# Two-Species Mixture of Quantum Degenerate Bose and Fermi Gases

Z. Hadzibabic, C. A. Stan, K. Dieckmann, S. Gupta, M. W. Zwierlein, A. Görlitz,* and W. Ketterle

*Department of Physics, MIT-Harvard Center for Ultracold Atoms, and Research Laboratory of Electronics, MIT, Cambridge, Massachusetts 02139*

(Received 26 December 2001; published 4 April 2002)

We have produced a macroscopic quantum system in which a $^6$Li Fermi sea coexists with a large and stable $^{23}$Na Bose-Einstein condensate. This was accomplished using interspecies sympathetic cooling of fermionic $^6$Li in a thermal bath of bosonic $^{23}$Na. The system features rapid thermalization and long lifetimes.

DOI: 10.1103/PhysRevLett.88.160401 PACS numbers: 05.30.Fk, 32.80.Pj, 39.10.+j, 67.60.–g

Experimental methods of laser and evaporative cooling, used in the production of atomic Bose-Einstein condensates (BEC) [1], have recently been extended to realize quantum degeneracy in trapped Fermi gases [2–5]. What makes gaseous fermionic systems particularly appealing to investigate is the relative ease with which their properties can be varied. This allows the exploration of a vast range of experimental regimes, from noninteracting to strongly correlated. In the first case, purely quantum statistical effects can be studied, such as the implications of Pauli exclusion on scattering properties of the system. In the other extreme, exciting new regimes of BCS-like fermionic superfluidity may be within reach [6–9]. An additional area of interest is the production of a dilute quantum degenerate mixture of Bose and Fermi gases, akin to the strongly interacting $^4$He-$^3$He liquid. This would extend the list of possible experimental studies even further, to include effects such as interaction-driven phase separation [10] or BEC-induced interactions between fermions.

In this Letter, we report the production of a new macroscopic quantum system, in which a degenerate $^6$Li Fermi gas coexists with a large and stable $^{23}$Na BEC. We have achieved high numbers of both fermions ($>10^5$) and bosons ($>10^6$), and $^6$Li quantum degeneracy characterized by a temperature of one-half the Fermi temperature ($T_F$). This provides us with the starting point for studies of the degenerate $^6$Li Fermi gas, which is regarded as a particularly promising candidate for the BCS transition [6,7]. Further, favorable collisional properties make the $^6$Li-$^{23}$Na system very promising for studies of the degenerate Bose-Fermi mixtures, including the limitations to the cooling process [11,12]. It is also worth noting that, in our experiment, a mixture of two different atomic species has been simultaneously brought into quantum degeneracy for the first time.

Our experimental approach is based on sympathetic cooling of fermions in a large bosonic "refrigerator." In contrast to the bosonic case, two-body elastic collisions are absent in a single-component Fermi gas at ultralow temperatures due to the Pauli exclusion principle. This lack of thermalization precludes direct implementation of forced evaporative cooling. Therefore, cooling of fermions into the quantum degenerate regime must rely on collisions between distinguishable atoms. In two experiments which produced degenerate Fermi gases, mixtures of two fermionic spin states were simultaneously evaporated and mutually cooled [2,5]. Two groups have also demonstrated sympathetic cooling of $^6$Li by the $^7$Li bosonic isotope, thus also producing the first quantum degenerate Bose-Fermi mixtures. However, this system has a limitation that, in the upper hyperfine state, the $^7$Li condensate is unstable [3], while scattering properties in the lower hyperfine state make sympathetic cooling inefficient, and limit the size of both $^6$Li and $^7$Li samples [4]. We have overcome both of these limitations by using a large $^{23}$Na cloud, instead of $^7$Li, for sympathetic cooling of $^6$Li. Our work provides the natural progression in the search for an ideal Bose-Fermi system, where a "good" Bose-Einstein condensate is chosen, and then combined with a favorable fermionic species. Similar two-species experiments are currently being pursued by three other groups [13–15]. Given the vast variety of collisional properties among alkali gases, and a limited choice of favorable Bose-Fermi combinations, the properties of the $^6$Li-$^{23}$Na mixture are truly fortuitous. In our experiment, we have observed rapid interspecies thermalization, while low rates for both intra- and interspecies inelastic collisions result in a lifetime longer than 10 s. Both the presence of sufficient "good" (elastic) collisions needed for interspecies thermalization and the slow rate of "bad" (inelastic) collisions could not be taken for granted before our studies.

