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Fermion Superfluidity with Imbalance Spin Populations and the Quantum Phase Transition to the Normal State, Martin W. Zwierlein, Andre Schirotzek, Christian H. S Chunck, and Wolfgang Ketterle, cond-mat/051197.

Pairing and Phase Separation in a Polarized Fermi Gas, Guthrie, B. Partidge, Wenhui Li, Ramsey I. Kamar, Yean-an Liao, Randall G. Hulet, cond-mat/0511752

Recommended with a Commentary by Jason Ho, Ohio State University.

What happens to an s-wave BCS superfluid when the numbers of up and down spin become unequal? This is a 40 year old problem which remains unresolved today. However, experiments in atomic Fermi gases such as the two mentioned above are beginning to yield information and will soon provide us with a definitive answer.

There have been many proposals for the solution to this problem. The most well known one is the proposal of Flude-Farrel-Larkin-Ovchinikov, (FFLO), which is a pairing state with an oscillatory gap function along a specific spatial direction. In the case of Fermi gases, where interactions are short range instead of Coulombic, it has also been suggested that the system will phase separate into a BEC superfluid and a fully spin polarized Fermi gas. (See the above papers for references).

The two papers above provide data on the density profiles of a Fermi gas of Li-6 with unequal spin population. In these experiments, the interaction between fermions can be tuned by an external magnetic field. (This is the phenomenon of Feshbach resonance, which is discussed in the November 2004 Recommendations of JCCM). By sweeping the magnetic field through a particular value B*, one can change a pair of unbound fermions (which exists in B>B*) to a bound pair (which exists in B<B*). The regions B>B* and B<B* are referred to as the BCS and BEC side of the resonance respectively.

In the MIT experiment, a Fermi gas of Li-6 is confined in a cylindrical harmonic trap rotating about its symmetry axis. Vortex lattices at the center of the cloud have been observed for various spin asymmetry, indicating that the center region is a superfluid. (See figure 1). It is found that

(1) Close to the resonance B*, on the BCS side, the majority spins pile up toward at the surface of the cloud as spin asymmetry increases, (See figure 2). For later comparison with the data from Rice, it is useful to note that the MIT data starts at asymmetry above 10%.
(2) As spin asymmetry increases, the condensate fraction drops to zero at a critical asymmetry. The phase boundary for condensate formation is shown in figure 3. This result implies that on the BEC side, spin asymmetry can destroy Bose condensation. This is a remarkable effect, for Bose condensation is a very robust mechanism in three dimension.

(3) Figure 1 shows that the spacing between vortices increases as spin asymmetry increases, even though the external rotation frequency remain the same. The authors considered this is an indication that the atom cloud spins slower than the external rotation, since it is hard to impart angular momentum to spin polarized fermions because they do not have contact interaction. This, however, would mean that the vortex lattice is not in mechanical equilibrium with the rotating potential.

In the Rice experiment, the Li-6 Fermi gas is confined in a stationary harmonic trap. The system is cooled down to a temperature believed to be well below the superfluid transition temperature. The density profiles for different spin populations for different spin asymmetry are show in figure 4.

(4) For spin asymmetry less than 10%, (see fig. (4B)), the density profiles of both up and down spin are similar except that the majority spin has a larger spatial extent. Should the system be a superfluid, this means that the system is a superfluid with a uniform magnetization!

(5) For spin asymmetry greater than 10%, the density profile of the two spin population becomes dissimilar, with the majority spin piling up toward the surface, similar to the finding in (1), (see fig. (4D)).

Result (4) is truly surprising, for since the beginning of BCS theory, theoretical studies within mean field theory all indicate that the uniform BCS superfluid is unstable against spin asymmetry. At present, the popular view is that the system will phase separate into a BCS superfluid and a normal gas of majority spin for *any* amount of spin inbalance, which is inconsistent with (4). However, a recent quantum Monte Carlo calculation (by Carlson et.al. PRL 95, 060401 (2005)) has found signs of a homogenous superfluid with spin asymmetry.

