

Observation of Heteronuclear Feshbach Resonances in a Mixture of Bosons and Fermions

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Three magnetic-field induced heteronuclear Feshbach resonances were identified in collisions between bosonic ^{87}Rb and fermionic ^{40}K atoms in their absolute ground states. Strong inelastic loss from an optically trapped mixture was observed at the resonance positions of 492, 512, and 543 ± 2 G. The magnetic-field locations of these resonances place a tight constraint on the triplet and singlet cross-species scattering lengths, yielding $(-281 \pm 15)a_0$ and $(-54 \pm 12)a_0$, respectively. The width of the loss feature at 543 G is 3.7 ± 1.5 G wide; this broad Feshbach resonance should enable experimental control of the interspecies interactions.

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Since their first observations in 1998 [1], magnetic-field Feshbach resonances in ultracold collisions [2] have been used as a versatile tool for manipulating quantum degenerate atomic gases. Simply by varying the strength of an applied magnetic field, experimenters can control the collisional interactions between ultracold atoms. The scattering length, which characterizes these interactions, can be tuned from positive infinity through zero to negative infinity. The unique tunability provided by Feshbach resonances has enabled the controlled collapse of a Bose-Einstein condensate (BEC) [3], the creation of bright matter wave solitons [4], the formation of ultracold diatomic molecules [5], and the realization of the BCS-BEC crossover in dilute gases [6]. Although Feshbach resonances have now been observed for many of the alkali atoms, including both bosonic and fermionic species, interspecies resonances involving heteronuclear collisions are only now being seen in experiments [7]. As pointed out in Ref. [8], an interspecies Feshbach resonance would open up new possibilities such as boson-mediated Cooper pairing [9] and the creation of ultracold polar molecules [10].

In this Letter we report the observation of Feshbach resonances in the scattering between two distinct species, ^{87}Rb (boson) and ^{40}K (fermion). We have located three interspecies resonances between ^{87}Rb atoms in the $|F, m_F\rangle = |1, 1\rangle$ state and ^{40}K atoms in $|9/2, -9/2\rangle$ states. Here F is the total spin, and m_F is the spin projection. Resonances at 492, 512, and 543 ± 2 G were located from measurements of inelastic loss in a search that initially covered the range from 18 to 635 G. The widest of the features we observe has a full width at half maximum (FWHM) of 3.7 ± 1.5 G; this resonance is sufficiently broad in the magnetic field to permit ready experimental control over the interspecies interactions in this boson-fermion quantum gas mixture.

The observation of magnetic-field Feshbach resonances can also play an important role in improving knowledge of the interatomic molecular potentials, often to an unprecedented level of accuracy [11,12]. Such accuracy is

possible because the location of the Feshbach resonance is very sensitive to the energies of the most weakly bound molecular states. For the case of heteronuclear collisions, in particular, there is often a lack of other spectroscopic data, such as two-color photoassociation spectra, that probe the long-range part of the interatomic potential. In the case of ^{87}Rb and ^{40}K , nonresonant collision measurements have provided information about the scattering parameters [13–15] and enabled a prediction for Feshbach resonances in this system [8]. We compare the observed magnetic-field locations of the ^{87}Rb - ^{40}K resonances reported here with this prediction and from our data provide an improved determination of both the triplet and singlet scattering lengths.

The details of our apparatus and cooling scheme are presented in Ref. [15] and are only briefly recounted here. We simultaneously laser cool ^{87}Rb and ^{40}K atoms in a two-species magneto-optical trap [16]. The ^{87}Rb (^{40}K) atoms are optically pumped to the $|2, 2\rangle$ ($|9/2, 9/2\rangle$) state and captured in a quadrupole magnetic trap mounted on a motorized translation stage. The trap is then physically transported to an ultrahigh vacuum cell, where the atoms are transferred into an Ioffe-Pritchard-type magnetic trap for forced radio-frequency (rf) evaporative cooling. The ^{87}Rb gas is selectively evaporated, with the ^{40}K gas cooled sympathetically through thermal contact with the Bose gas. At the end of the cooling cycle, a ^{87}Rb BEC coexists with a degenerate Fermi gas of ^{40}K atoms at temperatures down to $0.2T_F$, where T_F is the Fermi temperature. For the measurements reported here, however, the evaporation is stopped prior to achieving quantum degeneracy to minimize inelastic losses due to the high density of the ^{87}Rb BEC and prevent the possibility of mechanical collapse of the mixture [17].

