^{6}LI AND ^{7}LI: NON-IDENTICAL TWINS

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We have cooled a magnetically trapped gas of bosonic ^{7}Li and fermionic ^{6}Li atoms into the quantum degenerate regime. The atoms are loaded from a laser-slowed atomic beam into a magneto-optical trap, and then transferred to a magnetic trap. Forced evaporation is used to cool the ^{7}Li atoms, and the ^{6}Li are cooled "sympathetically" via collisional interaction with the ^{7}Li. As the temperature of the Fermi gas is reduced below the Fermi temperature, we observe that its spatial size is greater than that of the Bose gas. This effect is quite pronounced at the lowest temperature achieved of 0.25 times the Fermi temperature, and is a manifestation of the Fermi pressure resulting from the Pauli exclusion principle.

1 Introduction

The development of the techniques of atomic laser cooling and trapping culminated several years ago with the achievement of Bose-Einstein condensation (BEC) of a weakly interacting gas. This development has greatly expanded our ability to probe and understand bosonic matter in a regime dominated by quantum statistics rather than interactions. In contrast, prior to the results presented here, there has been only one realization of quantum degeneracy of a trapped Fermi gas, that being the work of Demarco and Jin with ^{40}K [1]. In this paper, we report the first realization of quantum degeneracy in a mixed Bose/Fermi gas of trapped lithium atoms [2]. Of the two stable isotopes of lithium, ^{7}Li is a composite boson, while ^{6}Li is a fermion. We have succeeded in cooling the gas to a temperature of 240 nK, which corresponds to 0.25 times the Fermi temperature T_F for the fermions. At this temperature, the spatial distribution of the fermions is strongly affected by Fermi pressure, in exact analogy with the stabilization of white dwarf and neutron stars, and is in stark contrast with the behavior of the Bose gas. Our experiment is very similar to one in Paris, and they report similar results [3].

Trapping and cooling fermions is similar to bosons except for one major difference: identical fermions are symmetry-forbidden to undergo *s*-wave rethermalization collisions needed to evaporatively cool. This obstacle can be circumvented by evaporative cooling using a two-component Fermi gas [1,4] or by sympathetic cooling with a Bose/Fermi mixture [2,5]. We have chosen the latter approach because any two magnetically trappable spin-states in ^{6}Li will rapidly undergo spin-exchange collisions [6]. In our experiment, ^{6}Li is cooled by thermal contact with the evaporatively cooled ^{7}Li. Ultimately, it may be possible to cause a BCS-like Cooper pairing of a two-spin state mixture of the ^{6}Li atoms [7].

2 Experimental Approach

We have constructed an entirely new apparatus for this experiment, although the techniques and apparatus are similar to those used to achieve BEC in ^{7}Li [8]. The apparatus consists of an ultrahigh vacuum chamber containing a magnetic trap. The trap is loaded from a dual-species magneto-optical trap (MOT). Approximately 3×10^{10} atoms of ^{7}Li are loaded into the MOT by laser slowing a thermal atomic beam using the Zeeman slower technique. The ^{6}Li MOT is loaded using the same Zeeman slower, but for only 20 ms to minimize interference with the ^{7}Li MOT. The interference arises because of a near coincidence of the D1-line transition frequency of ^{7}Li with the D2-line transition in ^{6}Li. Approximately 10^7 atoms of ^{6}Li are loaded into the MOT. Both isotopes are then optically pumped into the "stretched" low-field seeking Zeeman sub-level, corresponding to F=2, $m_F = 2$ for ^{7}Li, and F = 3/2, $m_F = 3/2$ for ^{6}Li. After further cooling, and compressing, approximately 10% of the atoms of each isotope are transferred to the magnetic trap.

The magnetic trap has an Ioffe-Pritchard field configuration, and was built using the "clover-leaf" design of MIT [9]. The trap produces an axial curvature of 75 G/cm^2 and a radial gradient of 110 G/cm, which at a 2 G bias field, correspond to measured axial and radial trapping frequencies for ^{7}Li of 39 Hz and 433 Hz, respectively. The trapped atom lifetime is limited by collisions with background gas, and has been measured to be in excess of 3 minutes.

Cooling to degeneracy is accomplished by microwave-induced evaporative cooling to an untrapped spin-state of ^{7}Li. The ^{6}Li atoms are cooled sympathetically through their elastic interactions with the ^{7}Li and are not themselves ejected. The triplet *s*-wave scattering lengths determine the elastic scattering cross sections for thermalization. For ^{7}Li/^{7}Li collisions the scattering length is –1.5 nm, whereas for ^{6}Li/^{7}Li it is 2.2 nm [10,11]. Although neither of these correspond to particularly large cross sections, they are sufficient to cool both species to quantum degeneracy in ~60 s. Similar methods of sympathetic cooling have been previously used in a two-species ion trap [12] and in a two-component Bose gas of ^{87}Rb cooled to BEC [13].

