Experiments with ultracold quantum-degenerate fermionic lithium atoms

Wolfgang Ketterle

Research Laboratory for Electronics, MIT-Harvard Center for Ultracold Atoms, and Department of Physics
Massachusetts Institute of Technology, Cambridge, MA 02139, USA
e-mail: ketterle@mit.edu

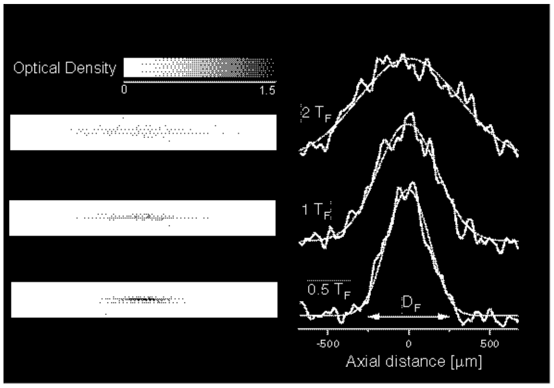
This article summarizes recent work at MIT on quantum-degenerate Fermi gases. An overview of this work was presented at the NASA workshop in Oxnard on 4/14/2003.

1. Two species mixture of quantum degenerate Bose and Fermi gases

Experimental methods of laser and evaporative cooling, used in the production of atomic Bose-Einstein condensates have recently been extended to realize quantum degeneracy in trapped Fermi gases [1]. Fermi gases are a new rich system to explore the implications of Pauli exclusion on scattering properties of the system, and ultimately fermionic superfluidity.

We have produced a new macroscopic quantum system, in which a degenerate ^{6}Li Fermi gas coexists with a large and stable ^{23}Na BEC [2]. This was accomplished using inter-species sympathetic cooling of fermionic ^{6}Li in a thermal bath of bosonic ^{23}Na. We have achieved high numbers of both fermions ($>10^5$) and bosons ($>10^6$), and ^{6}Li quantum degeneracy corresponding to one half of the Fermi temperature. This is the first time that a Fermi sea was produced with a condensate as a "refrigerator".

Low rates for both intra- and inter-species inelastic collisions result in a lifetime longer than 10 s. Hence, in addition to being the starting point for studies of the degenerate Fermi gas, this system shows great promise for studies of degenerate Bose-Fermi mixtures, including collisions between the two species, and of limitations to the sympathetic cooling process.



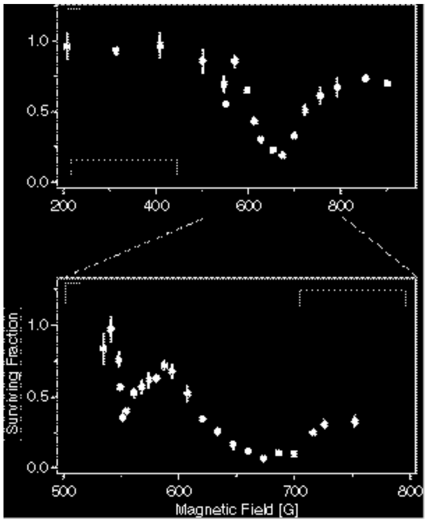
Onset of Fermi degeneracy. Three pairs of images (top to bottom) correspond to T/T_F= 2, 1, and 0.5. (a) Column densities of the ^{6}Li cloud were recorded by absorption imaging. (b) Axial line density profiles and the Fermi-Dirac fits to the data are plotted. The arrow indicates the size of the Fermi diameter, D_F, which is the diameter of the cloud at zero Kelvin.

2. Decay of an ultracold fermionic lithium gas near a Feshbach resonance

The interactions between atoms can be strongly modified by tuning magnetic fields to Feshbach resonances where a molecular state has the same energy as the colliding atoms.

For degenerate Fermi gases, such control over the interaction strength is crucial in the search for a superfluid phase transition. Otherwise, the phase transition temperatures are too low to be experimentally accessible. Near Feshbach resonances, the enhancement of the scattering length is usually accompanied by enhanced inelastic collisions, which lead to rapid trap loss. We have performed the first study of inelastic collisions in a fermionic system near a Feshbach resonance. We have observed resonant magnetic field dependent inelastic decay of an ultracold, optically trapped spin mixture of ^{6}Li [3].

