Fermion Pairing with Unequal Spin Populations

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Abstract: We have produced a two-component gas of ultracold, fermionic ^{6}Li atoms with unequal spin populations. The real-space densities reveal a superfluid/normal phase separation at very low temperatures, and a partially polarized paired phase at higher temperatures.

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1. Introduction

During the past three years, several groups have explored pairing of ultracold fermionic atoms. These experiments have exploited the fantastic tunability and control that is inherent to cold atomic gases to conduct unprecedented investigations of pairing when the interparticle interactions are large. These studies are relevant not only to the basic understanding of superconductivity in strongly interacting systems, but also to more exotic situations such as the pairing of quarks in quark-gluon plasmas, or perhaps even to quark pairing in the cores of neutron stars.

The so-called “BEC-BCS crossover” describes the transition from Bose-Einstein condensation (BEC) of tightly-bound pairs of fermions, in which the pairs are essentially bosonic molecules, to the Bardeen-Cooper-Schrieffer (BCS) regime of spatially large correlated pairs, applicable to conventional superconductors. In cold atoms, we are able to traverse the crossover by adjusting the interactions by tuning a collisional resonance between a pair of free atoms and a bound state of the diatomic molecule using an external magnetic field. This “Feshbach resonance” provides the means to tune to either the BEC or BCS regimes or directly on resonance to the unitarity regime, where the pair size is equal to the mean interparticle distance.

Fermi-Dirac statistics require that fermions interacting via an *s*-wave must be in different quantum states, such as spin-up or spin-down. In conventional BCS theory, the number of spin-up and spin-down particles is the same, corresponding to a superconductor with no internal magnetic field. As early as the 1960’s, however, it was realized that superfluidity may still occur in a mismatched system where the numbers of particles, or more generally, their Fermi energies, are different. Several exotic phases have been proposed for the mismatched case, two of which, the FFLO state (the initials of the originators of the idea) [2, 3] and the deformed Fermi surface (DFS) state [4] correspond to broken space symmetries and are of particular interest. Other paired phases include the polarized superfluid and phase separation. Experimental confirmation of these new phases in superconductors has remained elusive because of the fundamental incompatibility between magnetism and superconductivity. In contrast, it is relatively straightforward to create an atomic Fermi gas with unequal numbers of two spin states, and groups at MIT and Rice have conducted experimental investigations [5, 6]. The primary result of our experiment at Rice is the observation of phase separation between a fully paired superfluid core surrounded by the unpaired excess atoms, and the deformation of the core due to surface tension at the superfluid/normal interface [1, 6].

2. Experimental methods

Our methods for producing a degenerate Fermi gas of ^{6}Li have been discussed in several prior publications [1, 6, 7]. Laser-slowed lithium atoms are loaded into a magneto-optical trap, and then transferred to a clover-leaf magnetic trap where they are cooled by rf evaporation. Spin symmetry prevents spin-polarized fermions from undergoing *s*-wave interactions, so in order to thermalize the magnetically-trapped ^{6}Li atoms during evaporation we simultaneously cool and trap ^{7}Li, a boson. The ^{7}Li is directly evaporated, while ^{6}Li atoms in the $F = 3/2$, $m_F = 3/2$ state are cooled sympathetically by collisions with the ^{7}Li atoms [8]. The remaining ^{7}Li atoms are removed by rf spin flips at the end of the evaporation cycle.

A Feshbach resonance occurs between the $F = ½$, $m_F = ±½$ states at 834 G. These states form a quasi-spin-½ system in which the $m_F = ½$ and -½ states are labeled as states 1 and 2, respectively. Since these states are not magnetically trappable, following evaporation in the magnetic trap the atoms are transferred to an optical trap formed by a focused infrared laser beam before being prepared in states 1 and 2. An *incoherent* two-state mixture is necessary if the atoms are to interact. Coherence is destroyed by subjecting the atoms to a succession of sawtooth frequency ramps through the rf transition coupling states 1 and 2 in the presence of a weakly inhomogeneous magnetic field. The number of atoms in each spin-state, N_1 and N_2, is determined by the rf power. We denote the

