Fiftyfold Improvement in the Number of Quantum Degenerate Fermionic Atoms

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We have produced a quantum degenerate ^{6}Li Fermi gas with up to 7×10^7 atoms, an improvement by a factor of 50 over all previous experiments with degenerate Fermi gases. This was achieved by sympathetic cooling with bosonic ^{23}Na in the $F = 2$, upper hyperfine ground state. We have also achieved Bose-Einstein condensation of $F = 2$ sodium atoms by direct evaporation.

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Over the last few years, there has been significant progress in the production of quantum degenerate atomic Fermi gases (^{40}K [1,2] and ^{6}Li [3–6]) and degenerate Bose-Fermi mixtures (^{7}Li-^{6}Li [3,4], ^{23}Na-^{6}Li [6], and ^{87}Rb-^{40}K [2]). These systems offer great promise for studies of new, interaction-driven quantum phenomena. The ultimate goal is the attainment of novel regimes of BCS-like superfluidity in a gaseous system [7–11]. The current efforts to induce and study strong interactions in a Fermi gas [12–21] are complemented with the ongoing efforts to improve fermion cooling methods, which would lead to lower temperatures and larger samples.

The main reason why studies of degenerate Fermi gases are still lagging behind the studies of atomic Bose-Einstein condensates (BECs) is the complexity of cooling methods. The Pauli exclusion principle prohibits elastic collisions between identical fermions at ultralow temperatures and makes evaporative cooling of spin-polarized fermionic samples impossible. For this reason, cooling of fermions must rely on some form of mutual or sympathetic cooling between two types of distinguishable particles, either two spin states of the same atom [1,5] or two different atoms [2–4,6]. A key element in fermion cooling is the design of better ''refrigerators'' for sympathetic cooling.

In this Letter, we report the first production of degenerate Fermi samples comparable in size with the largest alkali BECs [22]. We successfully cooled up to 7×10^7 magnetically trapped ^{6}Li atoms to below half the Fermi temperature (T_F). This is an improvement in atom number by a factor of 50 over the largest previously reported Fermi sea [21]. Further, in samples containing up to 3×10^7 atoms, we observed temperatures as low as $0.05\,T_F$, the lowest ever achieved. At these temperatures, the fractional occupation of the lowest energy state differs from unity by less than 10^{-8}.

As in our previous work [6], ^{6}Li atoms were magnetically trapped in the $F = 3/2$, upper hyperfine ground state, and sympathetically cooled by bosonic ^{23}Na. The crucial improvement was our achievement of forced evaporation of sodium in the $|F, m_F\rangle = |2, +2\rangle$, upper hyperfine ground state, producing large and stable BECs with up to 10^7 atoms. This allowed us to create a magnetically trapped ^{23}Na-^{6}Li, Bose-Fermi mixture which is stable against spin-exchange collisions at all densities, and dramatically boosted our fermion atom number.

The criteria for designing sympathetic cooling experiments include the heat capacity of the refrigerator, and the interspecies collisional properties, both elastic and inelastic [23]. Large and stable ^{23}Na condensates are an appealing choice for sympathetic cooling of fermions. Further, a favorable mass ratio allows for simultaneous Zeeman slowing of ^{23}Na and ^{6}Li [6], and for simultaneous magnetic trapping without large differences in the gravitational sag. The interspecies collisional properties are generally not predictable and have to be tested experimentally. In order to minimize all possible inelastic processes, the natural choice is to magnetically trap both species in their lower hyperfine ground states. However, at temperatures reachable by laser cooling ($\geq 300\ \mu$K), ^{6}Li can be efficiently magnetically trapped only in the upper hyperfine state, $F = 3/2$ [4,6] [Fig. 1(a)]. On the other hand, until now sodium had been successfully evaporated only in the lower, $F = 1$ hyperfine state. This was a limiting factor for sympathetic cooling of ^{6}Li, since the mixture of sodium in the lower, and lithium in the upper hyperfine state is not stable against spin-exchange collisions. The inelastic loss rate increases as the temperature is lowered and the density grows. In our previous work [6], we partially overcame this problem by transferring lithium atoms into the lower hyperfine state after an initial sympathetic cooling stage to $\sim 50\ \mu$K. By achieving forced evaporative cooling and Bose-Einstein condensation of sodium in the $F = 2$ state, we have now realized a more robust sympathetic cooling strategy and dramatically improved the size and temperature of a degenerate Fermi system.