To avoid any complications from dipolar collisional loss, which is typically magnetic-field dependent, we put the atoms in the lowest energy magnetic sublevels for searching for Feshbach resonances (Fig. 1). Since these states are high-field seeking, and therefore not confined in our magnetic trap, we use a far off-resonance optical

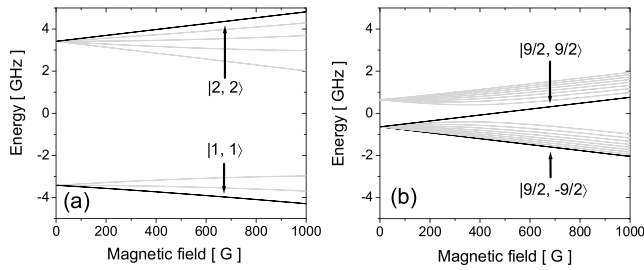


FIG. 1. (a) Hyperfine states of ^{87}Rb as a function of magnetic-field B . The solid black line in the upper ground state manifold is the $|2, 2\rangle$ state where we perform the evaporative cooling in the magnetic trap. Atoms are transferred to the absolute ground state ($|1, 1\rangle$ state; the solid black line in the lower manifold) by applying a frequency-swept microwave field. (b) Hyperfine states of ^{40}K as a function of magnetic field. The stretched state ($|9/2, 9/2\rangle$; the upper solid black line) used for sympathetic cooling resides in the lower manifold. Atoms are transferred to the absolute ground state ($|9/2, -9/2\rangle$; the lower solid black line) by driving a multilevel adiabatic rapid passage induced by a frequency-swept rf field.

dipole trap (FORT) to confine the gas mixture. We load 3×10^5 Rb atoms and 3×10^4 K atoms into the FORT formed at the focus of a Yb:YAG laser beam. The laser operates at a wavelength $\lambda = 1030$ nm and at the focus the intensity profile has a $1/e^2$ radius of $20.5 \mu\text{m}$. For loading, the laser power is linearly increased to 1 W over 500 ms and then the magnetic trap is shut off. A 3 G bias field remains in order to maintain the spin polarization of the atoms. At the end of the FORT loading sequence, the temperature of the mixture is $14 \mu\text{K}$. For comparison, at 1 W the calculated optical trap depth is $\sim 200 \mu\text{K} \times k_B$, where k_B is Boltzmann's constant, and the trap has a radial (axial) trapping frequency for ^{87}Rb atoms of 2.3 kHz (24 Hz).

After loading the optical trap, ^{87}Rb atoms are transferred from the $|2, 2\rangle$ state to the $|1, 1\rangle$ state via adiabatic rapid passage with a 20 ms frequency sweep of an applied microwave field. The efficiency of the transfer is better than 90%, and the remaining $|2, 2\rangle$ atoms are immediately removed from the trap by a 5 ms pulse of light resonant with the $F = 2 \rightarrow F' = 3$ transition. The magnetic field is then increased to 18 G in 100 ms, and the K atoms are transferred from the $|9/2, 9/2\rangle$ state to the $|9/2, -9/2\rangle$ state via adiabatic rapid passage induced by an rf field that is frequency swept across the ten magnetic sublevels [18]. The magnetic field could then be increased to as high as 635 G in order to search for magnetic-field Feshbach resonances. At our highest fields we estimate the magnetic-field difference across the long dimension of the cloud to be less than 10 mG.

To search for Feshbach resonances, we have looked for the enhanced inelastic loss that is common in their vicinities [1]. Data were taken by quickly (in 10 ms) increasing the field to some value and then applying a slow

(1.08 s duration) magnetic-field sweep over a limited range to look for loss features. After returning to the low magnetic field (in 10 ms), the number of remaining ^{40}K atoms was determined from resonant absorption images taken in the optical trap. Initial data covered magnetic fields from 18 to 635 G using 30 G sweeps. Subsequent data zoomed in on the only region where loss was observed. Finally having distinguished three loss features, data were taken holding the magnetic field at a constant value B for the entire 1.08 s to more precisely determine their magnetic-field locations and widths.

