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

Kevin E. Strecker, Guthrie B. Partridge, and Randall G. Hulet

Department of Physics and Astronomy and Rice Quantum Institute, Rice University, Houston, Texas 77251, USA

(Received 21 July 2003; published 22 August 2003)

We have converted an ultracold Fermi gas of ^{6}Li atoms into an ultracold gas of $^6Li_2$ molecules by adiabatic passage through a Feshbach resonance. Approximately 1.5×10^5 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.

DOI: 10.1103/PhysRevLett.91.080406 PACS numbers: 03.75.Ss, 03.75.Nt, 32.80.Pj, 34.50.–s

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 [1]. Molecules can be formed near a Feshbach resonance and have recently been detected in ultracold gases for fields close to a resonance [2]. 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 [3–8], as was recently demonstrated with a Fermi gas of ^{40}K atoms [9]. 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 [10], since there are close connections between Cooper pairing in the BCS theory and BEC of molecules in the strong coupling limit [11]. However, molecules produced by this method are vibrationally excited, and thus far, the observed molecular lifetimes have been only $\sim$1 ms [9,12]. 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 Letter, 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 [13,14]. After accumulating approximately 10^{10} bosons (^{7}Li) and 10^9 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 [13], we now evaporate both isotopes. This ''dual evaporation'' scheme is far more efficient, resulting in a hundredfold increase in the number of ^{6}Li atoms to $N = 7 \times 10^7$ and a threefold lowering of the relative temperature to $T = 0.1T_F$, 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 [14]. 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 boxlike axially with a length of 480 μm 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. [15] and recently observed [16]. 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 3×10^5, while the corresponding peak density of each state is 3×10^{12} cm^{-3}, giving $T_F \approx 1.4\ \mu$K. Although accurate determination 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 $0.1T_F$.

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

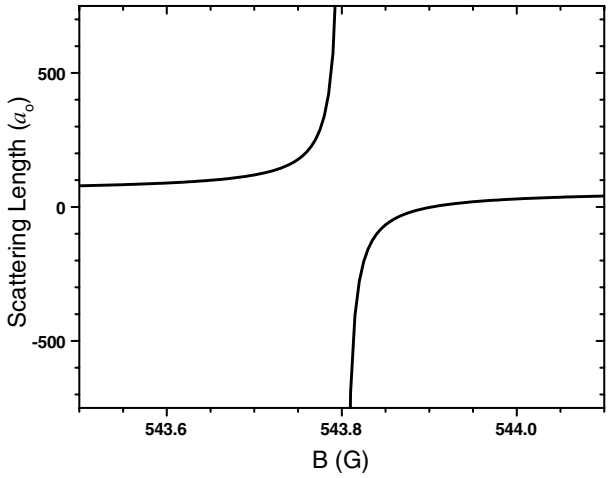

FIG. 1. Coupled-channels calculation of the narrow Feshbach resonance between the two lowest Zeeman sublevels of ^{6}Li. The scattering length is shown in units of the Bohr radius. The predicted location of the resonance is at a slightly higher field than observed (Figs. 2 and 4).

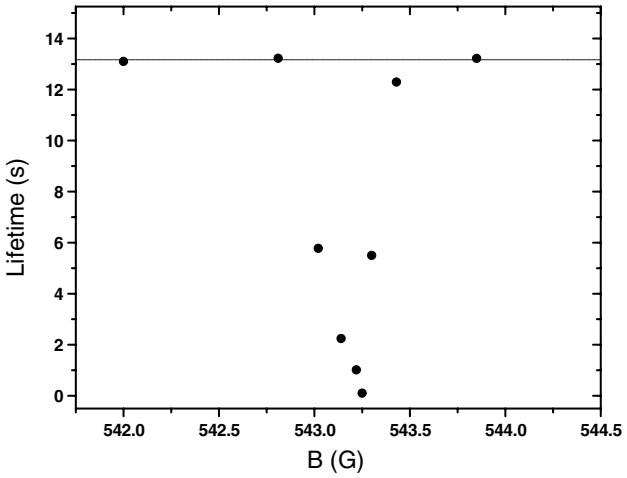

FIG. 2. Lifetime of an incoherent mixture of the two lowest Zeeman sublevels as a function of the static field strength. The field is calibrated to 0.05 G by the frequency of the resonance transition between the two sublevels. The lifetime here is defined as the time at which the total atom number has 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 $\pi/2$ 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.

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 [4,7]. Figure 1 shows the results of a coupled-channels calculation of the scattering length for this resonance. The singlet and triplet 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 falloff 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 [3–5,7,8]. 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 [5]. The Landau-Zener theory is applicable in this case and predicts that the transition probability is proportional to $1 - e^{-\alpha \dot{B}^{-1}}$, where α is a constant depending on the atom/molecule coupling strength and $\dot{B}^{-1}$ 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 $\dot{B}^{-1}$ 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 $\sim$50%. A similar maximum efficiency was reported in Ref. [9].