We loaded $\sim 3 \times 10^9$ sodium and up to 10^8 lithium atoms in their upper hyperfine states from a two-species magneto-optical trap (MOT) into the magnetic trap. The adverse effect of light assisted collisions in a two-species MOT [6,24] was minimized by slightly displacing the two MOTs with respect to each other. This was achieved in a reproducible manner by aligning both MOTs to the

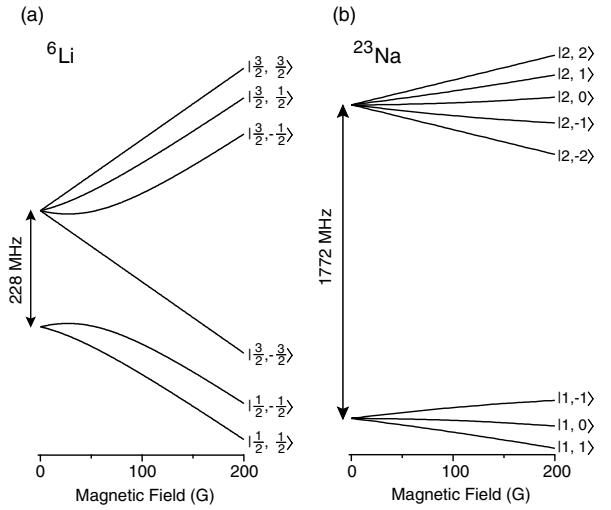

FIG. 1. Hyperfine structures of ^{6}Li and ^{23}Na. The states are labeled in the low field, $|F, m_F\rangle$ basis. (a) Because of finite trap depth of $\sim k_B \times 300\ \mu$K in the $|1/2, -1/2\rangle$ state, lithium can be efficiently loaded into the magnetic trap only in the upper, $F = 3/2$ hyperfine state. (b) Sodium is magnetically trappable in the $|1, -1\rangle$ and in the $|F = 2, m_F \geq 0\rangle$ states. Previously, sodium had been evaporatively cooled to BEC only in the $|1, -1\rangle$, lower hyperfine state.

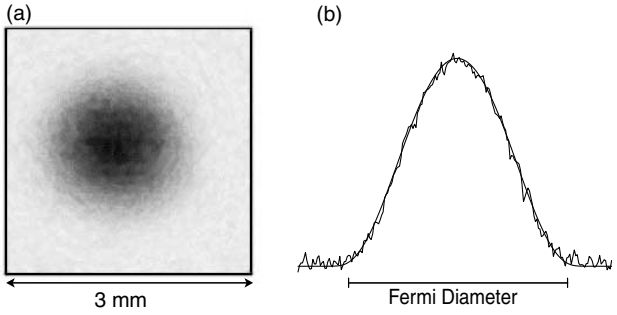

FIG. 2. Large and ultradegenerate Fermi sea. (a) Absorption image of 3×10^7 ^{6}Li atoms released from the trap and imaged after 12 ms of free expansion. (b) Axial (vertical) line density profile of the cloud in (a). A semiclassical fit (thin line) yields a temperature $T = 93$ nK $= 0.05 T_F$. At this temperature, the high energy wings of the cloud do not extend visibly beyond the Fermi energy, indicated in the figure by the momentum-space Fermi diameter.

zero of the magnetic field and then changing the balance of the ^{6}Li laser beams along one direction. The lithium MOT was thus displaced by 3–5 mm, comparable to the radius of the sodium cloud.

During the typical 30 s of sympathetic cooling, we observed no significant inelastic loss of lithium atoms (by three-body collisions or dipolar relaxation), the final number of degenerate atoms being at least half of the number initially loaded in the trap. On the other hand, we observed a favorable rate of elastic collisions between the two species, with the interspecies thermalization time being shorter than 1 s. Therefore, sodium atoms in the upper hyperfine state have ideal properties as a refrigerant for ^{6}Li.

Since our primary interest was cooling of fermions, we evaporated all sodium atoms in order to get lithium to the lowest possible temperatures. Even in our largest ^{6}Li samples, of $\sim 7 \times 10^7$ atoms, we achieved temperatures below $0.5 T_F$. Temperatures in the range 0.05–$0.2 T_F$ could be achieved by reducing the ^{6}Li atom numbers only slightly, to $\sim 3 \times 10^7$. Such big clouds had a high enough optical density for crisp absorption imaging even after ballistic expansion to a size larger than 1 mm [Fig. 2(a)].

Temperatures were extracted from the absorption images of expanding clouds released from the trap, using a semiclassical (Thomas-Fermi) fit to the Fermi-Dirac momentum distribution [6,25] [Fig. 2(b)]. In the ultradegenerate limit, the Fermi distribution is only weakly sensitive to the temperature. While the statistical uncertainty of our fits was generally very small, we have found that the fits along the axial and the radial direction of the cloud can yield slightly different temperatures. Using this discrepancy as the dominant source of uncertainty, we estimate the temperature of our coldest samples to be $0.05^{+0.03}_{-0.02} T_F$.