Once the sympathetic cooling cycle is complete, the atoms are held in the trap for at least 2 s to ensure complete thermalization. The ^{7}Li atoms are then probed with a near-resonant laser beam, and their absorption shadows imaged onto a CCD camera with a magnification corresponding to 5 μm/pixel. A high-intensity on-resonant laser pulse is applied for 10 μs to quickly remove all remaining ^{7}Li atoms from the magnetic trap. Because this pulse is detuned by more than 10 GHz from any ^{6}Li resonance, it has no measurable effect on the ^{6}Li atom cloud. The ^{6}Li are then imaged in a similar manner.

The number of atoms and their temperature are obtained from the images by fitting them to the appropriate quantum statistical density distribution functions. Unlike the fermions, the shape of the density distribution for bosons changes significantly as quantum degeneracy is approached. For this reason, the bosons prove to be a sensitive thermometer for determining the common temperature, which reduces the uncertainty in both the number and temperature of the Fermi gas. It is assumed that the interactions have a negligible effect on the density. This is a good approximation because ^{7}Li has attractive interactions that limit the number of condensate atoms, and hence the magnitude of the mean field [8,14]. This effect also constrains the magnitude of the mean-field experienced by the ^{6}Li as a result of the ^{7}Li, while the self-interaction between the fermions is identically zero in the *s*-wave limit.

3 Results

We have cooled the gas to temperatures as low as $T = 240$ nK, corresponding to $T/T_F = 0.25$, where the Fermi temperature $T_F = \hbar\varpi\,(6N_F)^{1/3}/k_B$, and ϖ is the geometric mean of the trap frequencies for ^{6}Li, N_F is the number of ^{6}Li atoms, and k_B is Boltzmann's constant. Density profiles for two pairs of images, corresponding to two different temperatures, are shown in Fig. 1. At high temperature, where classical statistics are a good approximation, the spatial distributions of the bosons and fermions show little difference, as can be seen in Fig. 1A. As the gas is cooled further, the ^{6}Li distribution is observed to be broader than that of the ^{7}Li. This difference is clearly visible at the lowest temperatures, as shown in Fig. 1B. The broadening is the result of Fermi pressure and is a direct manifestation of quantum statistics.

The square of the axial radius of the ^{6}Li clouds is plotted versus T/T_F in Fig. 2, where it can be seen that at relatively high temperatures, the radius decreases as $T^{1/2}$, as expected for a classical gas (dashed line). At a temperature near 0.5 T_F, however, the radius deviates from the classical prediction, and at the lowest temperatures, it plateaus to a value near the Fermi radius. At $T = 0$, every trap state is singly occupied up to the Fermi energy, giving rise to a nonzero mean energy and a resulting Fermi pressure. Fermi pressure is responsible for the minimum radius and is a striking manifestation of Fermi-Dirac statistics. In white dwarf and neutron stars, which are essentially "dead" due to the depletion of their nuclear fuel, it is the Fermi pressure that stabilizes the star against gravitational collapse. The stabilization of the size of the atom cloud with decreasing temperature is another manifestation of the same physics.

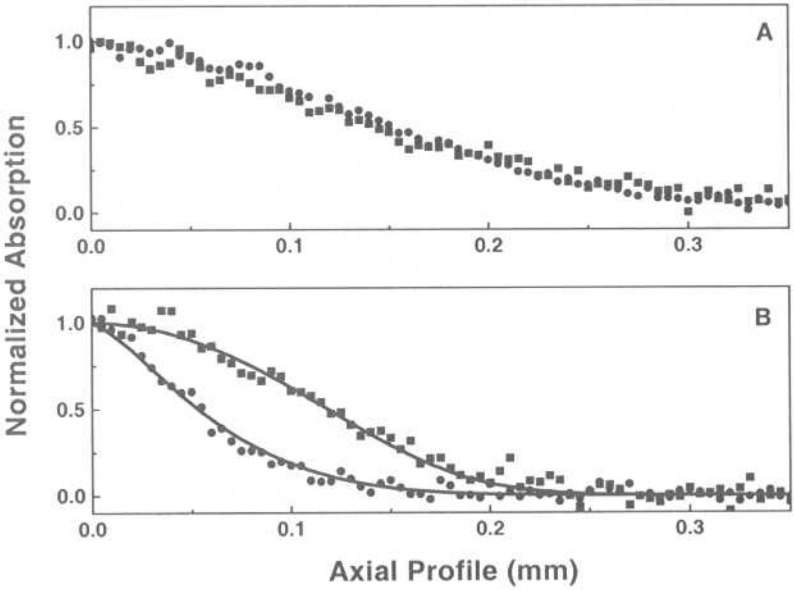

Figure 1. Axial profiles obtained from absorption images. The squares correspond to ^{6}Li, and the circles to ^{7}Li. (A) T = 810 nK, corresponding to T/T_F = 1.0 for the fermions and T/T_c = 1.5 for the bosons. (B) T = 240 nK, corresponding to T/T_F = 0.25 and T/T_c = 1.0. The fits to the data are shown as solid lines. (Reprinted from Ref. [2]).

