The Continued Saga of Fermions with Unequal Spin Population

Phase diagram of a two-component Fermi gas with resonant interactions

Authors: Yong-il Shin, Christian H. Schunch, Andre Schirotzek, Wolfgang Ketterle, arXiv:0709.3027

Deformation of a trapped Fermi gas with unequal spin population
Authors: G.B. Partridge, Wenhui Li, Y,.A. Liao, R.G. Hulet, M. Hague, H.T.C. Stoof, Phys. Rev. Lett. 97, 190407 (2006).

Recommended with a Commentary by Tin-Lun (Jason) Ho, Ohio State University

This is an update of a Commentary I wrote about a year ago on the intense experimental efforts at MIT and at Rice University to address a fundamental quantum many-body problem: the fate of the BCS ground state as the spin populations become unbalanced. Due to some profound differences of the findings of these two groups, there have been a lot of debate between the two experimental groups and among theoreticians. The two papers mentioned above are the latest results of these two groups. There is now (in my opinion) considerable clarification of the situation. However, the major puzzles still remain.

The evolution of the BCS ground state as a function of spin polarization is a long standing problem since the beginning of BCS theory. While it is clear that the system will turn normal above a critical chemical potential imbalance h_c (the so-called Chandrasekar-Clogston limit), the ground state below h_c has been a subject of discussion. There have been many proposals, with the so-called FFLO state being the most famous. Studies in recent years of cold fermions near Feshbach resonance, however, have shown that a phase separated state consisting of the BCS superfluid and normal phase is a much better candidate near Feshbach resonance.

The experiments at MIT and Rice are performed with Li-6 at Fesbhach resonance. The Fermi gas is strongly interacting and exhibits "universal" behavior. For example, the size of the Cooper pairs is given by inter-particle spacing, independent of the details of inter-atomic potentials, with T_c/T_F as high as 0.3. Since it is easy to adjust the relative spin populations of these systems using atomic transitions, they are perfect for studying the evolution of ground states with increasing spin polarization. In the Rice experiment, 10^5 fermions are confined in a very elongated trap. In contrast, MIT has a much rounder trap with a lot more (10^7) particles.

While both groups found phase separation and no sign of FFLO, they observed a vastly different critical polarization, i.e. the smallest polarization for which the normal gas is stable against pairing. This critical polarization is ~30% for MIT and >90% for Rice.

Another difference is the presence of a significant surface energy between the superfluid phase and a completely polarized normal phase in the Rice experiment, which appears to be absent in the MIT data. A third important difference is that there are strong evidences of a partially spin polarized normal phase in the MIT data, which is absent in the Rice data. Although some of these differences are caused by trap geometry and particle numbers, the huge difference in critical polarization still defies explanation.

Despite the lack of satisfactory resolution to these differences, from the collective body of theoretical work in the last two years, a clear picture has emerged. From the latest experiments (detailed in the paper above) , the MIT results appear to be consistent with the bulk phase diagram, which are obtained by many authors using a variety of methods, from analytic to Monte Carlo calculations. The key feature of the phase diagram is that at T=0, the system phase separates into a superfluid state with equal spin population and a normal state for polarization $P < P_c$~42%. At higher temperature, the tendency of phase separation reduces. Above a tri-critical point T_{tri}, the transition from BCS superfluid to the normal state becomes second order. All these features have essentially been found in the latest MIT experiments, after a detailed study temperature scale and 3D density profile.

For the Rice experiment, it is found that it can be explained satisfactorily by considering the phase separation between a superfluid and a fully polarized Fermi gas with a surface energy characterized by a single fitting parameter. In this scheme, the very high critical polarization is caused by the very low interaction energy of the normal state, which makes the superfluid phase favorable. Should the fully spin polarized normal phase (which occurs in the Rice experiment) be replaced by a partially polarized phase (which occurs in the MIT experiment), one would have a much lower critical polarization, incompatible with the experiment. So the mystery of the exceptionally high polarization can be traced back to the “mysterious” absence of partially polarized phase in the Rice experiment. Whether it is due to mesoscpic effects or other factors remain to be seen.

What next? In order to resolve these differences, it will be useful for both laboratories to perform experiments on traps with the same aspect ratio and the same particle number. The resolution of these differences is important for it is relevant for another major activity underway – the realization of superfliudity in Fermi gases with unequal masses. Whatever unsolved problem in the equal mass case will certainly come back to haunt us in the future.

Finally, I would like Erich Mueller and Roberto Diener for discussions on issues related to this Commentary.