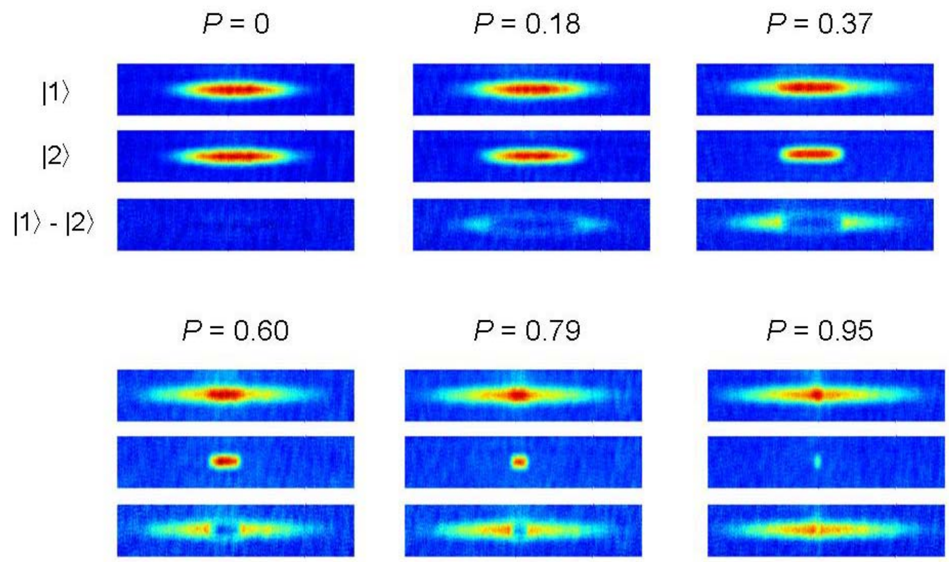

Figure 1. Absorption images of trapped atoms. The field of view for these images is 1654 μm by 81 μm. The displayed aspect ratio was reduced by a factor of 4.4 for clarity. (Reprinted from ref. [1]).

polarization $P = (N_1 - N_2)/ (N_1 + N_2)$. Since state 1 is the majority state in our experiment, $0 \le P \le 1$. The atoms are further evaporatively cooled in the optical trap by reducing the power of the infrared beam.

The real-space distributions of the atoms in the trap are obtained by *in-situ* absorption imaging, where each spin-state is sequentially and independently imaged. The resulting column density distributions are fit to model distributions to obtain estimates of N_1 and N_2, as well as the temperature T. Because of the inherent insensitivity of highly degenerate Fermi distributions to temperature, we can only obtain an upper estimate for our coldest distributions, $T \le 0.05\ T_F$, where T_F is the Fermi temperature. (The quoted temperatures are actually effective temperatures obtained by fitting to finite temperature Thomas-Fermi distributions [9]).

3. Results

Figure 1 shows a series of images corresponding to a range of P from 0 to 0.95 at the unitarity limit. The upper and middle images of each set correspond to images of states 1 and 2, respectively, while the third image is the difference of the two. These images reveal the essential results of this work, and we can make qualitative conclusions from them. Quantitative data in support of these assertions are presented subsequently. The case of $P = 0$ corresponds to the usual situation of equal numbers in each spin-state; the difference distribution is zero in this case, as expected. The difference distributions for non-zero P exhibit a dark central core, indicating that the column densities of each spin-state are nearly equal. Since the two states have nearly the same radial dimension we can conclude that the real 3D densities are also nearly equal in the dark region. This observation suggests a phase separation with a central, equally paired core, surrounded by the excess unpaired atoms in a completely polarized shell. With this interpretation, the distribution of state 2 corresponds to the paired core, while the difference distribution corresponds to the unpaired atoms. It is also apparent from these images that the interface between the core and the polarized shell is quite sharp. Finally, and perhaps most striking, is the observation that the core becomes highly deformed with increasing P. The polarized shell surrounding the core is not uniformly distributed, but rather is concentrated at the axial poles. In other words, the core does not assume the shape of the underlying harmonic trap, instead becoming less elongated with increasing P.

Figure 2 shows the aspect ratio for each spin-state as a function of P. This data clearly shows the effect of the deformation of the state 2 distribution, for which the aspect ratio decreases by an order of magnitude in going from $P = 0$ to $P = 0.98$. At the same time, the aspect ratio of the majority spin state (1) does not change appreciably from the value determined by the trap. This deformation has been explained by surface tension at the superfluid/normal boundary [10]. Haque and Stoof fit the data to a generalized model that includes surface tension [1, 11]. While there is no accurate microscopic model for the magnitude of the surface energy at unitarity, the Fermi energy E_F is the only energy scale and the surface energy must be proportional to it within a numerical factor of order unity. They find that the best fit, for all P, corresponds to a constant of proportionality of 0.6 [11]. Figure 3(a) shows a representative fit to a column density cut for $P = 0.35$. The fit is remarkably good, instilling confidence that surface tension is likely the correct explanation for the deformation, so that it can be considered a “smoking gun” for phase separation, as well as for superfluidity.

