Evidence of condensation of Fermion pairs in dilute Fermi gases near Feshbach resonance.

1. Observation of Resonance Condensation of Fermionic Atom Pairs.
Authors: C. A. Regal, M. Greiner, and D.S. Jin.

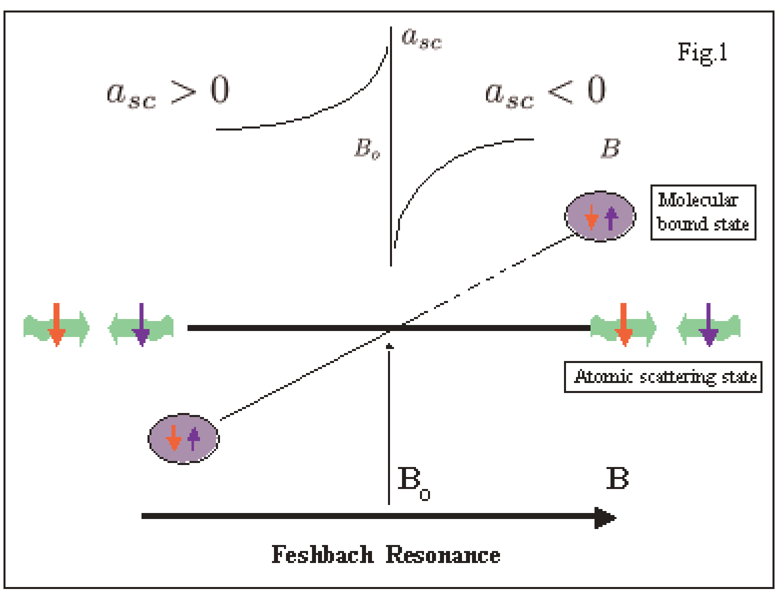
2. Observation of the Pairing Gap in a Strongly Interacting Fermi Gas.
Authors: C. Chin, M. Bartenstein, A. Altmeyer, S. Riedl, S. Jochim, J. Hecker Denschlag, and R. Grimm.

3. Heat Capacity of a Strongly-Interacting Fermi Gas.
Authors: J. Kinast, A. Turlapov, J.E. Thomas.

Recommended and a Commentary by Tin-Lun (Jason) Ho, The Ohio State University.

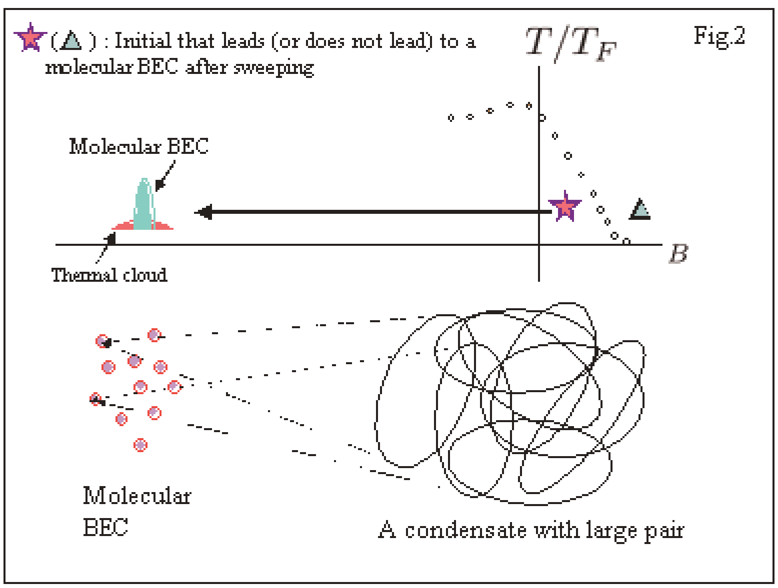
In the last 11 months, considerable progress has been made in the study of strongly interacting Fermi gases. At present, there is considerable evidence that the long sought superfluid phase of atomic fermions has been realized in the quantum gases of ^{40}K and ^{6}Li. The three papers mentioned above contain some of key evidence.

