Lifetime of molecule-atom mixtures near a Feshbach resonance in ^{40}K

C. A. Regal, M. Greiner, and D. S. Jin*
JILA, National Institute of Standards and Technology and Department of Physics, University of Colorado, Boulder, CO 80309-0440
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We report a dramatic magnetic field dependence in the lifetime of trapped, ultracold diatomic molecules created through an s-wave Feshbach resonance in ^{40}K. The molecule lifetime increases from less than 1 ms away from the Feshbach resonance to greater than 100 ms near resonance. We also have measured the trapped atom lifetime as a function of magnetic field near the Feshbach resonance; we find that the atom loss is more pronounced on the side of the resonance containing the molecular bound state.

Scattering resonances known as Feshbach resonances occur when the collision energy of two free atoms coincides with that of a molecular state in a closed channel. By varying the strength of an external magnetic field experimenters can tune the relative atom-molecule energy through the Zeeman effect. This has enabled control over the strength of cold atom interactions, characterized by the s-wave scattering length a, for both Bose and Fermi gases [1, 2, 3, 4, 5, 6]. More recently these resonances have allowed efficient creation of ultracold, weakly bound molecules [7, 8, 9, 10, 11, 12, 13].

For Fermi gases the regime of strong atom coupling near an s-wave Feshbach resonance is particularly interesting. For a sufficiently quantum degenerate, two-component Fermi gas of atoms, it is predicted that the resonance can provide a continuous crossover between two superfluid regimes, that of a Bardeen-Cooper-Schreiffer (BCS) superfluid and Bose-Einstein condensate (BEC) of strongly bound pairs [14, 15, 16, 17]. However, experimental realization will require that the molecular and atomic gases are sufficiently stable against inelastic decay. In particular, the lifetimes should be longer than both the collision time in the gas as well as the oscillator period of the external trapping potential. This requirement is nontrivial because inelastic collision rates typically increase by orders of magnitude near a Feshbach resonance.

In this Letter we present a systematic study of the lifetime of trapped molecules in the presence of atoms as well as the lifetime of exclusively atoms near a Feshbach resonance. The molecules, which are created using the Feshbach resonance, are highly vibrationally excited. Thus, one expects large trap loss rates due to collisional vibrational quenching of the molecules [18, 19, 20]. Yet, very near a Feshbach resonance the size of the molecules become extremely large. In this regime the wavefunction of the molecules has much less overlap with that of tightly bound molecules. Thus, the theoretical expectations for the lifetime of these molecules are less clear. We show that the molecule lifetime increases dramatically in this exotic regime.

For the case of inelastic atomic collisions, experiments using bosons have seen dramatic enhancement of two and three-body loss rates at Feshbach resonances [21, 22, 23, 24]. However, in general a suppression of three-body decay is expected for s-wave interactions in a two-component Fermi gas due to Fermi statistics. The magnitude of this suppression near a Feshbach resonance is unknown, although theoretical progress has been made [25, 26, 27]. Experiments suggest that three-body processes are not completely suppressed because strong inelastic loss has been observed near fermionic Feshbach resonances where two-body inelastic processes are not expected [4, 6, 28]. Here we observe resonantly enhanced inelastic loss, but we find that the largest loss rate occurs at a magnetic field that is shifted with respect to the peak in elastic interactions.

The experiments reported here employ previously developed techniques for cooling and spin state manipulation of a gas of ^{40}K atoms. Because of the quantum statistics of fermions a mixture of two components, for example atoms in different internal spin states, is required to have s-wave interactions in the ultracold gas. With a total atomic spin $f = 9/2$ in its lowest hyperfine ground state, ^{40}K has ten available Zeeman spin-states $|f, m_f\rangle$, where m_f is the spin projection quantum number. Mixtures of atoms in two of these spin states are used in evaporative cooling of the gas, first in a magnetic trap and then in a far-off-resonance optical dipole trap. The final experiments are performed with an incoherent mixture of atoms with $\sim 50\%$ in each of two Zeeman levels.