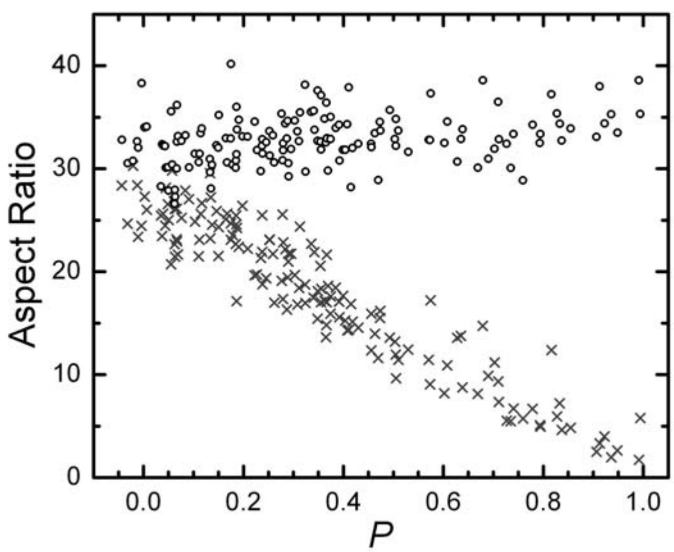

Figure 2. Aspect ratio vs. *P*. The circles correspond to state 1, while the x's to state 2. (Reprinted from ref. [1]).

The real-space density distributions can be extracted from the column densities obtained from the absorption images using the Abel transform [12]. This method only requires that the distributions be cylindrically symmetric, a requirement that is fulfilled by our single-beam optical trap. Figure 3(b) shows an example of an axial cut through the real-space density distribution obtained by the Abel transform. The difference distribution shows that the central density difference is indeed zero, as asserted previously, and as expected for an evenly paired core. The ratio of the central densities of the two spin states obtained by the Abel transform for all the data is plotted in Fig. 4(a). The central density ratio is approximately equal to 1 for all but the highest polarizations, and is quite different from what would be expected for a gas in the normal phase (dotted line). This result is somewhat unexpected, as it shows that phase separation is occurring in this system even above the so-called Clogston limit, where the difference is chemical potentials exceeds the superconducting gap, Δ [13]. A possible resolution of this discrepancy is that the large aspect ratio of our trapping geometry facilitates pairing at large *P*.

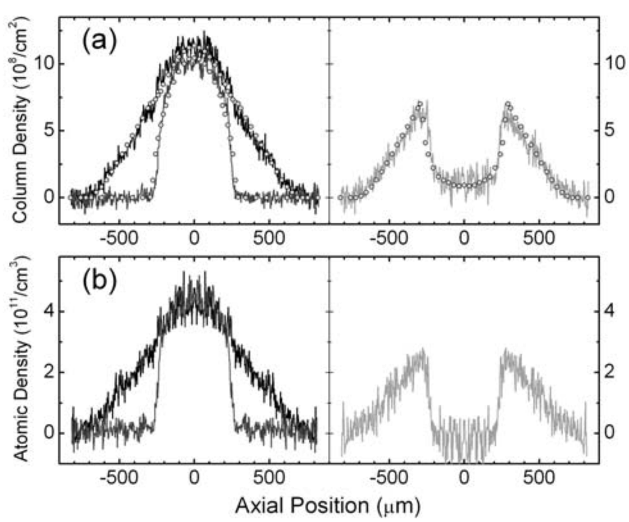

Figure 3. Axial cuts of (a) column densities and (b) 3D density reconstruction for $P = 0.35$. States 1 and 2 are shown on the left, while their difference is shown on the right. The circles are the results of a fit to a model that incorporates surface tension. (Reprinted from ref. [1]).

