Conversion of an Atomic Fermi Gas to a Long-Lived Molecular Bose Gas

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We have converted an ultracold Fermi gas of $^6$Li atoms into an ultracold gas of $^6$Li$_2$ molecules by
adiabatic passage through a Feshbach resonance. Approximately $1.5 \times 10^6$ molecules in the least-bound, $v = 38$, vibrational level of the $X^1\Sigma_g^+$ singlet state are produced with an efficiency of 50%.

The molecules remain confined in an optical trap for times of up to 1 s before we dissociate them by a reverse adiabatic sweep.

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Feshbach resonances have emerged as a major tool for altering the strength and sign of interactions in ultracold atomic gases. A Feshbach resonance is a collisional resonance between pairs of free atoms and a bound state of the diatomic molecule, for which differences between the atomic and molecular magnetic moments enable the resonance to be magnetically tuned. Molecules can be formed near a Feshbach resonance and have recently been detected in ultracold gases for fields close to a resonance. An adiabatic sweep of the magnetic field through the Feshbach resonance has been proposed as a highly-efficient method for converting ultracold atoms into ultracold molecules, as was recently demonstrated with a Fermi gas of $^{40}$K atoms. This method might be used to create a Bose-Einstein condensation (BEC) of molecules. There is heightened interest in the case where the initial atoms are fermions, since there are close connections between Cooper pairing in the BCS theory and BEC of molecules in the strong coupling limit. However, molecules produced by this method are vibrationally excited, and thus far, the observed molecular lifetimes have been only $\sim 1$ ms. This is likely to be shorter than the time needed for effective evaporative cooling, or for the thermal equilibration necessary for the molecules to Bose condense. In this paper, we report the efficient conversion of an atomic Fermi gas of $^6$Li atoms into a gas of molecules with an observed lifetime of $\sim 1$ s.

Major components of the apparatus have been described previously. After accumulating approximately $10^{10}$ bosons ($^7$Li) and $10^{10}$ fermions ($^6$Li) in a magneto-optical trap, the atoms are optically pumped into the $F = 2, m_F = 2$ and $F = 3/2, m_F = 3/2$ states, respectively, and transferred to a magnetic trap. In contrast to our previous work, where only the $^7$Li atoms were evaporated and the $^6$Li were cooled sympathetically, we now evaporate both isotopes. This “dual evaporation” scheme is far more efficient, resulting in a 100-fold increase in the number of $^6$Li atoms to $N = 7 \times 10^7$ and a three-fold lowering of the relative temperature to $T = 0.1 \ T_F$, where $T_F$ is the Fermi temperature. This is the largest number of trapped fermions cooled to temperatures below $T_F$ reported thus far. The states of interest are not magnetically trappable, so we transfer them to an optical trap. The optical trapping potential is approximately harmonic radially, with a frequency of $\sim 800$ Hz for $^6$Li and a depth of $\sim 10 \ \mu$K. The potential is box-like axially with a length of 480 $\mu$m and a depth of $\sim 7$ $\mu$K. The $^7$Li atoms are removed from the optical trap by a resonant laser pulse.

Feshbach resonances occur between the two lowest hyperfine levels, $F = 1/2, m_F = 1/2$ and $F = 1/2, m_F = -1/2$ in $^6$Li as was predicted in ref. and recently observed. An adjustable uniform magnetic bias field of $\sim 549$ G is applied to tune near a resonance. A frequency-swept microwave pulse transfers the $^6$Li atoms from the $F = 3/2, m_F = 3/2$ to the $F = 1/2, m_F = 1/2$ state with nearly 100% efficiency. The transition between the $F = 1/2, m_F = 1/2$ and $F = 1/2, m_F = -1/2$ states is driven by an RF pulse at $\sim 76$ MHz. Symmetry requires that the two state mixture be incoherent, otherwise the atoms remain indistinguishable and do not interact. We observe a remarkable degree of coherence in this system, including Rabi oscillations that persist for several seconds without evidence of decoherence. In order to create an incoherent mixture of equal populations in each state, a small magnetic gradient is applied and the transition is driven for 1 s by a frequency-swept triangle wave that is swept back and forth across the resonance 50 times. Decoherence of this mixture is readily verified by observation of rapid loss from the shallow optical trap as the gas thermalizes. The mixture does not decohere without the field gradient. At the end of this process, we estimate the number of atoms in each spin state to be $3 \times 10^6$, while the corresponding peak density of each state is $3 \times 10^{12}$ cm$^{-3}$, giving $T_F \approx 1.4$ $\mu$K. Although accurate determinations of the temperature is limited by the flat axial density distribution in the optical trap, it is expected to be quite low due to rapid evaporative cooling. The radial profiles are consistent with temperatures below 0.1 $T_F$.

Although $^6$Li exhibits an extremely large Feshbach resonance at $\sim 850$ G, we instead utilize the narrow resonance located at $\sim 543$ G. We chose the narrow resonance for two reasons: first, it is technically simpler to sweep over a smaller range of magnetic field; and second, recent theoretical results indicate that one of the primary mechanisms for loss of atoms, the creation of pairs of hot atoms during the sweep, is minimized for a narrow resonance compared with a broad one. Figure 1 shows the results of a coupled-channels calculation of the scattering length for this resonance. The singlet and triplet

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FIG. 1: Coupled channels calculation of the narrow Feshbach resonance between the two lowest Zeeman sublevels of $^6$Li. The scattering length is shown in units of the Bohr radius. The predicted location of the resonance is at a slightly higher field than observed (Figs. 2 and 4).

potentials necessary for this calculation were constructed from spectroscopic data [17] and were further refined by the observation of the location of a Feshbach resonance in $^7$Li [14]. The predicted location of the resonance, 543.8 G, deviates slightly from the measured location given by the data shown in the following figures. Figure 2 shows the lifetime of the trapped atoms for fixed fields near the resonance. The curve is asymmetric with a slower fall-off on the low-field side of the peak at 543.25 ± 0.05 G.