For this experiment, we have upgraded our $^{23}$Na BEC apparatus [16] to allow for both lithium and sodium operation, while making minimal modifications to the original setup. The additional laser light needed for optical cooling of $^6$Li was generated by a low power, diode laser system [17]. The lithium (671 nm) and sodium (589 nm) laser beams were overlapped using dichroic beam-splitters, and the spatial arrangement of the laser and atomic beams used to trap, cool, and detect lithium was identical to the original sodium setup. Specifically, a two-species magneto-optical trap (MOT) was loaded from a single two-species atomic beam, slowed in the same Zeeman slower previously used

  

in sodium-only experiments. The fact that the maximum spontaneous light force deceleration is twice as large for $^6$Li as for $^{23}$Na allowed us to slow lithium atoms without compromising the slowing efficiency for sodium.

To implement our experimental strategy, we have developed a two-species oven in which the vapors of $^6$Li and $^{23}$Na were mixed, and a single atomic beam containing both species was produced (Fig. 1). The main difficulty in designing such an oven is that, at the same temperature, the vapor pressure of lithium is 3 orders of magnitude lower than that of sodium. To achieve comparable atomic fluxes of both species, the alkali vapors must be produced in separate chambers, and then delivered to a mixing chamber, at controllable rates. In our design, the lithium chamber was also used for mixing. To operate the oven in either single- or two-species mode, we tuned the atomic fluxes independently by changing the temperatures of the alkali reservoirs. The maximum atom fluxes into the solid angle subtended by the MOT region were $3 \times 10^{11}$ s$^{-1}$ for $^6$Li and $2 \times 10^{12}$ s$^{-1}$ for $^{23}$Na.

Under typical operating conditions, 5 s of loading resulted in single-species MOTs with $2 \times 10^7$ lithium atoms or $6 \times 10^9$ sodium atoms. When both MOTs were operated simultaneously, interspecies light-assisted collisions reduced the number of lithium atoms by a factor of about 4, while the sodium atom number was not noticeably affected. The number of $^6$Li atoms in the MOT was maximized when the trapping and the repumping light frequencies were tuned 25 MHz below the corresponding resonances. The resulting temperature of the lithium atoms was $\sim$700 $\mu$K.

Since the $^{23}$Na BEC is produced in the $|F, m_F\rangle = |1, -1\rangle$ lower hyperfine ground state, to avoid inelastic spin-exchange collisions, it is preferred to magnetically trap $^6$Li in the corresponding $|1/2, -1/2\rangle$ state. (Here, $F$ is the total angular momentum, and $m_F$ is its projection along the quantization axis.) However, the maximum magnetic trap depth in the $|1/2, -1/2\rangle$ state is only 330 $\mu$K (see Fig. 2), considerably lower than our MOT temperature. Further, due to the inefficiency of sub-Doppler cooling mechanisms, it is not possible to optically cool lithium to temperatures which would make magnetic trapping in this state efficient [17]. Therefore, to avoid drastic losses due to the limited trap depth, lithium atoms were optically pumped and then magnetically trapped in the $F = 3/2$ manifold. Before loading the magnetic trap, 4 ms were allowed for the sub-Doppler polarization gradient cooling of sodium, during which the lithium cloud was in free expansion. This reduced the transfer efficiency of lithium atoms into the trap by a factor of 2, limiting it to about 12%. We have thus magnetically trapped $\sim 6 \times 10^5$ $^6$Li atoms in the upper hyperfine state and $\sim 2 \times 10^9$ $^{23}$Na atoms in the lower one. At low energies, our cloverleaf magnetic trap is harmonic and axially symmetric. In the lower hyperfine states, the trapping frequencies for lithium (sodium) are $\omega_z = 2\pi \times 26$ (16) Hz axially and $\omega_r = 2\pi \times 354$ (221) Hz radially.