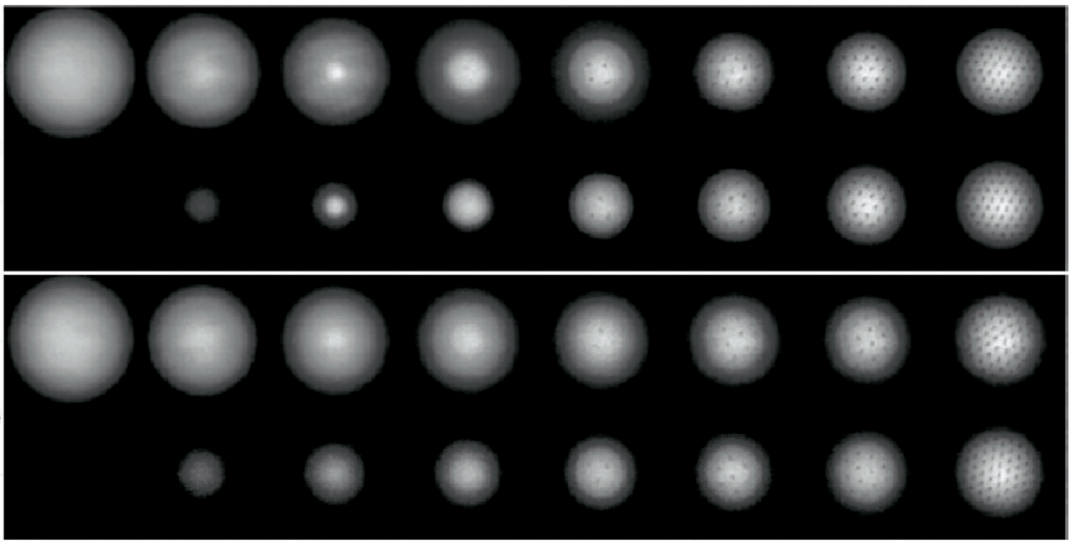
In any case, neither experiment shows clear signs of the FFLO state, whose existence would have implied a special direction in the system. If FFLO were never found in atomic Fermi gases, one might have to reconsider any interpretation of solid state phenomena involving the FFLO proposal, especially if Nature has a clever scheme to accommodate excess spins in a BCS superfluid.

Investigations of Fermi gases with spin asymmetry are just starting. With the speed of the experiments in quantum gases, it is likely that we shall have a solution to this 40 old fundamental problem in the near future.