We access an s-wave Feshbach resonance between atoms in the $|9/2, -7/2\rangle$ and $|9/2, -9/2\rangle$ states located at a magnetic field B of ~ 202 G [3, 28, 29, 30]. To create molecules we adiabatically ramp the magnetic field across the Feshbach resonance. The magnetic field is then lowered from $B = 207$ G at a rate between 0.5 G/ms and 1.5 G/ms to various final magnetic field values on the repulsive side of the resonance. The number of atoms remaining following the sweep is determined from an absorption image of the expanded atom cloud at a magnetic field below and away from the Feshbach resonance. Since the light for these images is resonant with an atomic transition, but not any molecular transitions, we selectively detect only atoms. Similar to Ref. [8], which used a

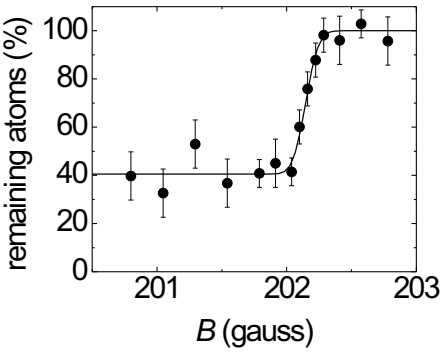

FIG. 1: Remaining atom number after creating molecules by lowering the magnetic field across the Feshbach resonance to B. For this measurement we start with a two-component Fermi gas in the $|9/2,-7/2\rangle$ and $|9/2,-9/2\rangle$ states. The line is a fit to an error function from which the center position is determined to be 202.15 ± 0.06 G.

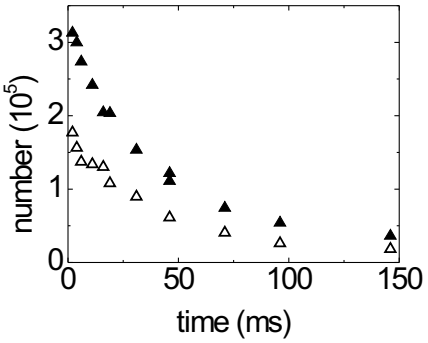

FIG. 2: Remaining total atom number without (open triangles) and with (solid triangles) transferring the molecules back to atoms. These data are plotted as a function of the amount of time spent at a magnetic field of B = 201.48 G (ΔB = -0.6 G). The curves are subtracted to determine the molecule decay rate.

different ^{40}K Feshbach resonance, atoms disappear in a narrow magnetic field region near the Feshbach resonance (Fig. 1). We interpret the missing fraction of atoms as diatomic molecules as demonstrated in [8].

We can measure the number of molecules present in the sample by converting the molecules back to atoms with one of two techniques [8]. We can apply radio frequency waves near the $|9/2,-7/2\rangle \rightarrow |9/2,-5/2\rangle$ atomic transition during time-of-flight expansion to dissociate the molecules into free atoms in the $|9/2,-9/2\rangle$ and $|9/2,-5/2\rangle$ states [31]. We can then detect only the molecules by selectively imaging the atom population in the initially unoccupied $|9/2,-5/2\rangle$ state. Alternatively, we can ramp the magnetic field back across the Feshbach resonance to convert the molecules back into atoms. We then measure the resulting total number of atoms with absorption imaging. In this case, to determine the molecule lifetime we must subtract a measurement of the atom lifetime. Figure 2 shows a typical measurement of the atom and molecule decay. The molecule decay rate is determined by subtracting the two curves and extracting the initial decay rate.

The first set of lifetime measurements presented in this Letter was performed after evaporating the Fermi gas by lowering the optical trap to a relatively small depth. The final trap was characterized by a radial frequency ν_r between 220 Hz and 240 Hz and an aspect ratio ν_r/ν_z fixed at 60. The temperature of the gas was determined from Thomas-Fermi surface fits to absorption images of expanded gases at magnetic fields away from the Feshbach resonance. The typical initial cloud temperature for these measurements was 70 nK, with a corresponding quantum degeneracy $T/T_F = 0.22$, and a total peak density of $n_{pk} = 1.5 \times 10^{13}$ cm^{-3} [32].

Figure 3 displays loss rate measurements as a function of the detuning from the Feshbach resonance, $\Delta B = B - B_0$. The rates are plotted as the decay rate of the number of molecules (atoms) $\dot{N}$ normalized to the initial molecule (atom) number N. Figure 3(a) shows the loss rate of the molecules for the $|9/2,-7/2\rangle$, $|9/2,-9/2\rangle$ Feshbach resonance (solid circles), where B_0 = 202.1 G (see Fig. 4). In this figure we also include two measurements of the decay rate of molecules created from the $|9/2,-5/2\rangle$ and $|9/2,-9/2\rangle$ Feshbach resonance (open circles), where B_0 = 224.21 G [33]. The solid circles in Fig. 3(b) show the corresponding atom loss rate with molecules present.

We find that the lifetime of the molecules increases dramatically as the Feshbach resonance is approached. Away from the Feshbach resonance the molecule lifetime is $\sim$ 1 ms as reported in Ref. [8]. Near the resonance the lifetime is greater than 100 ms, similar to that of atoms. It is interesting to compare the size of the molecules to the interatomic spacing of the atoms, which in the peak density region of the initial atom cloud is $\sim$ 7000 a_0. The molecule size as given by $a/2$ becomes 7000 a_0 at $\Delta B \approx -0.1$ G [34]. This suggests that very close to the Feshbach resonance the system exists in an exotic regime where atoms are likely to lie within the extent of a molecule.

