A Bose-Einstein condensate immersed in a Fermi sea: observation of degenerate mixture of dilute atomic Bose and Fermi gases

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Abstract

We report the formation mixtures of bosonic and fermionic quantum systems in a dilute atomic gases. Two isotopes of lithium are cooled by standard laser cooling techniques and transferred into a magnetic trap. Evaporative cooling is performed selectively on the bosonic isotope (^{7}Li), while its fermionic counterpart (^{6}Li) is cooled sympathetically until simultaneous quantum degeneracy is reached. The ^{7}Li Bose-Einstein condensate contains a very small fraction of thermal atoms and is in thermal equilibrium with ^{6}Li Fermi sea at a temperature of 1/5 of the Fermi temperature.

Key words: Fermi Degenerate gas; Bose-Einstein condensation

1. Introduction

Bose-Einstein condensation (BEC) in dilute atomic gases, first demonstrated in 1995 in a series of remarkable experiments [1], has become a very active field of research in recent years. Numerous experimental manifestation of this macroscopic quantum phenomenon has been observed. BEC provided a direct testing of many-body theories which were developed long time ago and waited for the experimental demonstrations. Atomic Fermi gases are also rising great interest, especially because of the link that can be made with the behavior of electrons in metals and semiconductors, and the possibility of Cooper pairing such as in superconductors and neutron stars.

A breakthrough for the observation of BEC in dilute gases was the combination of laser cooling techniques [2] with forced evaporation cooling [3]. These techniques however are not universal. Although laser cooling works well for some atomic Fermi gases, evaporative cooling fails to work at low temperatures. The last relies on elastic binary collisions to establish thermal equilibrium after selective removal of the most energetic atoms. At low temperatures, scattering through partial waves other than s-wave vanished [4] and s-wave collisions are prohibited between two identical fermions because of Fermi-Dirac statistics. Therefore, to cool Fermi gases, number of groups have adopted the sympathetic cooling technique where a buffer gas is used to cool fermionic species via elastic collisions. This technique was first proposed for two-component plasmas [5] and used for cooling ions confined in electromagnetic traps and more recently, to cool atoms and molecules via cryogenically cooled helium [6].

Sympathetic cooling of fermionic species below the Fermi temperature ($T_{\rm F}$) was demonstrated on two distinct spin states of ^{40}K atoms both of which were evaporatively cooled [7]. Earlier, similar sympathetic cooling using bosonic ^{87}Rb atoms in two different internal states had led to the production of two overlapping BECs [8]. Fermionic isotope of lithium (^{6}Li) was cooled sympathetically by thermal contact with evaporatively cooled bosonic isotope (^{7}Li) [9],[10]. Recently, ^{6}Li was cooled by bosonic ^{23}Na [11] and ^{40}K by ^{87}Rb [12]. Finally, two spin states of ^{6}Li atoms were cooled to quantum degeneracy in an optical trap [13].

Here we describe our experiments on sympathetic cooling of ^{6}Li atoms well into the quantum degenerate regime [10]. We demonstrated the formation of a

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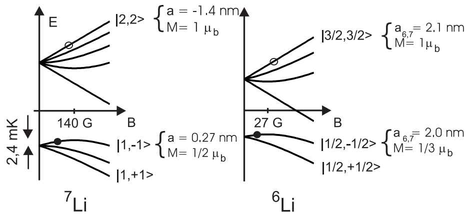

Fig. 1. Energy levels of ^{7}Li and ^{6}Li ground states in a magnetic field. Relevant scattering length, a, and magnetic moments M are given. The ^{7}Li $|F = 1, m_F = -1\rangle$ (^{6}Li $|F = 1/2, m_F = -1/2\rangle$) is trapped only in fields weaker than 140 G (27 G). Open circles: experiments on upper HF states (section 2); black circles: experiments on lower HF states (section 3).

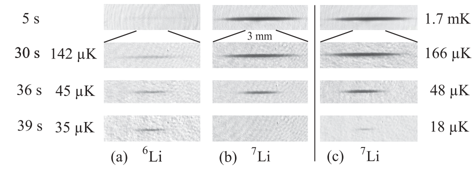

Fig. 2. Images of ^{6}Li and ^{7}Li atom clouds at various stages of sympathetic cooling (a),(b) and single-species evaporation (c) with identical initial numbers of ^{7}Li atoms. Top images are 1 cm long, the others are 3 mm. Tempeatures of ^{6}Li (^{7}Li) are given on the left (right).

new mixture of bosonic and fermionic system which can draw similarities with previously known ^{4}He-^{3}He system [14].