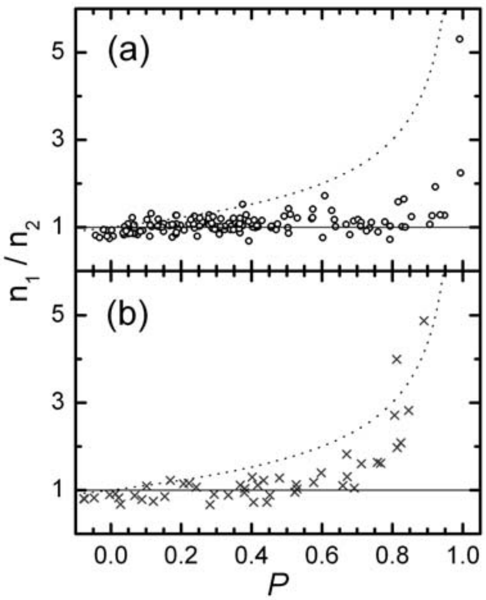

Figure 4. Ratio of central densites vs. P. (a) $T \leq 0.05\ T_F$ and (b) $T \approx 0.2\ T_F$. The dotted lines correspond to the expected central density ratio for a non-interacting gas at $T = 0$. (Reprinted from ref. [1]).

All of the preceding data corresponded to our lowest temperatures, $T \leq 0.05\ T_F$. We also obtained data at higher temperatures by not evaporating as deeply in the optical trap. These higher temperature data are markedly different than the low temperature data, as can be seen in the comparison shown in Fig. 5. The data of Fig. 5(a,b) correspond to the lowest values of T, while Fig. 5(c,d) corresponds to $T \approx 0.2\ T_F$. At higher T, there is no deformation evident in the state 2 distribution and the aspect ratio of both states 1 and 2 remain constant and equal, independent of P. Even so, the central region remains equally paired up to $P \approx 0.6 - 0.7$, as can be seen from Fig. 4(b), indicating that the central region is still superfluid at this temperature. At higher P, the central density ratio for this higher temperature data is consistent with that of a normal gas.

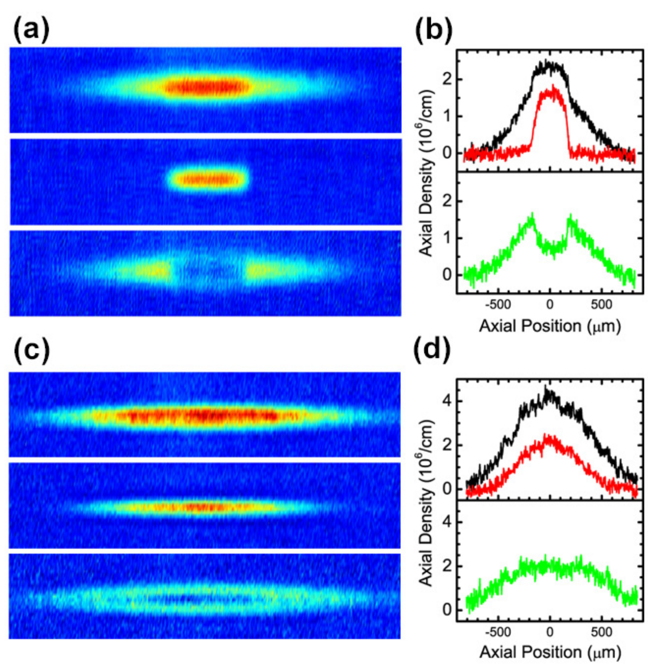

Figure 5. Absorption images and integrated profiles for (a), (b): $P = 0.50$, $T \leq 0.05\ T_F$; (c), (d): $P = 0.45$, $T \approx 0.2\ T_F$. (Reprinted from ref. [1]).

4. Discussion

Phase separation was first suggested by Bedaque *et al.* [14], and was explored theoretically by several other groups [15-18]. A phase separated region appears prominently in all proposed phase diagrams. Figure 6 shows a proposed phase diagram relevant to a trap where the density distribution is inhomogeneous [19]. This phase diagram is consistent with the others that have been proposed for finite temperatures [20, 21]. The phase diagram contains two superfluid regions: a lower T phase corresponding to phase separation, and at higher T, a polarized superfluid (Sarma) phase. The boundary between phase separation and the normal phase is first order (as expected for any phase separation), while the boundary between the polarized superfluid and the normal phase is second order. The point of intersection of the three phases is a tricritical point [22, 23]. In a trap, the polarized superfluid phase for P below the Clogston limit contains a central, evenly-paired BCS state, with gradually increasing polarization with increasing radius, accompanied by a transition to the normal state.

