Progress in year 2010

1. Suppression of Density Fluctuations in a Quantum Degenerate Fermi Gas

Systems of fermions obey the Pauli exclusion principle. Processes that would require two fermions to occupy the same quantum state are suppressed. In recent years, several classic experiments have observed different manifestations of Pauli suppression in Fermi gases. Here we study density profiles of an ideal Fermi gas and observe Pauli suppression of density fluctuations (atom shot noise) for cold clouds deep in the quantum degenerate regime.

The development of a technique to sensitively measure density fluctuations was motivated by the connection between density fluctuations and compressibility through the fluctuation-dissipation theorem. In this study, we validate our technique for determining the compressibility by applying it to the ideal Fermi gas [1, 2]. In future work, it could be extended to interesting many-body phases in optical lattices which are distinguished by their incompressibility including the band insulator, Mott insulator, and also the antiferromagnet for which spin fluctuations, i.e., fluctuations of the difference in density between the two spin states are suppressed. Furthermore, measuring the level of suppression provides sensitive thermometry at low temperatures.

![Comparison of observed variances (black dots) with a theoretical model (black line) and the observed atom number (gray), at three different temperatures (a, b, and c), showing 50, 40, and 15% suppression of density fluctuations. Noise thermometry is implemented by fitting the observed fluctuations, resulting in temperatures $T/T_F$ of 0.23, 0.33, and 0.60, in good agreement with temperatures obtained by fitting the shape of the expanded cloud.]

2. Spin gradient demagnetization cooling of ultracold atoms.

We have demonstrated a new cooling method in which a time-varying magnetic field gradient is applied to an ultracold spin mixture [3]. We prepare a two-component cloud of rubidium atoms, either in the superfluid or Mott insulator phase, in a strong field gradient separating the two components with a narrow mixed region between the pure-spin domains. In the Mott insulator, where tunneling is strongly suppressed, reduction of the magnetic field gradient leads to extremely low effective spin temperatures of less than 50 pK. Reversal of the magnetic field gradient leads to negative spin temperatures, with an absolute value smaller than 50 pK.
The spin system can also be used to cool other degrees of freedom when the magnetic field gradient is reduced while the system can tunnel and therefore reach equilibration with the spin degree of freedom (see figure). After adiabatic demagnetization in the superfluid phase and ramping up the optical lattice to the Mott insulator phase, we have observed an apparently equilibrated Mott insulator of rubidium atoms to 350 pK. These are the lowest temperatures ever measured in any system. The entropy of the spin mixture is in the regime where magnetic ordering is expected.

Illustrations of the new cooling technique. The top image is of a sample with many particle-hole excitations but no spin excitations, and the bottom image is of a sample with no particle-hole excitations but many spin excitations. These are intended to represent the sample before and after reduction of the magnetic field gradient.

3. Thermometry and Refrigeration in a Two-Component Mott Insulator of Ultracold Atoms.

In this work [4], we describe and analyze theoretically the two techniques of spin-gradient thermometry and spin gradient demagnetization cooling developed earlier by our group [3, 5].

In rubidium, the different scattering lengths for inter-spin interactions and intra-spin interactions differ by about 1%. The simulation of this interaction effect resulted in spin profiles to be curved, in agreement with experimental observations (see figure). This curvature arises from a buoyancy effect - the species with greater intra-spin repulsion will preferentially populate the outer regions of the trap.
Comparison of simulated and measured spin images. Simulated images are on the left. Magnetic field gradients and temperatures for simulated images are: (a) 0.7 G/cm and 6 nK, (b) 0.06 G/cm and 2 nK, and (c) 0.0024 G/cm and 0.4 nK.

4. Speckle Imaging of Spin Fluctuations in a Strongly Interacting Fermi Gas

Spin fluctuations and density fluctuations are studied for a two-component gas of strongly interacting fermions along the BEC-BCS crossover [6]. Spin fluctuations are observed by directly measuring the difference in densities for the two spin states. This was done by using a probe laser which had equal detuning from both states, but with opposite signs.

The fluctuations in the atomic cloud led to an observed speckle pattern. The atoms imprint a phase shift into the transmitted beam. Upon propagation, this dispersive signal is transformed into an intensity speckle signal. Since the depth of the cloud is larger than the Rayleigh range associated with the resolution of the imaging systems, the transformation from phase signal to intensity signal takes place already within the atomic cloud. The random density fluctuations lead to a speckle pattern corresponding to the imaging resolution.

This new sensitive method easily resolves a tenfold suppression of spin fluctuations below shot noise due to pairing. Compressibility and magnetic susceptibility are determined from the measured fluctuations (see figure). They reproduce the expected qualitative behavior: for the sample at unitarity and on the BEC side the spin susceptibility is strongly suppressed relative to the compressibility. This reflects the fact that the atoms form bound molecules or generalized Cooper pairs. The spin susceptibility should be exponentially small in the binding energy, while the enhanced compressibility reflects the bosonic character of the molecular condensate.

This new technique is directly applicable to studying pairing and magnetic ordering of two-component gases in optical lattices [7, 8].
(a) The ratio $\chi/\kappa$, (b) the normalized susceptibility $\chi$, and (c) the normalized compressibility $\kappa$ in the BEC-BCS crossover. The variances derived from sequence sof images are converted into thermodynamic variables using the measured temperatures and a calibration factor determined from the noninteracting gas. The vertical line indicates the onset region of superfluidity, as determined via condensate fraction measurements. The curves show theoretical zero temperature estimates based on 1st (dotted) and 2nd order(solid) perturbative formulas obtained from Landau's Fermi liquid theory integrated along the line of sight, and results from a Monte Carlo calculation (dashed) for the compressibility in a homogeneous system [9].