The spin mixture of the two lowest hyperfine states showed two decay resonances at 550 G and 680 G. The feature near 680 G may be related to the long-predicted Feshbach resonance around 800 G. The resonance at 550G was unexpected, but new theoretical calculations have now identified it as an additional Feshbach resonance [4], which was not found in previous calculations. Even on resonance, the observed decay happened on a time scale longer than the trap oscillation time, the time for elastic collisions, and the expected sub-millisecond time needed for the formation of Cooper pairs.

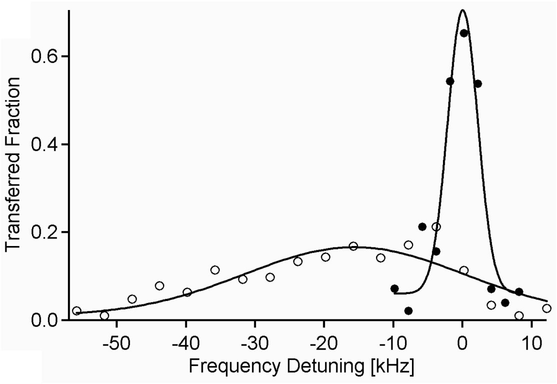


Magnetic field dependence of inelastic decay of lithium in a 50%-50% mixture of the lowest two hyperfine states. The fraction of the atoms remaining after a 500 ms magnetic field pulse is shown (upper graph). The two resonances are shown in more detail for 2 s magnetic field pulses (lower graph).

3. Radio-Frequency Spectroscopy of Ultracold Fermions

Radio-frequency techniques were used to study ultracold fermions [5]. By starting with a sample in one quantum state (state 2) and driving it to another state (state 3) we verified the prediction of the absence of mean-field “clock ”shifts, the dominant source of systematic error in current atomic clocks based on bosonic atoms. This absence is a direct consequence of fermionic antisymmetry which prevents two atoms in the same state to interact with contact interactions.

Resonance shifts proportional to interaction strengths were observed in a three-level system when the transition between states 2 and 3 was driven in the presence of atoms in a third state (state 1). When the interactions were weak, the observed shifts agreed with theoretical calculations. However, in the strongly interacting regime, these shifts became very small, reflecting the quantum unitarity limit and many-body effects. This insight into an interacting Fermi gas is relevant for the quest to observe superfluidity in this system.



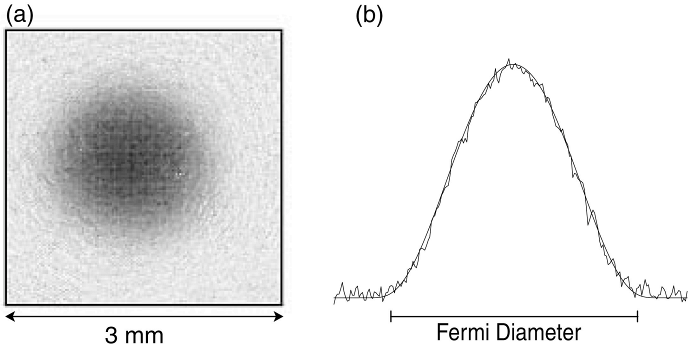
Measurement of the mean-field energy in an interacting Fermi gas. The fraction of atoms transferred by the radio-frequency pulse from state 2 to state 3.with atoms in state 1absent (solid circles)and present (open circles). The mean-field shift due to the presence of atoms in state 1 is computed from Gaussian fits to the data (solid lines).

4. Fifty-fold improvement in the number of quantum degenerate fermionic atoms

For a long time, the cooling of Fermi gases was lagging behind the studies of atomic Bose-Einstein condensates (BECs) due to the complexity of cooling methods. The Pauli exclusion principle prohibits elastic collisions between identical fermions at ultra-low temperatures, and makes evaporative cooling of spin-polarized fermionic samples impossible. For this reason, cooling of fermions must rely on some form of mutual or sympathetic cooling between two types of distinguishable particles. A key element in fermion cooling is the design of better "refrigerators" for sympathetic cooling.

We have realized evaporative cooling of sodium in the upper hyperfine state (F=2) and achieved Bose-Einstein condensates in this state by direct evaporation. Sympathetic cooling of lithium with that cloud decreased losses due to inelastic collisions encountered in earlier experiment with sodium in the lower (F=1) state.

This further cooling of the lithium resulted in the production of degenerate Fermi samples comparable in size with the largest alkali BECs [6]. We successfully cooled up to 7 X 10^7 magnetically trapped ^{6}Li atoms to below half the Fermi temperature (T_F), an improvement in atom number by a factor of 50 over the largest previously reported Fermi sea. Further, in samples containing up to 3 X 10^7 atoms, we observed temperatures as low as 0.05 T_F, the lowest ever achieved. At these temperatures, the fractional occupation of the lowest energy state differs from unity by less than 10^{-8}.