Fermi gases like ^{40}K and ^{6}Li are weakly interacting. As a result, T_c for superfluid pairing between two fermions in different spin states are too low to be achieved in current experiments. To increase T_c, one brings the system towards a Feshbach resonance to make it strongly interacting. It works as follows. When the energy of two like spins in a scattering (or delocalized) state is almost degenerate with that of a singlet bound pair, considerable resonance scattering between these two states can occur, leading to a diverging scattering length a_{sc}, and hence a diverging coupling constant in effective field theory description. (See fig.1). Since the bound pair and the scattering pair has different magnetic moments, their energy difference can be easily tuned by a magnetic field.



By November 2003, due the great success of achieving molecular BEC by Innsbruck, JILA, and MIT group, (see JCCM_Jan_01) the general feeling was that fermion superfluid would soon be realized. In January 04, Regal, M. Griener, and D. Jin at JILA made the dramatic announcement of observation of condensation of fermion pairs in the Fermi gas of K-40 near Feshbach resonance, [Paper 1]. Soon later, similar condensation effects were observed in ^{6}Li by Ketterle's group at MIT. It followed by measurements of collective modes (Innsbruck, Duke). By summer 2004, clear evidence of a pairing gap was reported by Rudi Grimm's group at Innsbruck, [Paper 2]. Recently, evidence of specific heat jump is also reported by John Thomas's group at Duke [Paper 3].

In Paper 1, an equilibrium Fermi gas is first created near resonance at a low temperature. In order to determine the existence pair condensation, the authors sweep the field quickly toward the molecular side. (See fig.2). The idea is that if the system consists of a large number of condensed pairs with zero total momentum, a substantial fraction of them will turn into a condensate of molecules after the sweep. Indeed, a molecular BEC is found to emerge if the initial state is within a neighborhood of Fesbhach resonance. By separating out the magnetic field regions where the initial state will or will not lead to a molecular BEC after sweeping, (denoted as star and triangle in fig.2), a phase boundary is obtained.



In Paper 2, the authors try to detect the formation fermion pair (say, made up of fermions in spin states A and B) by exciting spin state A to a higher spin state C. In the absence of pairing, a single line with energy E_C - E_A is found in the absorption spectrum. If pairing is present, an addition line will be observed since a fraction of the A atoms are now bounded in pairs, leading to a shift in frequency. These features, as well as many other features consistent with pairing, are observed in Paper 2.

Paper 3 is the first attempt to study the thermodynamics of the system. The idea is to deposit a controlled amount of energy into the system and then detect the temperature of the system using time of flight experiments. The total energy of the system measured in this way shows a kink at the temperature consistent with the phase boundary observed in Paper 1, implying a jump in the specific heat at that temperature, which is expected for superfluid transition. The data also show an interesting $E \sim T^{5/2}$ behavior below the kink. This feature, as well as the numerical value of the energy change, suggest that the excitations resemble free bosons pairs with a renormalized mass.

These data, together with other impressive evidence from collective mode measurements (which are not included here), form a strong case for the presence of a fermion superfluid. These systems, however, are different from the familiar weak coupling BCS superfluid in that they exist in the regime where scattering is maximum, as reflected in the diverging scattering length. The latter implies that the only energy scale at T=0 is the Fermi energy. Interaction energy, pairing gap, and all thermodynamic properties are controlled by this scale and are therefore universal.

What next? A clear demonstration of broken gauge symmetry will require phase sensitive measurements, or producing quantized vortices. At present, a number of experimental groups are working in these directions. In addition, there are considerable efforts of putting fermions in optical lattices. Yet at the verge of these intense activities, new and exciting directions are emerging. In a very recent report, Salomon?s group at Ecole Normal Superiore has reported the production of p-wave molecules in ^{6}Li using a p-wave Feshbach resonance. Realization of molecular condensates and Fermi superfluids made up of pairs with non-zero orbital angular momentum pairs are now real possibilities.