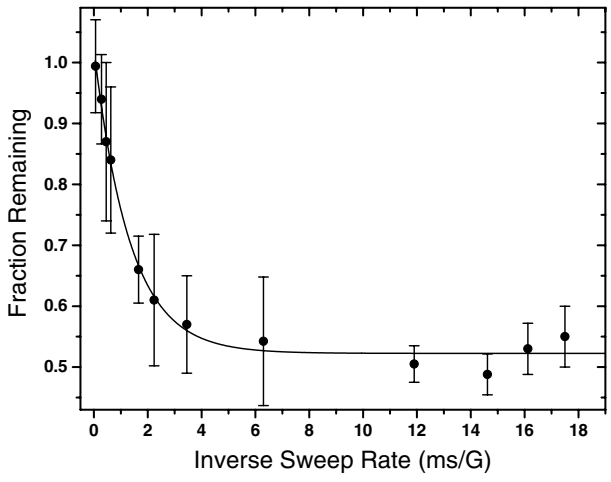

FIG. 3. Dependence of atom loss on inverse sweep rate. The field is ramped linearly from high to low field. The solid circles represent the average of 6–10 measurements and the error bars are the standard deviations of these measurements. The solid line is an exponential fit, giving a decay constant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

Figure 4 gives the fraction of atoms remaining when the field ramp begins at 549 G and is stopped at various final fields. The ramp rate is sufficiently slow to ensure maximum conversion efficiency. We fit the resulting data to the empirical equation $1/2[1 + 1/(1 + e^{-(B-B_o)/\Delta B})]$ and find that $B_o = 543.26 \pm 0.1$ G and $\Delta B = 0.23$ G. To within our resolution of 0.1 G, which is comparable to the width of the resonance itself, the peak of the loss (Fig. 2) and the center of the resonance, given by B_o, occur at the same field.

The results presented thus far indicate that atoms are lost while traversing the Feshbach resonance, but they do not distinguish between molecule conversion and other loss processes, such as inelastic collisions. To demonstrate that molecules are indeed produced, we show that the atom/molecule conversion process is reversible, as in Ref. [9], by first sweeping downward through the resonance, waiting for a fixed amount of time, then sweeping back to the original field. Molecules created by the downward ramp will be returned as atoms by the upward ramp, as long as the molecules themselves have not been lost during the time interval τ between their creation and subsequent dissociation back to atom pairs. It can be seen from Fig. 5 that close to 85% of the original atom population survives the double ramp, which demonstrates that no more than 15% of the original atom population is lost by inelastic processes. Furthermore, the data in Fig. 5 show that the molecules survive for an unexpectedly long time, of order 1 s.

The molecules produced by this method are vibrationally excited and can deexcite 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 $^6Li_2$. 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}Rb [12] and Na [4,6,19], and of the fermion ^{40}K [9], 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 H_2 by H [20] and of the $v = 1$ level of Na_2 by Na atoms [21] produce rate constants of approximately the same value. In contrast, we find an effective rate constant that is 2 to 3 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 wave function overlap with lower-lying levels. However, this is

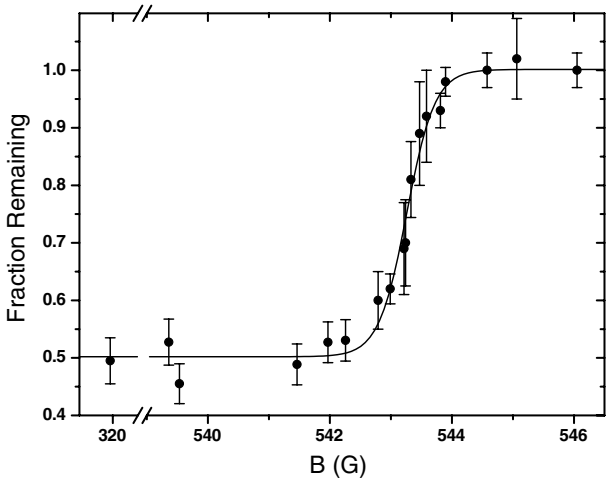

FIG. 4. Dependence of atom loss on final field. The field is ramped down from 549 G to various final fields. The inverse sweep rate, $\dot{B}^{-1}$, is greater than 12 ms/G for all of the data. The data points and error bars correspond to multiple averages, as in Fig. 3. The solid line is a fit to an empirical function (given in the text).

