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.

2. 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 [2], 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 phase-transition to a ferromagnetic state [3].

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.

References

1. A. Schirotzek, Y. Shin, C.H. Schunck, and W. Ketterle, Phys. Rev. Lett. 101, 140403 (2008).
2. E.C. Stoner, Phil. Mag. 15, 1018 (1933).
3. G.-B. Jo, Y.-R. Lee, J.-H. Choi, C.A. Christensen, T.H. Kim, J.H. Thywissen, D.E. Pritchard, and W. Ketterle, Science, in print.

Publications

Papers (in refereed journals) and major book chapters

1. G.B. Jo, Y.R. Lee, J.H. Choi C.A. Christensen, T.H. Kim, J.H. Thywissen, D.E. Pritchard, and W. Ketterle:
   Itinerant ferromagnetism in a Fermi gas of ultracold atoms.
   Science, in print.
2. A. Schirotzek, Y. Shin, C.H. Schunck, and W. Ketterle:
   Determination of the Superfluid Gap in Atomic Fermi Gases by Quasiparticle Spectroscopy.
   Phys. Rev. Lett. **101**, 140403 (2008).

Theses

David Hucul, “Magnetic Super-Exchange with Ultra Cold Atoms in Spin Dependent Optical Lattices”, Masters Thesis, Department of Physics, MIT, 2009