4 Discussion

In the current experiment, ^{6}Li in the F = 3/2, m_F = 3/2 state is sympathetically cooled by allowing it to thermalize with evaporatively cooled ^{7}Li in the F = 2, m_F = 2 state. We found that it was not possible to cool below ~0.25 T_F with this method. We believe that this is a fundamental limit of sympathetic cooling of fermions with bosons. For sympathetic cooling to work, the heat capacity of the evaporatively cooled gas, the bosons in this case, must exceed that of the sympathetically cooled gas [2]. For a quantum degenerate Fermi gas, the heat capacity $C_F \approx \pi^2 N_F k_B (T/T_F)$ [15]. For a harmonically confined Bose gas at the critical temperature T_c for Bose-Einstein condensation, the heat capacity $C_B \approx 10.86\, N_B\, k_B$, where N_B is the number of bosons [16]. By equating these heat capacities, we find that $C_B > C_F$, only for $T/T_F > 0.3$ [2]. The key aspect of this argument is that the heat capacity of the bosons takes the value at T_c. This is clearly true for bosons with attractive

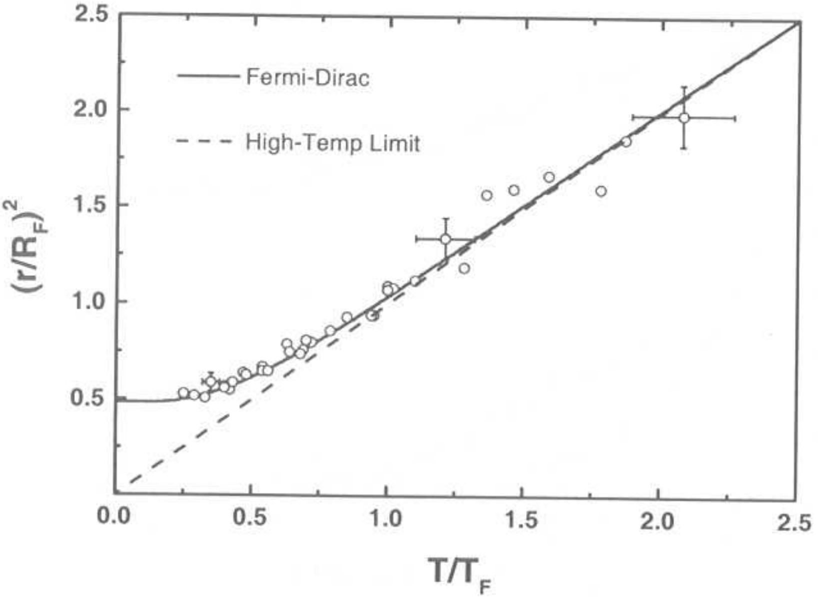

Figure 2. Square of the 1/e axial radius vs. T/T_F. The radius is normalized by $R_F = (2k_BT_F/m\omega_a^2)^{1/2}$, where ω_a is the axial trap frequency, and m is the atomic mass of ^{6}Li. The solid line is the prediction for an ideal Fermi gas, whereas the dashed line is the high-temperature limit. The divergence of the data from the classical prediction is the result of Fermi pressure. Several representative errors bars are shown. (Reprinted from Ref. [2]).

interactions, as for the F = 2, m_F = 2 state of ^{7}Li. In this case, the condensate number is limited to values much less than N_B, and T is therefore restricted to values only incrementally below T_c. Although not as obvious, the same restriction on C_B also applies to condensates with repulsive interactions. Only the thermal atoms in a Bose gas contribute to the heat capacity as the condensate itself has none. Therefore, below T_c, the total heat capacity is the heat capacity of the gas at T_c, 10.86 N_c k_B, where N_c is the critical number at temperature T. Again, the same limit on sympathetic cooling, $T/T_F > 0.3$, is found. There are several possible ways to achieve lower temperatures, but the most straightforward is simply to evaporate both isotopes simultaneously, so that C_F is lowered at the same rate as C_B.

A strong, attractive interaction in a two spin-state gas will be required to induce *s*-wave Cooper pairing. The best candidate states for ^{6}Li seem to be the energetically lowest pair of Zeeman sublevels, the F = ½, m_F = ½ and the F = ½, m_F = -½ states. These states are predicted to exhibit an enormous Feshbach resonance, for which the interaction may be arbitrarily tuned [6]. Because these states are energetically the lowest states, there are no open two-body inelastic collision channels. Furthermore, three-body recombination should also be suppressed, since there is no way to produce a totally anti-symmetric three-body state from a gas with only two-spin states.

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