The phase diagram of Fig. 6 agrees well with the data. The lower dashed line indicates qualitatively where the lowest T data fits in this diagram. At low T there is phase separation at nearly all P, and the first-order phase boundary results in sharp interfaces, as observed. The higher dashed line corresponds to the higher T data, where the central region is a BCS superfluid, with no abrupt changes in polarization with increasing radius, as expected for a second-order phase transition. In our prior work, the data fit to $T \approx 0.1\ T_F$, and phase separation was observed only for $P > 0.1$ [6]. This observation is again consistent with the phase diagram, with an intermediate temperature below the tricritical point.

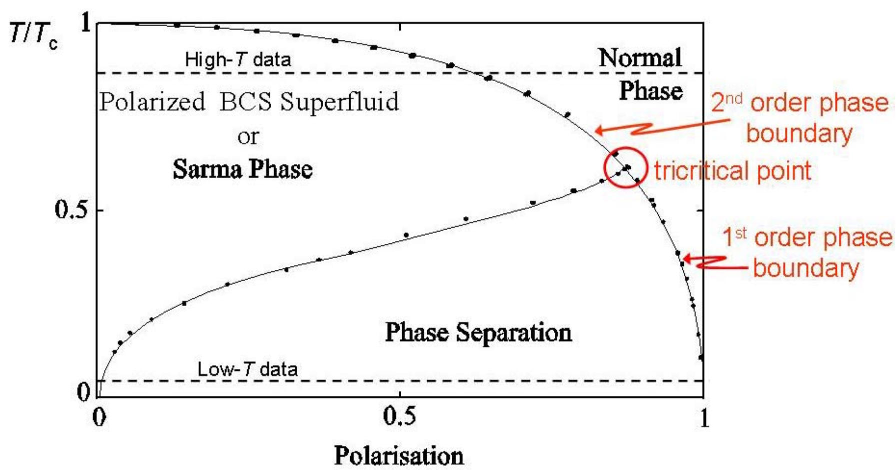

Figure 6. Proposed phase diagram at unitarity. Dashed lines indicate qualitatively where the low and high-T data from Fig. 5 fit. (Reprinted from ref. [19]).

The MIT group has performed a very similar experiment to ours and has reported *in-situ* images of the trapped atom distributions [24]. Their data is qualitatively similar to our higher temperature data in that they see no evidence for surface tension and no change in aspect ratio. Furthermore, they observe that pairing persists only to $P \approx 0.7$, consistent with the high-T data shown in Fig. 4(b). Their claim for phase separation is based upon a measurement showing an evenly paired central region, which as shown by Fig. 4(b), does not necessarily imply phase separation. The fact that no evidence for surface tension is found is particularly significant. Although the effect of surface tension is expected to be reduced by the relatively small aspect ratio (5 vs. 30) and relatively large numbers (5×10^6 vs. 10^5) in the MIT experiment, the scaling of these effects is well-known [10, 11, 25], leading to the prediction that surface tension in the MIT experiment should result in a reduction of the aspect ratio by 15% [11]. No such deformation is observed even though a change of this magnitude would easily be detected in the integrated column densities shown in ref. [24]. There is as yet no resolution to this discrepancy, but it could be related to temperature as surface tension is expected to be strongly T dependent. The MIT group reports temperatures below 0.1 T_F, which is expected to be below the tricritical point.

5. Conclusions

We have used a two spin-state mixture of ultracold ^{6}Li atoms with unequal populations to explore the phase diagram of a strongly-interacting polarized Fermi gas. At the lowest temperatures the gas phase separates into an evenly paired superfluid core surrounded by a shell of excess, unpaired atoms. Surface tension at the phase boundary in the trap causes the superfluid core to deform markedly, becoming more spherical with increasing polarization. In the inhomogeneous environment of the trap, the transition from the superfluid to normal regions is abrupt, as expected for a first-order phase transition. At higher temperatures, the density profiles are consistent with a polarized superfluid, containing an evenly paired central region with gradually increasing polarization with radius. These observations are in agreement with proposed phase diagrams containing two superfluid phases and a tricritical point.

The phase diagram shown in Fig. 6 was constructed without consideration for the FFLO or DFS phases. From other work, however, it is believed that the FFLO phase occupies at most a very small segment of phase space, and only on the BCS side of the crossover (e.g. ref. [26]). Our future work is to map out the phase diagram as a function of interaction strength (a), T, and P.

6. Acknowledgments

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7. References

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