Observation of Heteronuclear Feshbach Molecules from a ^{85}Rb–^{87}Rb Gas

S. B. Papp* and C. E. Wieman

JILA, National Institute of Standards and Technology and University of Colorado, Boulder, Colorado 80309-0440, USA

(Received 3 August 2006; published 31 October 2006)

We report on the observation of ultracold heteronuclear Feshbach molecules. Starting with a ^{87}Rb Bose-Einstein condensate and a cold atomic gas of ^{85}Rb, we utilize previously unobserved interspecies Feshbach resonances to create up to 25 000 molecules. Even though the ^{85}Rb gas is nondegenerate, we observe a large molecular conversion efficiency due to the presence of a quantum degenerate ^{87}Rb gas; this represents a key feature of our system. We compare the molecule creation at two different Feshbach resonances with different magnetic-field widths. The two Feshbach resonances are located at 265.44 ± 0.15 G and 372.4 ± 1.3 G. We also directly measure the small binding energy of the molecules through resonant magnetic-field association.

DOI: 10.1103/PhysRevLett.97.180404 PACS numbers: 05.30.Jp, 03.75.Nt, 34.50.−s, 36.90.+f

The creation of ultracold molecules from ultracold atoms is currently a topic of great experimental and theoretical interest [1–4]. Ultracold heteronuclear molecules in low-lying vibrational states are particularly interesting since they are predicted to exhibit a permanent dipole moment due to the unequal distribution of electrons. Numerous proposals for utilizing polar molecules exist, including quantum computation [5] and the search for the electron electric dipole moment [6]. Although no significant permanent dipole moment is expected to exist in a ^{85}Rb–^{87}Rb molecule, our work demonstrates a first step toward the efficient production of ground-state ultracold heteronuclear molecules.

To date cold heteronuclear molecules in high-lying vibrational levels have been created using photoassociation [7–9]. These molecules can then be pumped toward low-lying vibrational levels by exciting bound-bound molecular transitions [3] via, for example, stimulated Raman-type transitions [5] that enhance the probability of populating the lowest vibrational level. The initial photoassociation step used in this process is inefficient, and many final vibrational levels of the molecule are occupied. An alternative to this initial photoassociation step is the direct conversion of two free atoms into a molecule in the highest vibrational levels using a Feshbach resonance [1,2,10–15]. High conversion efficiency using a Feshbach resonance has been demonstrated in single-species gases via adiabatic magnetic-field sweeps across the resonance [4,16], three-body recombination [13], resonant magnetic-field association [15], and nonadiabatic magnetic-field sweeps [1,17]. Feshbach resonances between two different atomic species [18,19] have previously been reported. Our work builds upon these observations by demonstrating stable heteronuclear Feshbach molecules.

In this Letter we present a systematic study of the creation of heteronuclear molecules from an atomic gas of ^{85}Rb and ^{87}Rb. We find that these molecules can be created using the standard techniques already proven with single-species gases. The presence of two species with different quantum degeneracy provides a rich system for testing our understanding of the conversion efficiency from atoms to molecules. Furthermore, the molecule creation process allows us to determine the location and width of Feshbach resonances in the two-species system; this information will be required for future studies of the ^{85}Rb–^{87}Rb system with a tunable interspecies interaction.

Our apparatus is designed to create a two-species Bose gas through sympathetic cooling of ^{85}Rb with ^{87}Rb. The details of our system are similar to those described in Refs. [20,21] and are only briefly described here. We initially collect approximately 3×10^9 ^{87}Rb atoms and 10^7 ^{85}Rb atoms in a two-species vapor cell magneto-optical trap. The atoms are loaded into a quadrupole magnetic trap and physically transported to another region of the apparatus with lower vacuum pressure [20,22]. Here the atoms are prepared in the ^{85}Rb $|f = 2, m_f = -2\rangle$ state and the ^{87}Rb $|f = 1, m_f = -1\rangle$ state and loaded into an Ioffe-Pritchard–type magnetic trap. Selective rf evaporation is used to lower the temperature of the ^{87}Rb gas, while the ^{85}Rb gas is sympathetically cooled through thermal contact with the ^{87}Rb [23].