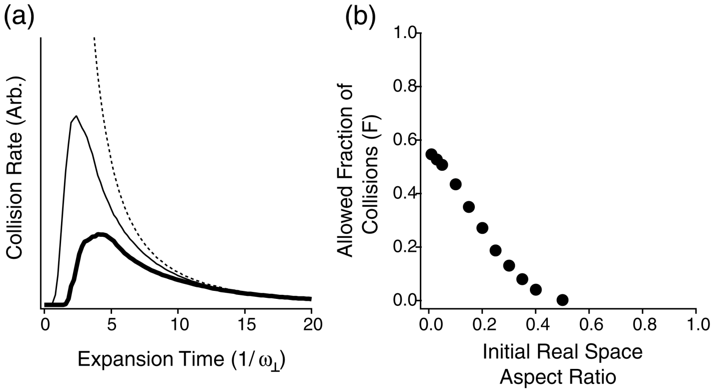


Large and ultra-degenerate Fermi sea. (a) Absorption image of 3 _ 10^7 ^{6}Li atoms released from the trap and imaged after 12 ms of free expansion. (b) Axial (vertical) line density profile of the cloud in (a). A semiclassical fit (thin line) yields a temperature T = 93 nK= 0.05 T_F . At this temperature, the high-energy wings of the cloud do not extend visibly beyond the Fermi energy, indicated in the figure by the momentum-space Fermi diameter.

5. Collisions in zero temperature Fermi gases

The smoking gun of Bose-Einstein condensation has been the anisotropic "superfluid" expansion of elongated condensates released from the trap. Similarly, superfluid Fermi gas would show anisotropic expansion due to superfluid hydrodynamics [7]. A recent observation of anisotropic expansion of an ultracold, interacting, two-spin fermionic mixture [8] has created considerable excitement and raised the question under what conditions is this expansion a signature of fermionic superfluidity and not of collisional hydrodynamics.

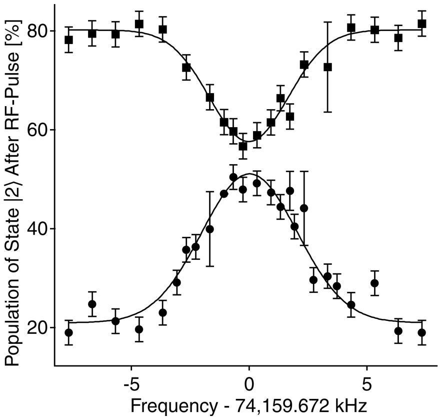
We examined the collisional behavior of two-component Fermi gases released at zero temperature from a harmonic trap [9]. Using a phase-space formalism to calculate the collision rate during expansion, we find that Pauli blocking plays only a minor role for momentum changing collisions. As a result, for a large scattering cross-section, Pauli blocking will not prevent the gas from entering the collisionally hydrodynamic regime. In contrast to the bosonic case, hydrodynamic expansion at very low temperatures is therefore not evidence for fermionic superfluidity.



(a) Collision rate as a function of expansion time in the perturbative approximation for an initial aspect ratio of 0.03. Dashed line: total classical collision rate, thin line: classical rate for momentum changing collisions, thick line: collision rate for fermions. (b) Allowed fraction of collisions for a zero-temperature two-spin Fermi gas. For an initial aspect ratio of 0.05, the fraction is 0.5, and approaches 0.55 for large anisotropy.

6. Spectroscopic insensitivity to cold collisions in a two-state mixture of fermions

We have experimentally addressed the relation between coherence and spectroscopic measurements in a binary mixture of ultracold fermions. We demonstrated that shifts of spectroscopic lines are absent even in a fully decohered binary mixture, in which the particles are distinguishable, and the many-body mean-field energy in the system has developed [10]. We theoretically showed that this is a direct consequence of the coherent nature of the RF excitation, and is not dependent on the coherence of the sample on which spectroscopy is performed. Our calculation intuitively explains both our results for fermions, and previous results for bosons obtained in Boulder [11].



Absence of mean-field shift of an RF transition in a binary Fermi system. The resonance curves were measured for fully decohered 80%/20% two-state mixtures of fermions. The measured frequency difference between the two lines is (34 ± 146) Hz, even though a simple mean-field model would predict a splitting of 20 kHz.

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