At present, it is not clear what are the fundamental limits of our sympathetic cooling strategy. One potential limitation could arise from the superfluid nature of the BEC, which prevents further cooling of fermions with velocities lower than the speed of sound in the condensate [23,26]. However, in our large ^{6}Li samples, the Fermi velocity, $\sqrt{2 k_B T_F / m}$, greatly exceeds the typical sound velocity in the largest ^{23}Na BECs. Further, when the sympathetic cooling was optimized to produce the largest and the coldest ^{6}Li samples, the ^{23}Na cloud remained thermal at all times. Therefore, we do not expect the superfluidity of bosons to be a limiting factor.

We have also produced stable degenerate Bose-Fermi mixtures, with more than 10^6 atoms in each species (Fig. 3). In typical samples, the peak density of ^{6}Li was $n_{\mathrm{Li}} \sim 3 \times 10^{12}$ cm^{-3}, while peak densities of the thermal and the condensed ^{23}Na components were $n_{\mathrm{Na}}^{\mathrm{th}} \sim 7 \times 10^{12}$ cm^{-3} and $n_{\mathrm{Na}}^{\mathrm{BEC}} \sim 5 \times 10^{13}$ cm^{-3}. At these densities, the mixture had a lifetime of several seconds. This observation could be used to estimate upper limits for the rate constants of various two- and three-body inelastic processes in the mixture.

In the rest of the Letter, we summarize the numerous steps which were introduced to prepare sodium in the $F = 2$ state as a refrigerant.

In contrast to ^{87}Rb, condensation of sodium by evaporative cooling was previously achieved only in the lower, $|1, -1\rangle$ hyperfine state. $F = 2$ sodium condensates could thus be studied only by transferring optically trapped $F = 1$ BECs into this state [27,28]. Condensation in the upper hyperfine state of sodium is more difficult than in the lower state for two reasons: (1) the requirement for efficient optical pumping in dense laser-cooled samples,

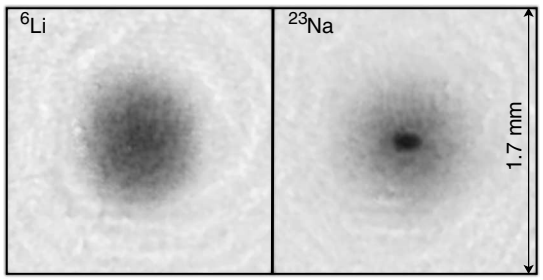

FIG. 3. Two-species mixture of degenerate Bose and Fermi gases. After release from the magnetic trap, both ^{6}Li and ^{23}Na clouds were imaged onto the same camera using separate light pulses. The times of free expansion of the two gases could be varied independently. This dual-imaging technique allowed for optimizing the cooling strategy for either single- or two-species experiments. For the displayed image, the expansion times were $t_{\mathrm{Li}} = 8$ ms and $t_{\mathrm{Na}} = 25$ ms, and the atom numbers were $N_{\mathrm{Li}} \sim 10^7$ and $N_{\mathrm{Na}} \sim 6 \times 10^6$. Sodium was cooled below the condensation temperature, corresponding to $\sim 0.2 T_F$ for the lithium cloud.

and (2) an order of magnitude higher three-body loss rate coefficient [27].

The basic setup of our experiment is described in [6]. In 10 s, we collected typically $\sim 10^{10}$ ^{23}Na atoms, and $\sim 10^8$ ^{6}Li atoms in a magneto-optical trap. Typical MOT temperatures were 0.7–1 mK. Sodium was collected in a dark spontaneous-force optical trap (SPOT) variant of the MOT [29], and therefore most of the atoms were in the $F = 1$ hyperfine state. Lithium was collected in a standard MOT, with about 2/3 of the atoms in the $F = 3/2$ state.

Before the transfer into the magnetic trap, the atoms were optically pumped into the stretched hyperfine ground states, $|2, +2\rangle$ for ^{23}Na, and $|3/2, +3/2\rangle$ for ^{6}Li. A magnetic guide field of 3 G was applied, and the atoms were optically pumped for 2 ms, using σ^+ polarized light tuned to the D_2 transitions. The intensities of the pumping laser beams were about 0.1 mW/cm^2. To achieve both F (hyperfine) and m_F (Zeeman) pumping, two light beams were used for each species.

In the case of lithium, the excited state hyperfine structure is not resolved, and the two laser beams were simply tuned in resonance with the $F = 1/2$ and the $F = 3/2$ ground state manifolds. In the case of sodium, we explored the efficiency of optical pumping using transitions to different excited hyperfine states F'. We observed the most efficient transfer into the magnetic trap if the $F = 1 \rightarrow F' = 1$ transition was used for hyperfine pumping, even though Clebsch-Gordan coefficients favor the $F = 1 \rightarrow F' = 2$ transition for more efficient pumping. Zeeman pumping of sodium was done on the $F = 2 \rightarrow F' = 2$ transition, in order to make $|2, +2\rangle$ a dark state and avoid unnecessary heating of the sample.