The mixed-species gas is evaporatively cooled in the magnetic trap to approximately 10 μK and then further evaporatively cooled in an optical dipole trap by lowering the depth. The optical trap is formed at the focus of a Yb:YAG laser beam with a $1/e^2$ radius of 23.5 μm. This trap has the distinct advantage of holding any spin state in the same spatial location while allowing a variable magnetic field to be applied. A Helmholtz pair of coils provides a magnetic field up to 700 G; the magnetic field is calibrated using rf-driven Zeeman transitions with a systematic uncertainty of 0.01%. We perform the optical trap evaporation slightly above the ^{85}Rb Feshbach resonance at 155 G where density-dependent ^{85}Rb–^{85}Rb loss is minimized [24]. We typically produce a ^{87}Rb Bose-Einstein condensate (BEC) with 300 000 atoms and 50% condensate fraction and a nondegenerate ($T/T_c = 2.4$) gas of ^{85}Rb with 40 000 atoms. Measurements are performed in an optical trap with a radial trap frequency of $\omega_r = 2\pi \times$ 200 Hz and an aspect ratio of approximately 100.

We have discovered two heteronuclear s-wave Feshbach resonances in the ^{85}Rb $|f = 2, m_f = -2\rangle$ state and the ^{87}Rb $|f = 1, m_f = -1\rangle$ state, one near 265 G and the other near 372 G. The binding energy of the bound molecular state increases with magnetic field above the position of each Feshbach resonance. To create heteronuclear molecules, we adiabatically (450 μs/G) sweep [2] the magnetic field from low to high field through a Feshbach resonance. Figure 1(b) shows an absorption-image cross section of the ^{85}Rb gas following a sweep through the resonance. Prior to imaging, the gas is released from the optical trap and expands for 3 ms; at the same time as the optical trap release is initiated, the magnetic field is switched off within 50 μs. A significant fraction ($\sim$60%) of the atoms disappear as compared to an absorption-image cross section without sweeping the magnetic field [Fig. 1(a)]. When we reverse the molecule creation process by immediately applying a second field sweep in the opposite direction less than 100 μs after the first sweep ends [Fig. 1(c)], a large fraction of the atoms reappear [2]. The atoms that reappear represent reversible heteronuclear molecule formation. The small fraction of atoms that do not return are lost to ^{85}Rb–^{87}Rb inelastic collisions that remove atoms from the trap. We verified this by sweeping across the resonance at the same rate in the opposite direction. At a typical ^{87}Rb peak density of 1×10^{14} cm^{-3}, we observe approximately 15% ^{85}Rb number loss during a sweep. By monitoring the reappearance of atoms as a function of time, we find that the molecules decay with a lifetime of approximately 1 ms. This decay is due to a combination of inelastic collisions with the ^{87}Rb gas and a one-body spontaneous process [25,26].

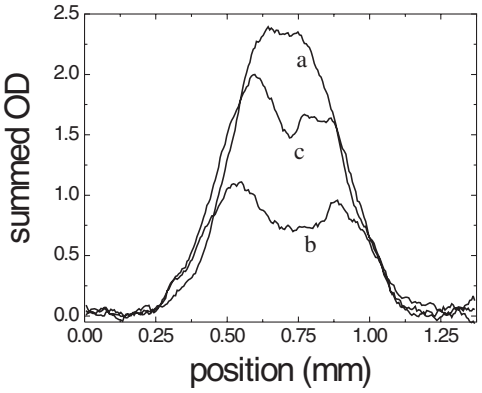

FIG. 1. Absorption-image axial cross sections of the ^{85}Rb gas demonstrating reversible molecule creation. The measured two-dimensional optical density (OD) was summed in the remaining radial direction of the absorption image. (a) Prior to sweeping the magnetic field the atom number is 26 500. (b) Sweeping through the resonance converts $\sim$60% of the gas into molecules. (c) By reversing the molecule creation process approximately 85% of the initial atom number is observed to reappear. Note that most of the ^{85}Rb loss occurs in the center of the gas where the ^{87}Rb BEC density is largest.

