Progress in year 2009

1. 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 [1], 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. [2]

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.
2. Spin gradient thermometry for ultracold atoms in optical lattices

A major goal of current research with ultracold atoms in optical lattices is the realization of magnetic ordering. This requires temperatures on the order of the second order tunneling rate, $J^2/U$ where $U$ is the interaction energy and $J$ the tunneling amplitude. Such temperatures are about ten times less than 1 nK, the lowest temperature reached thus far in optical lattices. Additional cooling methods will be needed to reach this very interesting temperature scale. However, even to assess current methods, new methods of low-temperature thermometry of the Mott insulator are needed.

We have demonstrated a novel, simple and direct method of thermometry using a magnetic field gradient which works in a two-component Mott insulator [3]. The two states are assumed to have different magnetic moments, and are thus pulled towards opposite sides of the trapped sample by the gradient. At zero temperature, the spins will segregate completely with a sharp boundary (a small width due to superexchange coupling is negligible). At finite temperature, spin excitations will result in an increase in the width of the domain wall which is proportional to the temperature.

We developed this method in a system of ultracold rubidium atoms. We observed the lowest measured temperature in a Mott insulator thus far, 1 nK, indicating that the system has reached the quantum regime, where insulating shells are separated by superfluid layers. The interface between the two components of the Mott insulator provide new opportunities beyond thermometry: It can be used to study relaxation processes, and to realize a two dimensional layer with spontaneous transverse magnetization at very low temperature.

Images used for spin gradient thermometry. Data on the left were taken at a lower optical trap depth than data on the right resulting in a lower temperature (52 nK vs. 296 nK). The upper panels are images of the spin distribution, created by subtracting the image of atoms in the $|1,1>$ state from the image of the $|2,2>$ atoms. The lower panels show the mean spin versus $x$ position.