All previous experiments performed with ^{7}Li in internal state $|F = 2, m_F = 2\rangle$ had condensate numbers limited to $N \leq 1400$ and temperatures limited to the critical temperature (T_C) because of the negative scattering length in this state, which means effective attractive interactions between atoms (fig. 1) [15]. However, the scattering length in the internal state $|F = 1, m_F = -1\rangle$ is positive (repulsive interactions) and therefore allows a stable BEC with large atom numbers. Lower temperatures and ultimately, a mixture of nearly pure BEC immersed in a Fermi sea can be observed.

With standard laser cooling technique, a mixture of ^{6}Li and ^{7}Li is cooled to a temperature of about 2 mK and is loaded into a strongly confined magnetic trap. As depicted in fig. 1, this relatively high temperature precludes direct magnetic trapping of the atoms in their lower hyperfine (HF) state because of the shallow magnetic trap depth, 2.4 mK for ^{7}Li in $|F = 1, m_F = -1\rangle$ and 0.2 mK for ^{6}Li in $|F = 1/2, m_F = -1/2\rangle$. Therefore we proceed in two steps. Both isotopes are first cooled in their upper HF states for which the trap depth can be large (Section 2). Then atoms are transferred in their lower HF states and the cooling is resumed (Section 3).

2. Experiments with higher HF states

In the first series of experiments both Li isotopes are trapped in their higher HF states. ^{6}Li ($|F = 3/2, m_F = 3/2\rangle$) is sympathetically cooled to Fermi degeneracy by performing evaporative cooling on ^{7}Li ($|F = 2, m_F = 2\rangle$) [16]. The images recorded at various stages of the evaporation ramp are shown in fig. 2 for mixtures ((a) and (b)) and for ^{7}Li alone with identical initial number (c). In (a) the optical density of the 6Li cloud is seen to increase considerably because of the reduction in size without apparent loss of atoms, a signature of sympathetic cooling. Comparison of the cloud sizes between (a) and (b) indicate that ^{6}Li and ^{7}Li are in thermal equilibrium, except for the end of the evaporation. Here the absence of ^{7}Li indicates that between 36 s and 39 s, the numbers of ^{6}Li and ^{7}Li have become equal. Beyond this point, the temperature of ^{6}Li no longer decreases significantly. The thermal capacity of ^{6}Li soon exceeds that of ^{7}Li, resulting in heating and loss of ^{7}Li during the final stage of the evaporation (b). Under the same conditions but without ^{6}Li, normal evaporative cooling of ^{7}Li proceeds to a smaller temperatures (c).

By reducing the initial number of ^{6}Li atoms we were able to further push sympathetic cooling into the quantum degeneracy regime [10]. Typical absorption images are shown in fig.3. Here the temperature T is $1.4(1)\,\mu$K and $T/T_F = 0.33(5)$ where the Fermi temperature T_F is $(\hbar\bar{\omega}/k_B)(6N)^{1/3}$, with $\bar{\omega}$ the geometric mean of the three oscillation frequencies in the trap and N the number of fermions. On these images recorded in the magnetic trap, the common temperature is measured from the spatial extent of the bosonic cloud in the axial direction since the shape of the Fermi cloud is much less sensitive to temperature changes when $T/T_F < 1$ [17]. The two isotopes experience the same trapping potential. Thus the striking difference between the sizes of the Fermi and Bose gases is a direct consequence of Fermi pressure (see also [9]). The measured axial profiles in fig. 3 are in excellent agreement with the calculated ones (solid lines) for a Bose distribution at T_C.

Our highest Fermi degeneracy in the ^{6}Li $F = 3/2$ state is $T/T_F = 0.25(5)$ with $T_F = 4\mu K$, very similar to the results obtained in ref.[9]. We observed that the boson temperature cannot be lowered below T_C. For our trap parameters the number of ^{7}Li condensed atoms cannot exceed about ~ 300, because of the negative scattering length [15]. Since sympathetic cooling stops when approximately equal heat capacity is reached for bosons and fermions, this limits the obtainable Fermi degeneracy to about 0.3.