We precisely located the Feshbach resonances with an experimental technique that avoids the need for rapid magnetic-field sweeps. At the lower (higher) field resonance, we sweep the magnetic field from 269 G (397 G) downward toward the resonance stopping at various final values. The rate of this magnetic-field sweep is fast compared to both the time scale for molecule creation and atom loss due to inelastic collisions. The field is held at the final value for 0.3 ms and then returns to 269 G (397 G) at a rate of 450 μs/G (70 μs/G), which is slow compared to the molecule creation rate. The magnetic field remains here for 5 ms to ensure that any molecules made during the second sweep decay and are lost from the optical trap [25,26]. We then simultaneously turn off the magnetic field and the optical trap to let the gas expand for 6 ms and measure the number of ^{85}Rb atoms remaining. In Fig. 2 we show the atom number remaining as a function of the final magnetic field for the two Feshbach resonances. The key to this method is that, if the field passes through the Feshbach resonance on the first sweep, then a fraction of the atoms will be converted into molecules by the second sweep. The

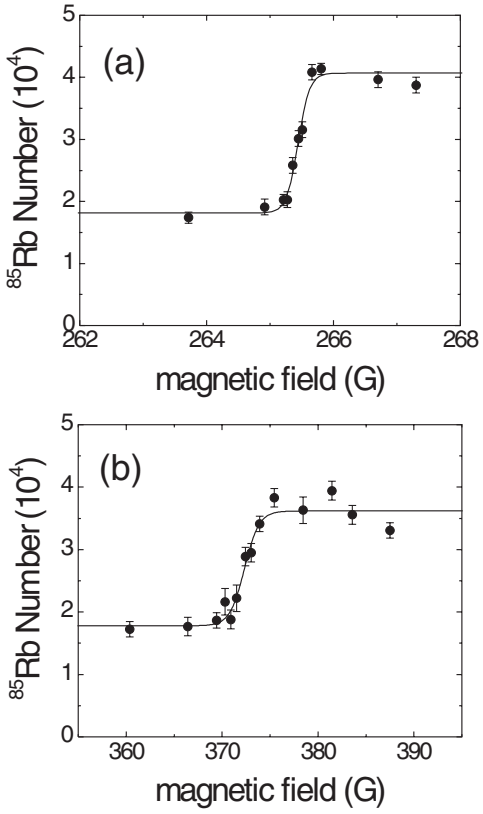

FIG. 2. Atom loss after magnetic-field sweeps through a Feshbach resonance. The number of ^{85}Rb atoms is a function of the final magnetic field during the sweeps near the (a) 265 G and (b) 372 G Feshbach resonances. Initially there are 2.1–2.3 $\times$ 10^5 ^{87}Rb atoms with T/T_c near 0.8. The data are fitted to an error function to extract the center position and width. The resulting positions of the two transitions are 265.44 $\pm$ 0.15 G and 372.4 $\pm$ 1.3 G with the uncertainty given by the fitted rms width.

rapid onset of atom loss due to molecule creation when the magnetic field is swept below 265.44 G (372.4 G) represents crossing the peak of the Feshbach resonance.

The dependence of molecule conversion efficiency on sweep rate was measured in Ref. [16] and is well characterized by a Landau-Zener model. For our two-species gas with similar number and temperature, we observe a factor of 5.3 ± 1.9 decrease in the ramp rate required to create molecules at the 372 G Feshbach resonance as compared to the 265 G resonance. This factor is consistent with the ratio of the predicted widths of the two resonances, which is in the range of 6–8 [27–29]. This verifies the predicted inverse relationship between the Feshbach resonance width and the sweep rate required to create molecules.