We have also performed experiments in which we do not deliberately create molecules; in this way we can measure exclusively the atom lifetime. Instead of ramping the magnetic field to reach the Feshbach resonance, we access the Feshbach resonance by suddenly changing the Zeeman level of one of the two spins in the system. (This will result in a nonequilibrium sample.) The atom loss rate is then measured by watching the decay of the atom number in time to determine the initial atom loss rate. The results are shown as the squares in Fig. 3(b). In general, we find that the atom lifetime is similar whether or not there is a large molecule component in the gas.

Using the spin-changing technique described above we have also measured the loss rate in a trap whose depth

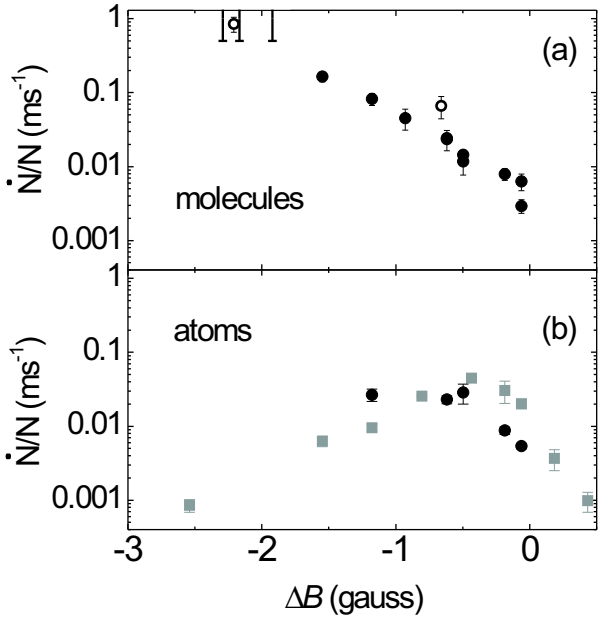

FIG. 3: (a) Decay rate of molecules near a Feshbach resonance. These data are plotted as a function of magnetic field detuning from the $|9/2,-7/2\rangle$, $|9/2,-9/2\rangle$ Feshbach resonance peak (solid circles) and $|9/2,-5/2\rangle$, $|9/2,-9/2\rangle$ Feshbach resonance peak (open circles). The bars indicate a lower limit on the decay rate of $|9/2,-7/2\rangle$, $|9/2,-9/2\rangle$ molecules. The fraction of atoms present for these measurements ranged from 0.4 to 0.6, as indicated in Fig. 1. (b) Decay rate of atoms in the $|9/2,-7/2\rangle$, $|9/2,-9/2\rangle$ states. The black circles are data with molecules present; the grey squares are data taken with no deliberate creation of molecules. All of these measurements start with the Fermi gas in a relatively shallow optical trapping potential at a typical temperature of 70 nK and a typical density of $n_{pk} = 1.5 \times 10^{13}$ cm^{-3}.