Figure 1

BCS side, B = 812G

100% 90% 80% 62% 28% 18% 10% 0%

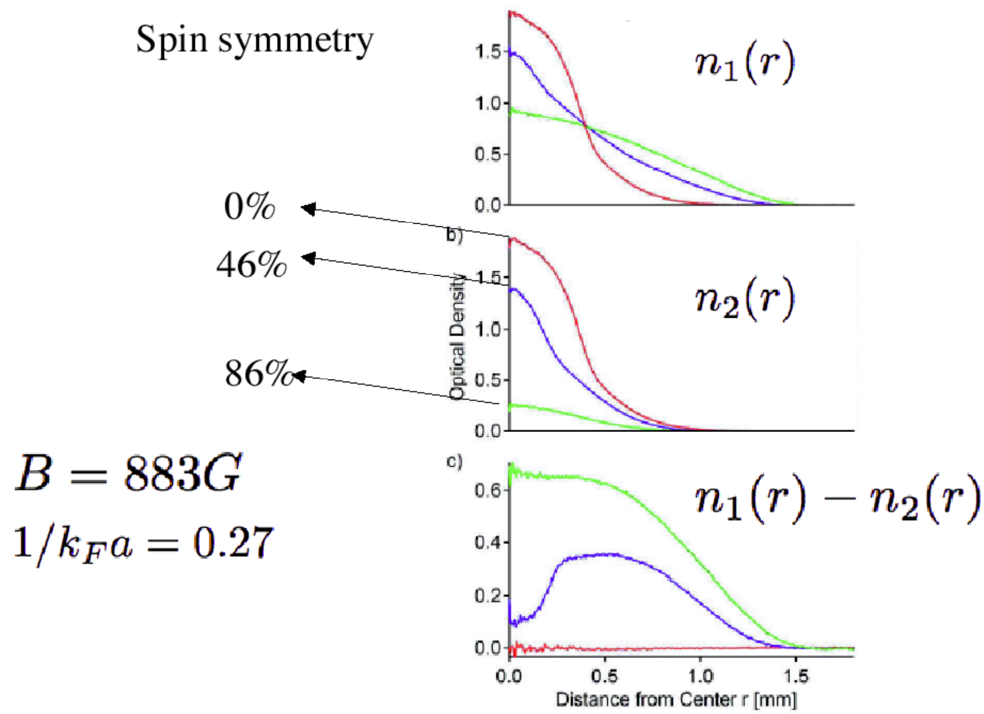


100% 74% 58% 48% 32% 16% 7% 0%

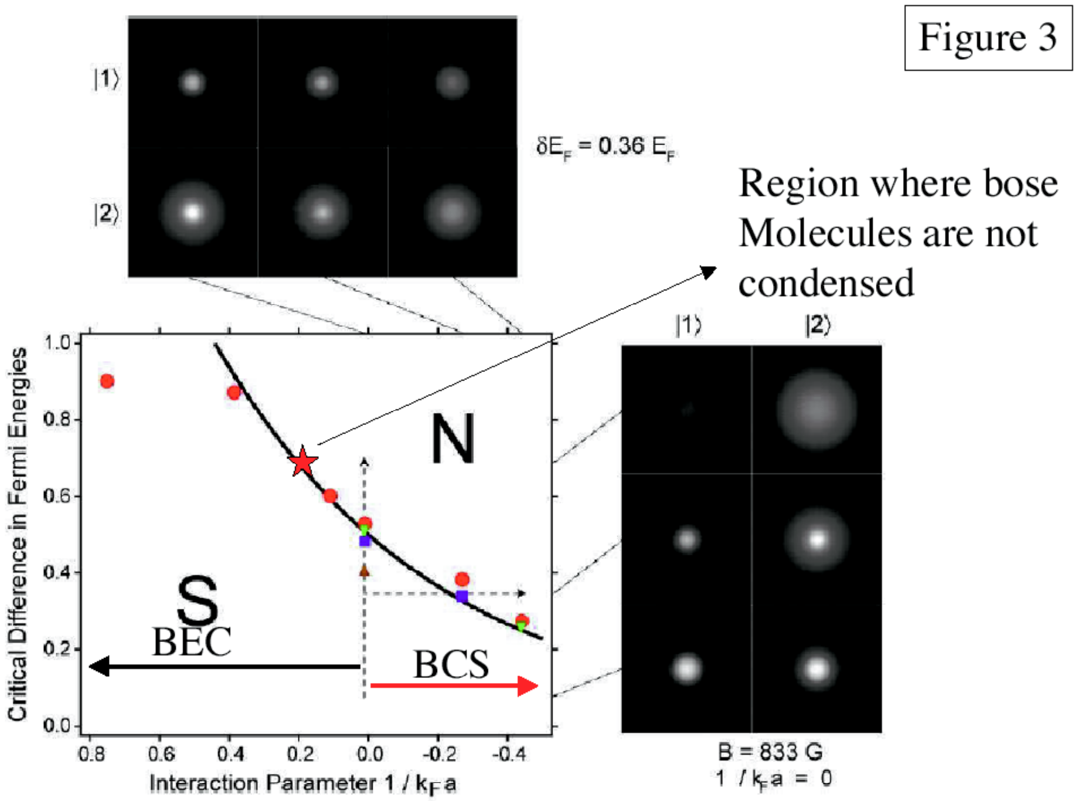
BEC side, B = 853G

Caption for figure 1: The numbers are different spin asymmetry.

Figure 2

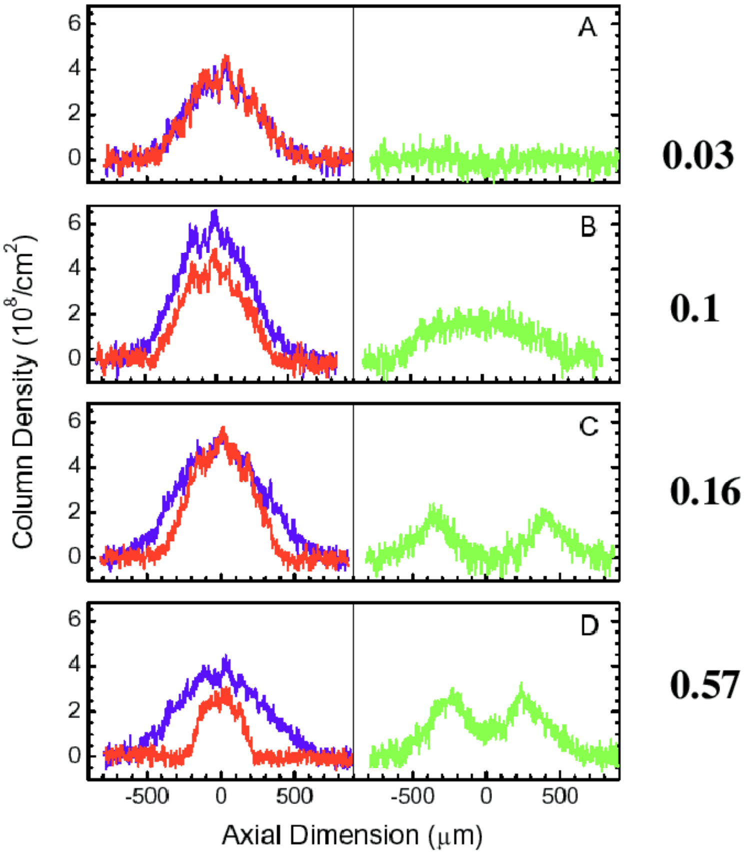


Caption for figure 2: The density profile of the Fermi gases in the MIT experiment.



Caption for figure 3: The phase boundary obtained in the MIT experiment.

Figure 4



Caption for figure 4: The density profiles of the Fermi gas as different spin asymmetry observed in the Rice experiment.