We have investigated the adiabatic conversion efficiency of atoms to molecules. We begin by sweeping the magnetic field upward through the 265 G Feshbach resonance at a rate that is slow with respect to the molecule conversion rate. It is then held at 269 G for 5 ms to allow the molecules to decay and be lost from the trap. The number of molecules formed is simply the difference in ^{85}Rb number before and after the sweep with a small correction applied to account for measured inelastic atom loss during the field sweeps. The conversion efficiency to heteronuclear molecules is shown in Fig. 3 as a function of ^{87}Rb T/T_c. We varied T/T_c by either changing the number of ^{87}Rb atoms or the temperature. The ^{85}Rb gas had a T/T_c in the range of 2.2 to 4. We observe up to 60% conversion of the ^{85}Rb gas into molecules even when the ^{85}Rb gas is far from quantum degeneracy. The largest conversion efficiency is observed when ^{85}Rb is least quantum degenerate, indicating that the conversion efficiency primarily depends on ^{87}Rb T/T_c.

In a single-species gas the molecule conversion efficiency of an adiabatic field sweep was shown to depend

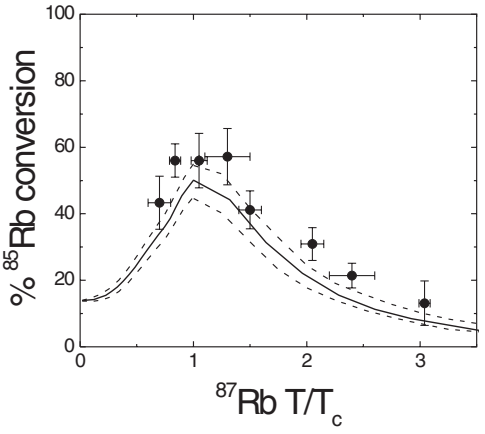

FIG. 3. Heteronuclear molecule conversion efficiency at the 265 G Feshbach resonance as a function of ^{87}Rb T/T_c. At our largest conversion efficiency the ^{85}Rb gas has $T/T_c = 2.6$. The solid line shows a simulation based on our conversion model, and the dashed lines represent the uncertainty. The conversion drops below $T/T_c = 1$ since the BEC is spatially smaller than the thermal ^{85}Rb gas and the conversion process depends on the proximity of two atoms in phase space.

only on the degree of quantum degeneracy [16,30]. A molecule is formed during an adiabatic sweep if two free atoms are sufficiently close in phase space so that their wave function can smoothly evolve to a bound molecule as the Feshbach resonance is crossed. We used a Monte Carlo simulation to model the observed heteronuclear molecule conversion efficiency. Phase space distributions of position and momenta of ^{85}Rb and ^{87}Rb are randomly generated based on the number and temperature of each gas and the trap frequencies. For the ^{87}Rb gas at temperatures above T_c a Maxwell-Boltzmann (MB) distribution is used. Below T_c we use a combination of a Thomas-Fermi distribution for the BEC and a Bose-Einstein distribution for the thermal component. A MB distribution is always used for the ^{85}Rb gas since the temperature of the gas does not fall below $T = 2.2T_c$. For each ^{85}Rb atom, the simulation searches the ^{87}Rb gas to find a pair that is sufficiently close in phase space. After a pairing occurs, the two atoms are removed from the simulation. Two atoms are considered sufficiently close in phase space if the following conditions are met: (1) If a BEC is present, any ^{85}Rb atoms inside the Thomas-Fermi radius of the condensate form a molecule, and (2) outside the BEC, an ^{85}Rb atom and a partner ^{87}Rb atom must satisfy the relation found in Ref. [16]: $|\delta r_{\mathrm{rel}} m \delta v_{\mathrm{rel}}| < \gamma h$, where δr_{rel} is the separation of the pair, m is the atomic mass, δv_{rel} is the relative velocity, and $\gamma = 0.44 \pm 0.03$.

The results of our simulation are shown by the solid line in Fig. 3. For $T/T_c > 1$ each gas has roughly the same spatial size in the optical trap, and therefore molecule conversion can occur anywhere in the gas as long as the local phase space criterion is met. At $T/T_c = 1$ and below, a significant fraction of the ^{87}Rb atoms are part of the condensate, which is spatially small compared to the extent of the ^{85}Rb gas. If the ^{85}Rb gas were a BEC, our simulation predicts that the molecule conversion efficiency approaches 100% as the T/T_c of each gas drops below one. There is good agreement between the experiment and simulation in both the nondegenerate and quantum degenerate regimes, suggesting that the pairing model in Ref. [16] is also applicable to heteronuclear molecule creation.