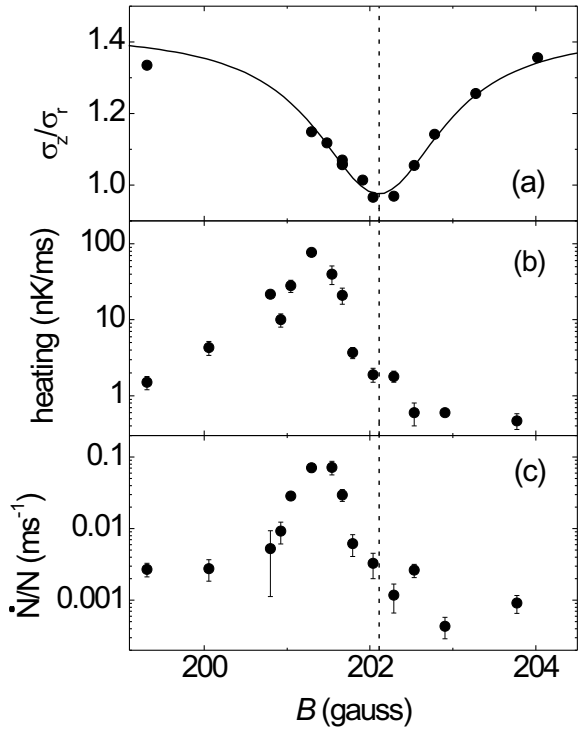

FIG. 4: (a) Anisotropic expansion of a nearly equal mixture of the $|9/2,-7/2\rangle$ and $|9/2,-9/2\rangle$ states of ^{40}K near a Feshbach resonance. The aspect ratio of the cloud σ_z/σ_r decreases at the Feshbach resonance peak due to an enhanced elastic collision rate. The line is a Lorentzian fit of the data to determine the resonance position, $B_0 = 202.1$ G. (b) Heating of the $|9/2,-7/2\rangle$ and $|9/2,-9/2\rangle$ gas near the Feshbach resonance. The typical initial temperature is 670 nK. (c) Loss of the $|9/2,-7/2\rangle$ and $|9/2,-9/2\rangle$ gas near the Feshbach resonance. The typical initial density of the cloud is $n_{pk} = 1.4 \times 10^{13}$ cm^{-3}. The dotted line corresponds to the Feshbach resonance peak ($\Delta B = 0$).

is large compared to the atoms' energy. In this case the loss rate is more accurately determined, since heating does not lead to evaporative loss. For these data the optical trapping potential was recompressed after evaporative cooling. The final trap had a depth of ~ 10 μK and a radial trapping frequency of $\nu_r = 725$ Hz. The final gas was at $T = 670$ nK and $T/T_F = 0.85$, but had a similar peak density to data in Fig. 3, $n_{pk} = 1.4 \times 10^{13}$ cm^{-3}. To determine the atom loss and heating rates we measure the total atom number as a function of time until $\sim 20\%$ of the atoms are lost. From the slope of these data in time we determine the heating and loss rates (Fig. 4(b),(c)).

Additionally, in Fig. 4 we plot hydrodynamic expansion data from which we determine the position of the Feshbach resonance. To measure the aspect ratio of the expanded cloud σ_z/σ_r we started with a gas in a trap characterized by $\nu_r = 440$ Hz at $T/T_F = 0.55$ and $n_{pk} = 1.7 \times 10^{13}$ cm^{-3}. We access the Feshbach resonance with the previously described spin changing technique. We then turn off the optical trapping light, and the gas expands for a total of 21.3 ms, where 7 ms of this expansion takes place at the magnetic field value near the Feshbach resonance. As shown in Refs. [6, 33, 35, 36] anisotropic expansion of the gas in this regime is a signature of a large elastic collision rate. Thus, we interpret the magnetic field location of the maximal decrease in the aspect ratio of the expanded cloud as the position of the Feshbach resonance, B_0. We find that $B_0 = 202.1 \pm 0.1$ G (Fig. 4(a)).

As shown in Fig. 4, we find large loss rates on primarily the repulsive side of the $|9/2,-7/2\rangle$, $|9/2,-9/2\rangle$ Feshbach resonance peak. Recognize that the $|9/2,-7/2\rangle$ and $|9/2,-9/2\rangle$ spin states are distinguished as being the two lowest energy states of the ^{40}K atom at these magnetic fields; they are therefore immune to any two-body losses associated with the s-wave resonance [29]. Hence,

we interpret the loss as three-body recombination associated with the Feshbach resonance. The strong heating can be explained by the density dependence of the three-body loss process as well as by the binding energy released in a recombination process to a weakly bound molecular state [23]. We note that the observed peak in the inelastic processes for an s-wave Feshbach resonance in ^{6}Li is also shifted to the repulsive side of the maximum of the elastic scattering [4, 6].

In conclusion, we have measured the magnetic-field dependence of the lifetime of both molecules and atoms near an s-wave ^{40}K Feshbach resonance. Away from resonance the molecules have a short lifetime due to vibrational quenching, while the atoms have a long lifetime due to Fermi statistics. However, the situation is drastically changed very close to the Feshbach resonance as the molecule size begins to be comparable to the interatomic spacing. Here the molecule decay rate is suppressed by orders of magnitude, while the atoms exhibit strong three-body recombination rates. The atom loss occurs primarily on the repulsive side of the resonance where the weakly bound molecular state exists. We speculate that this state plays an important role in the asymmetry of the three-body recombination. Furthermore, our results suggest that near a Feshbach resonance the strong overlap of atom pair and molecule wavefunctions plays an important role in inelastic processes.

This study shows that the outlook is good for studying long-lived molecules and strongly interacting Fermi atoms. The molecule lifetime near the Feshbach resonance has been shown to be much longer than collision times and trap oscillator periods (Fig. 3). Further, the attractive (high magnetic field) side of the resonance, where fermionic superfluidity is predicted, displays strong elastic interactions with a relatively inconsequential inelastic rates (Fig. 4).

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* Quantum Physics Division, National Institute of Standards and Technology.

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