Once the atoms were loaded into the magnetic trap, we started the forced evaporative cooling of sodium [1]. A varying microwave field near 1.77 GHz was used to gradually lower the trap depth for $^{23}$Na, selectively transferring the most energetic atoms into the untrapped $|2, -2\rangle$ state. This microwave field does not affect the $^6$Li atoms, which were therefore not evaporated. Cooling of the lithium sample was instead achieved through thermal contact with sodium. We observed efficient sympathetic cooling of $^6$Li in the *upper* hyperfine state by $^{23}$Na in the *lower* one, and have successfully cooled this Bose-Fermi mixture into simultaneous quantum degeneracy. This observation indicates a surprisingly favorable ratio between

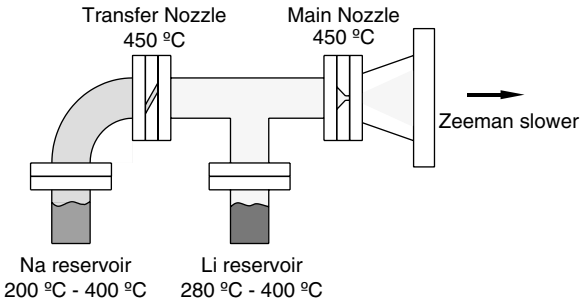


FIG. 1. Two-species oven. $^6$Li and $^{23}$Na vapors were produced in separate chambers to allow for independent control of the atom fluxes. The two species were mixed in the lithium chamber. The transfer nozzle has a conductance 40 times lower than the main nozzle, and limits the undesirable diffusion of lithium into the sodium chamber.

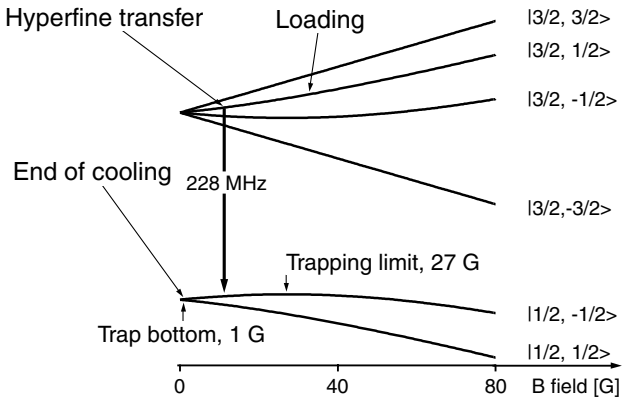


FIG. 2. $^6$Li in the magnetic trap. Ground state energy levels: The six hyperfine states are labeled in the low magnetic field, $|F, m_F\rangle$ basis. The $|1/2, -1/2\rangle$ state becomes strong field seeking for fields above 27 G, limiting the trap depth to 330 $\mu$K. Cooling path: Atoms in the $|3/2, 1/2\rangle$ upper hyperfine state were loaded into the magnetic trap at a temperature of 700 $\mu$K. After the initial cooling stage to 50 $\mu$K, the atoms were transferred to the $|1/2, -1/2\rangle$ state, and further cooled to a final temperature of 330 nK.

the good and bad interspecies collisions in this mixture. The losses due to inelastic spin-exchange collisions took place only on a time scale of several seconds, comparable to the total evaporation time of 15 s.