We created heteronuclear molecules using a small oscillating magnetic field to do spectroscopy on the Feshbach bound state. The oscillating field causes two atoms to bind together and form a molecule [15,31]. We first ramp the magnetic field from 269 G to a selected value between 266.2 and 267 G in 0.3 ms. The field modulation is then applied using the Helmholtz coil pair for 20 ms with a peak-to-peak amplitude between 0.6 and 1.0 G at a frequency up to 40 kHz. Next the field is returned to 269 G and held there for 5 ms, allowing any molecules made during the modulation to decay. Finally, we determine the number of atoms remaining as before. As in Ref. [15], we observe strongly enhanced atom loss at certain frequencies, and the loss depends on the duration and amplitude of the modulation. A typical loss spectrum is shown in the inset of Fig. 4; the frequency at which we observe maxi-

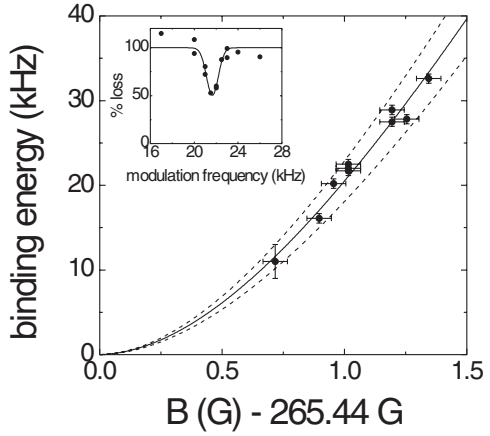

FIG. 4. Resonant frequency of atom loss as a function of magnetic field. The solid line is a fit to the data based on the universal binding energy of *s*-wave Feshbach molecules and the dashed lines represent the uncertainty in the Feshbach resonance width. (Inset) An atom-loss spectrum at 266.5 G as a function of the modulation frequency. The modulation converts roughly 50% of the gas to molecules. The loss is centered at 21.7 kHz with a width of 0.6 ± 0.2 kHz. The solid line is a Gaussian fit to the data. We report the uncertainty in the binding energy as the width of the loss spectrum because we lack a detailed understanding of the line shape.

mum atom loss gives a measure of the binding energy of the molecules [32].

The resonant frequency of maximum atom loss is shown in Fig. 4 for various magnetic fields near the Feshbach resonance. For each loss curve the amplitude used converted roughly half the ^{85}Rb gas into molecules. The solid line is a fit to the data based on the universal form of the molecular binding energy near an *s*-wave Feshbach resonance [4]. In the fit, the background scattering length is fixed to the value $213 \pm 7\ a_0$ [33], and the Feshbach resonance peak position and width are varied; the best fit finds the peak position and width to be 265.42 ± 0.08 G and 5.8 ± 0.4 G, respectively. These results are consistent with our previously discussed determination of the Feshbach resonance peak position and with the predicted width of the Feshbach resonance in Refs. [27–29].

In summary, we have created heteronuclear Feshbach molecules from an ultracold gas of ^{85}Rb and ^{87}Rb. We demonstrated that molecules can be produced with two methods, magnetic-field sweeps and resonant-field modulation. The conversion efficiency of ^{85}Rb into molecules can reach 60% even when that gas is not quantum degenerate. The heteronuclear molecules described here are ultracold and are stable for at least 1 ms. These conditions may provide a first step toward the efficient production of ground-state heteronuclear molecules.

Recently, evidence of heteronuclear molecule creation has been reported using ^{40}K and ^{87}Rb in Refs. [34,35].

We gratefully acknowledge useful discussions with Debbie Jin, John Bohn, Servaas Kokkelmans, and Cindy Regal. We thank Josh Zirbel and Juan Pino for experimental assistance. S. B. P. acknowledges support from the NSF. This work has been supported by NSF and ONR.