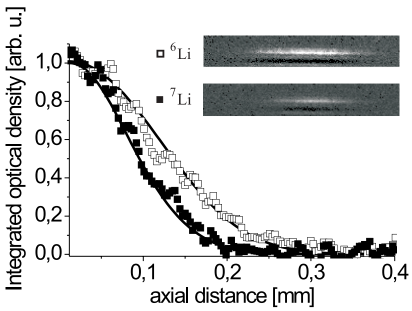

Fig. 3. Observation of Fermi pressure. Images in the trap and spatial profiles of $8.1\,10^4$ ^{6}Li and $2.7\,10^4$ ^{7}Li atoms are shown. Solid lines are the expected Bose and Fermi distributions.

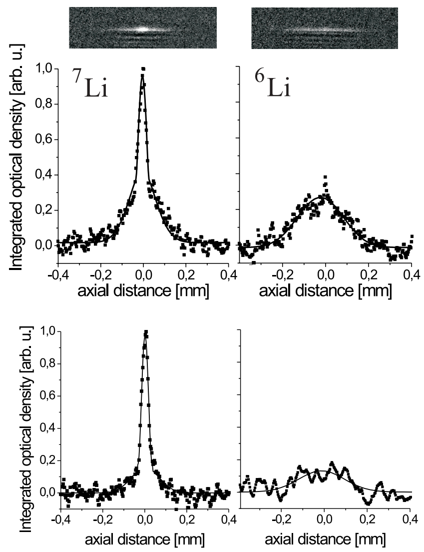

Fig. 4. Mixture of Bose and Fermi gases. Top: Images and spatial distributions of $3.5\,10^4$ ^{7}Li and $2.5\,10^4$ ^{6}Li. The common temperature $T = 1.6\mu$K$= 0.87T_{\rm C} = 0.57T_{\rm F}$ is determined from the thermal cloud which surrounds the BEC. Bottom: profiles with nearly pure condensate with 10^4 ^{7}Li and $4\,10^3$ ^{6}Li. The barely detectable thermal cloud indicates a temperature of $T = 0.28\mu$K$= 0.2T_{\rm C} = 0.2T_{\rm F}$.

3. Experiments with lower HF states

In order to produce a mixture of gases well into the quantum degenerate regime, we have, in a second step, transferred both isotopes in their lower HF state, where the ^{7}Li scattering length is positive. Avoiding large dipolar relaxation requires ^{6}Li to be also in its lower HF state [18]. When both isotopes are cooled to a common temperature of about 10 μK, atoms are transferred using microwave and RF pulses in states $|F = 1, m_F = -1\rangle$ and $|F = 1/2, m_F = -1/2\rangle$ with an energy far below their respective trap depths (fig.1). Evaporative cooling is then performed on one or two of the species until the BEC threshold is reached for ^{7}Li [10].

In fig. 4 typical in-situ absorption images of bosons and fermions at the end of the evaporation are shown. The bosonic distribution shows the typical double structure: a strong and narrow peak form the condensate in the center surrounded by a much broader distribution, the thermal cloud. As the Fermi distribution is very insensitive to temperature, this thermal cloud is a very useful tool for the determination of the common temperature. In fig. 4(top), the temperature is just below T_C, $T = 1.6\mu$K$= 0.87T_C = 0.57T_F$. In fig. 4(bottom), the condensate is quasipure; the thermal fraction is near our detectivity limit, indicating a temperature $T = 0.28\mu$K$\leq 0.2T_C = 0.2(1)T_F$ with 10^4 bosons and $4\,10^3$ fermions. We have also obtained samples colder than those presented in fig. 4 for which the ^{7}Li thermal fraction is below our detectivity floor. A more sensitive thermal probe is required to investigate this temperature domain. An elegant method relies on the measurement of thermalization rates with impurity atoms [19].

4. Conclusions

In summary, we have produced a new mixture of Bose and Fermi quantum gases. Analysis of the temperature limits of this BEC-Fermi gas cooling scheme can be further explored in such a mixture. First, boson-fermion mean field interactions can induce a spatial phase separation between the components, preventing their thermal contact [20]. For the parameters of fig. 4 we estimate that the density of fermions is only slightly modified. To observe such a phase separation, a Feshbach resonance between ^{6}Li and ^{7}Li can be used which was predicted theoretically in ref. [18]. This resonance should allow accurate tuning of the interactions and even changing of their sign. Second, because of the superfluidity of the condensate, impurity atoms (fermions), which move through the BEC slower than the sound velocity, are no longer scattered. In this case, fermions can serve as a probe of superfluidity of the condensate. For our parameters this effect was estimated to play no role [10].

The large effective attractive interaction between two spin sublelvels of ^{6}Li atoms in their lower HF state makes this atom an attractive candidate for searcing for BCS pairing at lower temperatures [21].

Acknowledgements

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