In order to produce a collisionally stable Bose-Fermi mixture, it is necessary to transfer the lithium atoms to the lower hyperfine state. To minimize the initial losses due to spin-exchange collisions, this transfer should take place as early in the cooling process as possible. On the other hand, before lithium atoms can be efficiently trapped in the lower hyperfine state, they must be cooled significantly below 330 $\mu$K. Therefore, we implemented sympathetic cooling in two stages (see Fig. 2). We optimized the initial evaporation stage to reach a temperature of $\sim 50$ $\mu$K in 5 s, while losing less than half of the lithium atoms, and maintaining the conditions for efficient sodium evaporation. At this point, we found that a substantial fraction of lithium atoms was in the $|3/2, 1/2\rangle$ state. They could thus be transferred to the $|1/2, -1/2\rangle$ state on a single-photon rf transition at 228 MHz, which is, to first order, independent of the magnetic field. This simplification over a similar hyperfine transfer previously employed in [4] was not expected. After the rf pulse was applied, the remaining $F = 3/2$ atoms were optically pumped into untrapped hyperfine states, and expelled from the trap. If this "cleanup" light pulse was omitted, spin-exchange collisions between lithium atoms in different hyperfine states led to a rapid loss of atoms from the trap [18]. The overall efficiency of our hyperfine transfer was $\sim 50\%$. The evaporation was then resumed for another 10 s. We observed efficient sympathetic cooling of the $|1/2, -1/2\rangle$ atoms, and cooled both gases into quantum degeneracy without observable losses in the lithium atom number.

Figure 3(a) displays the effect of sympathetic cooling on the $^6$Li cloud. Absorption images of the trapped $^6$Li gas were taken after the $^{23}$Na evaporation was terminated at different trap depths, and the sample was allowed to equilibrate for 1 s. Cooling (from top to bottom) is seen in the shrinking of the density distribution and an increase in the peak optical density. In contrast to standard evaporative cooling, and the mutual cooling between two Fermi species, the total number of atoms remains constant.

Quantitative analysis of the $^6$Li clouds is depicted in Fig. 3(b). We performed two-dimensional fits to the recorded column densities using both a simple Gaussian model and a semiclassical (Thomas-Fermi) distribution for trapped noninteracting fermions. In the latter approach, the probability that an atom has position $\vec{r}$ and momentum $\vec{p}$ is obtained from the Fermi-Dirac distribution for the total (kinetic and potential) energy of the particle. The fitting function for the spatial distribution of atoms in the trap is then obtained by integrating over the momentum degrees of freedom. While the Gaussian model gives a valid description of the gas only in the classical, high temperature limit, the Thomas-Fermi approach is valid at all temperatures, as long as the number of particles in the system is large [19]. Indeed, at higher temperatures, the two fits performed equally well, and yielded the same temperature. However, at a temperature of about 400 nK, the classical fits started to fail. This was indicated by the relative growth of the reduced $\chi^2$ values, by up to 20% above the corresponding values for the fermionic fits. For the coldest samples, Gaussian fits also overestimated the temperature by $\sim 15\%$. From the fitted number of atoms in the system ($N_{\mathrm{Li}} \sim 1.4 \times 10^5$, $T_F \approx 670$ nK), we found that the noticeable inadequacy of the classical fits occurred at $\sim 0.6\, T_F$, which is a clear signature of the Fermi degeneracy. Figure 3(b) shows projected line densities along the axial direction of the $^6$Li cloud and the Thomas-Fermi fits to the data. The arrow indicates the size of the Fermi diameter, $D_F = 2\sqrt{2k_B T_F/(m\omega_z^2)}$, for the fitted atom number. The spatial extent of the coldest cloud ($T \approx 330$ nK $\approx 0.5\, T_F$) is already comparable to the minimum size the system would assume at zero temperature. Typical densities of the coldest lithium samples were $\sim 10^{12}$ cm$^{-3}$.