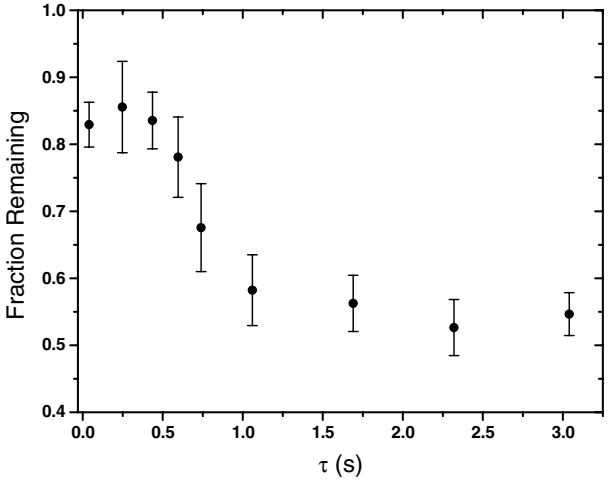

FIG. 5. Measurement of the molecular lifetime. The field is ramped downward through the Feshbach resonance and back to the starting field. The time τ is defined as the interval between traversing the field B_o on the downward sweep and again on the upward sweep. The inverse sweep rate is 3.5 ms/G and the starting field is 549 G. The field is ramped down to a final field, whose value depends on τ, and immediately ramped back to the starting field. For the data point at 40 ms the final field is 538 G, while for $\tau = 248$ ms, the final field is 508 G, and so on. For the three points with the largest τ, the field is ramped down to 369 G and held there for the required time before being brought back. Although we did not perform a systematic study of lifetime as a function of field, the molecular lifetime was observed to be field independent for the range of final fields used here. The data points and error bars are the averages and standard deviations, respectively, of 8 to 16 measurements.

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 nonadiabatic 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].

The authors gratefully acknowledge the contributions of Ying-Cheng Chen and helpful conversations with Michael Jack and Andrew Truscott. This work was funded by grants from the NSF, ONR, NASA, and the Welch Foundation.

[1] W. C. Stwalley, Phys. Rev. Lett. **37**, 1628 (1976); E. Tiesinga, B. J. Verhaar, and H. T. C. Stoof, Phys. Rev. A **47**, 4114 (1993).

[2] E. A. Donley, N. R. Claussen, S. T. Thompson, and C. E. Wieman, Nature (London) **417**, 529 (2002); C. Chin, A. J. Kerman, V. Vuletić, and S. Chu, Phys. Rev. Lett. **90**, 033201 (2003).

[3] E. Timmermans, P. Tommasini, M. Hussein, and A. Kerman, Phys. Rep. **315**, 199 (1999).

[4] F. A. van Abeelen and B. J. Verhaar, Phys. Rev. Lett. **83**, 1550 (1999).

[5] F. H. Mies, E. Tiesinga, and P. S. Julienne, Phys. Rev. A **61**, 022721 (2000).

[6] V. A. Yurovsky, A. Ben-Reuven, P. S. Julienne, and C. J. Williams, Phys. Rev. A **62**, 043605 (2000).

[7] V. A. Yurovsky and A. Ben-Reuven, Phys. Rev. A **67**, 043611 (2003).

[8] M. Mackie *et al.*, cond-mat/0210131.

[9] C. A. Regal, C. Ticknor, J. L. Bohn, and D. S. Jin, Nature (London) **424**, 47 (2003).

[10] E. Timmermans, K. Furuya, P. W. Milonni, and A. K. Kerman, Phys. Lett. A **285**, 228 (2001).

[11] For a review, see M. Randeria, *Bose-Einstein Condensation*, edited by A. Griffin, D. W. Snoke, and S. Stringari (Cambridge University, Cambridge, 1995), p. 355.

[12] R. Wynar, R. S. Freeland, D. J. Han, C. Ryu, and D. J. Heinzen, Science **287**, 1016 (2000).

[13] A. G. Truscott, K. E. Strecker, W. I. McAlexander, G. B. Partridge, and R. G. Hulet, Science **291**, 2570 (2001).

[14] K. E. Strecker, G. B. Partridge, A. G. Truscott, and R. G. Hulet, Nature (London) **417**, 150 (2002).

[15] M. Houbiers, H. T. C. Stoof, W. I. McAlexander, and R. G. Hulet, Phys. Rev. A **57**, R1497 (1998).

[16] K. M. O'Hara, S. L. Hemmer, M. E. Granade, M. E. Gehm, and J. E. Thomas, Phys. Rev. A **66**, 041401(R) (2002); K. Dieckmann *et al.*, Phys. Rev. Lett. **89**, 203201 (2002); S. Jochim *et al.*, Phys. Rev. Lett. **89**, 273202 (2002); T. Bourdel *et al.*, Phys. Rev. Lett. **91**, 020402 (2003).

[17] E. R. I. Abraham *et al.*, Phys. Rev. A **55**, R3299 (1997).

[18] L. Landau, Phys. Z. Sowjetunion **2**, 46 (1932); C. Zener, Proc. R. Soc. London, Ser. A **137**, 696 (1932).

[19] J. Stenger *et al.*, Phys. Rev. Lett. **82**, 2422 (1999).

[20] N. Balakrishnan, R. C. Forrey, and A. Dalgarno, Chem. Phys. Lett. **280**, 1 (1997).

[21] P. Soldán, M. T. Cvitaš, J. M. Hutson, P. Honvault, and J. Launay, Phys. Rev. Lett. **89**, 153201 (2002).