*Electronic address: papp@jilau1.colorado.edu

[1] E. A. Donley, N. R. Claussen, S. T. Thompson, and C. E. Wieman, Nature (London) **417**, 529 (2002).
[2] C. A. Regal, C. Ticknor, J. L. Bohn, and D. S. Jin, Nature (London) **424**, 47 (2003).
[3] J. M. Sage, S. Sainis, T. Bergeman, and D. DeMille, Phys. Rev. Lett. **94**, 203001 (2005).
[4] T. Köhler, K. Góral, and P. Julienne, cond-mat/0601420 [Rev. Mod. Phys. (to be published)].
[5] D. DeMille, Phys. Rev. Lett. **88**, 067901 (2002).
[6] J. J. Hudson, B. E. Sauer, M. R. Tarbutt, and E. A. Hinds, Phys. Rev. Lett. **89**, 023003 (2002).
[7] A. J. Kerman *et al.*, Phys. Rev. Lett. **92**, 033004 (2004).
[8] D. Wang *et al.*, Phys. Rev. Lett. **93**, 243005 (2004).
[9] M. Mancini *et al.*, Phys. Rev. Lett. **92**, 133203 (2004).
[10] S. Dürr, T. Volz, A. Marte, and G. Rempe, Phys. Rev. Lett. **92**, 020406 (2004).
[11] J. Herbig *et al.*, Science **301**, 1510 (2003).
[12] J. Cubizolles *et al.*, Phys. Rev. Lett. **91**, 240401 (2003).
[13] S. Jochim *et al.*, Phys. Rev. Lett. **91**, 240402 (2003).
[14] K. E. Strecker, G. B. Partridge, and R. G. Hulet, Phys. Rev. Lett. **91**, 080406 (2003).
[15] S. T. Thompson, E. Hodby, and C. E. Wieman, Phys. Rev. Lett. **95**, 190404 (2005).
[16] E. Hodby *et al.*, Phys. Rev. Lett. **94**, 120402 (2005).
[17] N. R. Claussen, E. A. Donley, S. T. Thompson, and C. E. Wieman, Phys. Rev. Lett. **89**, 010401 (2002).
[18] S. Inouye *et al.*, Phys. Rev. Lett. **93**, 183201 (2004).
[19] C. A. Stan *et al.*, Phys. Rev. Lett. **93**, 143001 (2004).
[20] H. Lewandowski, J. Low Temp. Phys. **132**, 309 (2003).
[21] S. L. Cornish *et al.*, Phys. Rev. Lett. **85**, 1795 (2000).
[22] M. Greiner *et al.*, Phys. Rev. Lett. **87**, 160405 (2001).
[23] I. Bloch *et al.*, Phys. Rev. A **64**, 021402(R) (2001).
[24] J. L. Roberts, N. R. Claussen, S. L. Cornish, and C. E. Wieman, Phys. Rev. Lett. **85**, 728 (2000).
[25] S. T. Thompson, E. Hodby, and C. E. Wieman, Phys. Rev. Lett. **94**, 020401 (2005).
[26] T. Köhler, E. Tiesinga, and P. S. Julienne, Phys. Rev. Lett. **94**, 020402 (2005).
[27] J. P. Burke, Jr., J. L. Bohn, B. D. Esry, and C. H. Greene, Phys. Rev. Lett. **80**, 2097 (1998).
[28] S. J. J. M. F. Kokkelmans and E. G. M. van Kempen (personal communication).
[29] J. L. Bohn (personal communication).
[30] J. E. Williams, N. Nygaard, and C. W. Clark, cond-mat/0511011.
[31] J. F. Bertelsen and K. Mølmer, Phys. Rev. A **73**, 013811 (2006).
[32] The atom-loss spectrum was recorded for a ^{87}Rb gas with 50% condensate fraction and two noncondensed gases with temperatures of 130 and 190 nK. Over this range in temperature, the measured resonant frequency shifts by only 5(2) Hz/nK.
[33] J. P. Burke and J. L. Bohn, Phys. Rev. A **59**, 1303 (1999).
[34] D. S. Jin, posters at DAMOP and ICAP in 2006.
[35] C. Ospelkaus *et al.*, Phys. Rev. Lett. **97**, 120402 (2006).