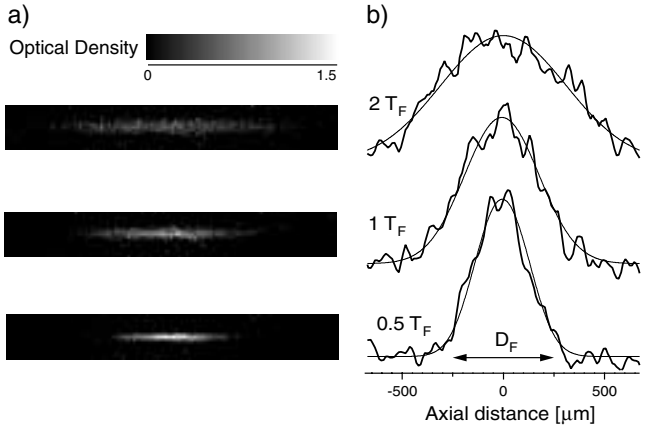


FIG. 3. Onset of Fermi degeneracy. Three pairs of images (top to bottom) correspond to $T/T_F = 2$, 1, and 0.5. (a) Column densities of the $^6$Li cloud were recorded by absorption imaging. (b) Axial line density profiles and the Thomas-Fermi fits to the data are plotted. The arrow indicates the size of the Fermi diameter, $D_F$.

In Fig. 4, the temperature of the $^6$Li cloud is plotted as a function of the final $^{23}$Na trap depth. The coldest lithium samples were produced in coexistence with almost pure sodium condensates with $\sim 2 \times 10^6$ atoms. The lifetime of this degenerate mixture was limited to about 10 s by the three-body decay of the BEC, while the lithium cloud had a lifetime longer than 100 s. The lifetime of either species was not detectably affected by the presence of the other one. Even after sodium was lost from the trap, the energy of the lithium cloud did not increase noticeably ($<5$ nK/s) during its slow decay. We also compared the $^6$Li temperatures with the temperatures of the $^{23}$Na cloud, extracted from the thermal wings of the bosonic density distribution. In hotter samples, the two agreed to within 10%. However, for the coldest samples we observed a discrepancy between the two temperatures. The lowest measurable temperature

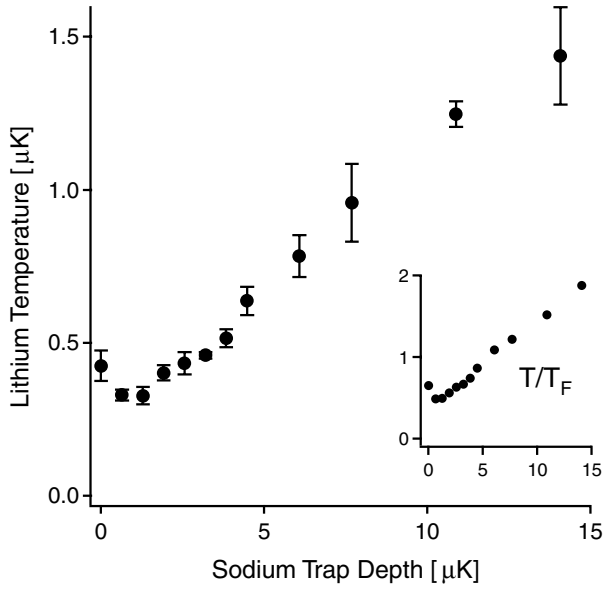


FIG. 4. Temperatures of the $^6$Li cloud as a function of the $^{23}$Na trap depth. Each data point is an average of three measurements. The error bars indicate the shot-to-shot fluctuations, while the uncertainties of the fits are comparable or smaller. In the case when sodium was completely evaporated from the trap (c.f. zero trap depth data point), the very last stage of sympathetic cooling became inefficient due to the vanishing heat capacity of the bosonic reservoir. The inset shows the same temperature data scaled to the Fermi temperature.

of sodium was $T \approx 170$ nK, about half the corresponding lithium value. We verified that, in these samples, extending the thermalization time at the end of evaporation up to 10 s did not lower the lithium temperature any farther. The reasons for the observed temperature discrepancy are worthy of further investigation. Simple spatial separation of the two clouds due to different gravitational sags can be readily ruled out. However, some form of phase separation of the two species [10], or constant heating of the fermionic cloud [12], could play a role.