In this way, almost all the lithium atoms could be pumped into the $|3/2, +3/2\rangle$ state. On the other hand, the density of sodium atoms in the dark SPOT is $\geq 10^{11}$ cm^{-3}, and Zeeman pumping is notoriously difficult at such high densities. In our experiments, the fraction of atoms pumped into the $|2, +2\rangle$ state was limited to about 30%, with most of the remaining atoms distributed among the other m_F sublevels of the $F = 2$ manifold.

After the optical pumping stage, the atoms were loaded into a Ioffe-Pritchard magnetic trap with a radial gradient of 164 G/cm and axial curvature of 185 G/cm^2. Sodium atoms in all three $|F = 2, m_F \geq 0\rangle$ states are, at least weakly, magnetically trappable [Fig. 1(b)]. However, only pure $|2, +2\rangle$ samples are stable against inelastic spin-exchange collisions. A crucial step in preparing the samples for efficient forced evaporation was to actively remove $|F = 2, m_F = 0, +1\rangle$ atoms from the trap, before they engaged in inelastic collisions with the $|2, +2\rangle$ atoms. The atoms were loaded into a weak magnetic trap, with a high bias field of 80 G. This field splits the $F = 2$ Zeeman sublevels by $\sim k_B \times 2.8$ mK. Since this splitting was larger than the temperature of the cloud, the different states could be resolved in microwave or rf spectroscopy, and the $|F = 2, m_F = 0, +1\rangle$ atoms could be selectively transferred to the untrapped $|F = 1, m_F = 0, +1\rangle$ lower hyperfine states. This transfer was done with a microwave sweep near the ^{23}Na hyperfine splitting of 1.77 GHz. In this way, all the $|2, +2\rangle$ atoms initially loaded into trap could be preserved. We were also able to load some of the untrapped atoms produced during the sweep by optically pumping them out of the $F = 1$ ground states, thus giving them a second chance to fall into the $|2, +2\rangle$ state. The final setup consisted of two microwave sweeps, the first of 0.8 s duration with the optical pumping light on, and the second of 2.4 s duration without the light. In this way, the overall transfer efficiency from the MOT to the magnetic trap was improved to about 35%, comparable to our standard $F = 1$ BEC experiments [30].

After this purification of the $|2, +2\rangle$ sample, the magnetic trap was tightened by reducing the bias field to 3.8 G in 2.4 s. Resulting trapping frequencies were 204 Hz (400 Hz) radially and 34 Hz (67 Hz) axially for the sodium (lithium) stretched state. This provided good conditions for forced runaway evaporation of sodium. Evaporation was done on the $|2, +2\rangle \rightarrow |1, +1\rangle$ microwave transition near 1.77 GHz. In contrast to radio-frequency evaporation, this ensured that ^{6}Li was far off resonance. Further, microwave evaporation avoided any undesirable aspects of incomplete evaporation into the $|F = 2, m_F = 0, +1\rangle$ states, which could lead to inelastic losses [31].

After 15 s of evaporation, the sodium atoms reached a temperature of $T \sim 10$ μK. At this point, to avoid three-body losses in the $|2, +2\rangle$ state [27], the trap was weakened to frequencies of 49 Hz (96 Hz) radially, and 18 Hz (35 Hz) axially for sodium (lithium). The final evaporation to BEC took another 15 s. In this way, in the absence

of lithium atoms, we could produce almost pure $|2, +2\rangle$ BECs containing up to 10^7 atoms. The lifetime of the BEC in the weak trap was longer than 3 s. In contrast to our previous work [27,28], studies of $F = 2$ condensates are now possible without the added complexity of an optical trap.

In conclusion, by creating a superior refrigerant for sympathetic cooling of ^{6}Li, we have produced the coldest and the largest quantum degenerate Fermi gas so far. The atom numbers in our samples are comparable with the largest alkali BECs, and the temperatures are reaching the current practical detection limit. In analogy with Bose-Einstein condensates, we expect these large samples to ensure a sufficient signal-to-noise ratio for all the standard techniques of BEC research, such as velocimetry using long expansion times, rf spectroscopy with Stern-Gerlach separation during ballistic expansion, direct nondestructive imaging of the trapped clouds, and Bragg spectroscopy. The next challenge is to maintain a similar combination of number and temperature for an interacting two-component Fermi gas [20].

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Note added.—Very recently, a similar number of ^{6}Li atoms were cooled into quantum degeneracy using sympathetic cooling with ^{7}Li [32].

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