To convert atoms to molecules, the magnetic field is ramped from high field to low so that the molecular energy goes from above dissociation, to below. This creates molecules energetically stable against dissociation, and minimizes the creation of translationally hot atom pairs [3, 4, 5, 7, 8]. Although a Fermi gas contains a spread of atomic energies, the process can be approximated as an adiabatic passage through a two-level avoided crossing, where the two states are a pair of free atoms and a bound vibrational level of the diatomic molecule [3]. The Landau-Zener theory is applicable in this case, and predicts that the transition probability is proportional to $1 - e^{-B^{-1}}$, where $B^{-1}$ is the inverse ramp rate [18].

Experimentally, we start the ramp at a field far above the resonance (549 G) and end it far below (∼350 G). The measured fraction of atoms remaining as a function of $B^{-1}$ is shown in Fig. 3, which exhibits the predicted exponential dependence. The Landau-Zener model also predicts that the conversion should be 100% if the ramp rate is sufficiently slow, while we observe a maximum efficiency of ∼50%. A similar maximum efficiency was reported in ref. [9].

Figure 4 gives the fraction of atoms remaining when the field ramp begins at 549 G and is stopped at various

FIG. 2: Lifetime of an incoherent mixture of the two lowest Zeeman sublevels as a function of the static field strength. The field is calibrated to 0.05 G by the frequency of the resonance transition between the two sublevels. The lifetime here is defined as the time at which the total atom number has fallen to $1/e$ of its initial value. There are no detectable atoms at 543.25 G following the 1 s triangle wave which creates the incoherent mixture, but by monitoring the decay of atom signal following a short π/2 pulse instead, the lifetime is found to be less than 200 ms. The background lifetime of 13 s, shown by the light horizontal line, is mainly due to off-resonant scattering induced by the trap lasers.

FIG. 3: Dependence of atom loss on inverse sweep rate. The field is ramped linearly from high to low field. The filled circles represent the average of 6-10 measurements and the error bars are the standard deviations of these measurements. The solid line is an exponential fit, giving a decay constant of 1.3 ms/G.

FIG. 4: Coupled channels calculation of the narrow Feshbach resonance between the two lowest Zeeman sublevels of $^6$Li.
The molecules produced by this method are vibrationally excited and can de-excite by inelastic collisions with atoms or other molecules. These vibrational quenching collisions impart kinetic energy to the participants in the collision equal to the energy difference between the initial and final vibrational levels. In the present case, the coupled-channels calculation indicates that the Feshbach resonance couples electronically spin-polarized pairs of atoms interacting via the molecular triplet potential with the least-bound \((v = 38)\) vibrational level of the \(X^1\Sigma^+_g\) singlet state of \(^{6}\text{Li}_2\). We have calculated that the \(v = 37\) and \(v = 38\) levels are separated by over 50 GHz, so any vibrational quenching collision results in the release of over 2 K of energy, far exceeding the depth of the optical trap. Previous determinations of vibrational quenching of weakly bound vibrational levels of the bosons \(^{87}\text{Rb}\) \(^{12}\) and \(^{23}\text{Na}\) \(^{4}\) \(^{11}\), and of the fermion \(^{40}\text{K}^{2}\), are consistent with lifetimes of \(\sim 1\) ms and rate constants of \(\sim 10^{-10}\) cm\(^3\) s\(^{-1}\). Similarly, calculations for quenching of high-lying vibrational levels of \(\text{H}_2\) by \(\text{H}\) \(^{20}\) and of the \(v = 1\) level of \(\text{Na}_2\) by Na atoms \(^{21}\) produce rate constants of approximately the same value. In contrast, we find an effective rate constant that is two to three orders of magnitude smaller. One might expect the quenching rate to be minimized by stopping the field ramp within the Feshbach resonance. In this case, the molecules are extremely weakly bound, and will have poor wavefunction overlap with lower-lying levels. However, this is not the origin of the rate reduction seen.
here, as the final field is well below the resonance, and the molecules are essentially pure singlet in character. Fermi statistics might cause a reduction in the rate of quenching if the size of the molecule is smaller than the size of the region over which the pair correlation is depleted.

The long molecular lifetime may enable the formation of a molecular BEC by allowing enough time for thermalization and evaporative cooling of the gas. Additionally, if the initial Fermi gas is already at $T = 0$ and the conversion is slow with respect to the translational degrees of freedom, the conversion should proceed along the ground state of the system directly into a molecular BEC. For faster sweeps that are non-adiabatic with respect to the translational motion, but still adiabatic with respect to molecule formation, the molecular gas will have the same mean energy as the initial Fermi gas. In this case, the temperature is essentially equal to the BEC transition temperature of the molecules. If a molecular BEC can be formed, a completely adiabatic sweep back across the Feshbach resonance will maintain $T = 0$, and allow the formation and investigation of Cooper pairs at any adjustable interaction strength [10].

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