In conclusion, we have produced a system in which a $^6$Li Fermi sea coexists with a $^{23}$Na BEC. This provides us with a starting point for studies of the degenerate Bose-Fermi mixtures. In particular, the observed temperature difference between the two spatially overlapped species might provide further insight into the limits of sympathetic cooling. Further, by loading the degenerate Fermi cloud into an optical trap, effects of magnetically tunable interactions between lithium atoms in different spin states can be studied [18]. A particularly appealing prospect is the observation of the BCS transition to a fermionic superfluid state, for which $^6$Li is a very promising candidate.

We thank Florian Schreck for useful discussions and Christian Schunck for experimental assistance. This research was supported by NSF, ONR, ARO, NASA, and the David and Lucile Packard Foundation. M. W. Z. acknowledges the support of the Studienstiftung des deutschen Volkes and the Ecole Normale Supérieure, Paris.

*Current address: Universität Stuttgart, 5. Phys. Inst., Stuttgart, Germany.

[1] *Bose-Einstein Condensation in Atomic Gases,* Proceedings of the International School of Physics "Enrico Fermi," Course CXL, edited by M. Inguscio, S. Stringari, and C. Wieman (IOS Press, Amsterdam, 1999).
[2] B. DeMarco and D. S. Jin, Science **285**, 1703 (1999).
[3] A. G. Truscott, K. E. Strecker, W. I. McAlexander, G. B. Partridge, and R. G. Hulet, Science **291**, 2570 (2001).
[4] F. Schreck, L. Khaykovich, K. L. Corwin, G. Ferrari, T. Bourdel, J. Cubizolles, and C. Salomon, Phys. Rev. Lett. **87**, 080403 (2001).
[5] S. R. Granade, M. Gehm, K. M. O'Hara, and J. E. Thomas, Phys. Rev. Lett. **88**, 120405 (2002).
[6] H. T. C. Stoof, M. Houbiers, C. A. Sackett, and R. G. Hulet, Phys. Rev. Lett. **76**, 10 (1996).
[7] M. Houbiers, R. Ferwerda, H. T. C. Stoof, W. I. McAlexander, C. A. Sackett, and R. G. Hulet, Phys. Rev. A **56**, 4864 (1997).
[8] M. A. Baranov and D. S. Petrov, Phys. Rev. A **58**, R801 (1998).
[9] M. Holland, S. J. J. M. F. Kokkelmans, M. L. Chiofalo, and R. Walser, Phys. Rev. Lett. **87**, 120406 (2001).
[10] K. Mølmer, Phys. Rev. Lett. **80**, 1804 (1998).
[11] E. Timmermans and R. Côté, Phys. Rev. Lett. **80**, 3419 (1998).
[12] E. Timmermans, Phys. Rev. Lett. **87**, 240403 (2001).
[13] J. Goldwin, S. B. Papp, B. DeMarco, and D. S. Jin, Phys. Rev. A **65**, 021402(R) (2002).
[14] G. Modugno, G. Ferrari, G. Roati, R. J. Brecha, A. Simoni, and M. Inguscio, Science **294**, 1320 (2001).
[15] M. Mudrich, S. Kraft, K. Singer, R. Grimm, A. Mosk, and M. Weidemüller, physics/0111213.
[16] M. O. Mewes, M. R. Andrews, N. J. van Druten, D. M. Kurn, D. S. Durfee, and W. Ketterle, Phys. Rev. Lett. **77**, 416 (1996).
[17] U. Schünemann, H. Engler, M. Zielonkowski, M. Weidemüller, and R. Grimm, Opt. Commun. **158**, 263 (1998).
[18] M. Houbiers, H. T. C. Stoof, W. I. McAlexander, and R. G. Hulet, Phys. Rev. A **57**, R1497 (1998).
[19] D. A. Butts and D. S. Rokhsar, Phys. Rev. A **55**, 4346 (1997).