Figure 2 shows in-trap absorption images of ^{40}K after holding the ^{87}Rb - ^{40}K gas mixture at constant B in the vicinity of the broadest observed resonance. The reduced number of ^{40}K atoms near $B = 542.4$ G can clearly be seen as a decreased optical depth of the trapped gas. Figure 3 shows the measured number of ^{40}K atoms remaining as a function of B . We observe three distinct loss features which we interpret as resulting from enhanced rates for three-body inelastic collisions near interspecies Feshbach resonances [19]. One would also expect a corresponding loss of Rb atoms from the mixture. However, this was not discernible with our 10:1 ratio of Rb to K atoms. To verify that the K loss features depend on interspecies collisions, we repeated the measurements adding a complete removal of the ^{87}Rb atoms by forced evaporation prior to loading the FORT. For this case, we do not observe any loss in the single-species ^{40}K gas at any B .

The loss features occur at 492, 512, and 543 ± 2 G, where the uncertainty comes from a systematic uncertainty in our calibration of B . The widths are measured to be 0.7 ± 0.2 , 0.4 ± 0.2 , and 3.7 ± 1.5 G, respectively. However, for the two lowest field resonances the measured width may be limited by imperfect magnetic-field stability over the 1.08 s measurement. While a detailed prediction for the inelastic loss line shape near a heteronuclear Feshbach resonance does not yet exist, we note that the observed 3.7 G width of the high-field feature may suggest a Feshbach resonance that is sufficiently

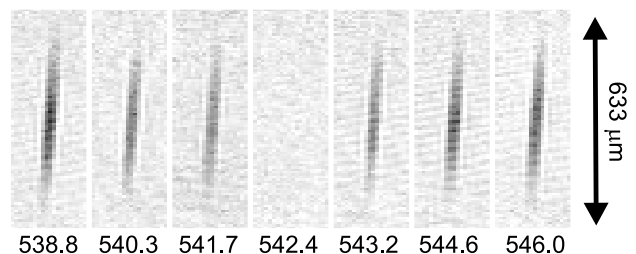


FIG. 2. In-trap absorption images of ^{40}K after holding 1.08 s at various magnetic fields in the vicinity of an interspecies Feshbach resonance with ^{87}Rb atoms. The label on each figure gives the magnetic field in Gauss. There is a systematic ± 2 G uncertainty on the magnetic-field value from our calibration. No ^{40}K atoms could be seen after holding at 542.4 G.

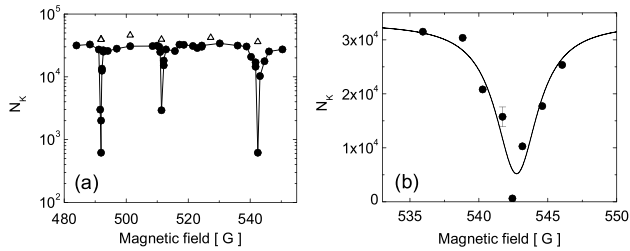


FIG. 3. Observation of the three interspecies Feshbach resonances. (a) Inelastic loss of ^{40}K atoms in the $|9/2, -9/2\rangle$ state was measured by holding the ^{87}Rb - ^{40}K mixture in the optical dipole trap for 1.08 s in a fixed magnetic field B . The number of remaining ^{40}K atoms (shown in filled circles) shows three narrow features as a function of B . The loss features were not observed when ^{87}Rb atoms were removed from the mixture (empty triangles). (b) A closeup of the highest field resonance. The solid line is a Lorentzian fit to the loss with FWHM of 3.7 ± 1.5 G. The error bar reflects only the statistical uncertainty.

broad to enable a wide variety of experiments. Furthermore, the fact that we could observe such narrow features with a 1-s hold, which is long compared to any dynamics of the trapped gas, suggests that inelastic losses near the resonances should be easily managed during future experiments. Finally we note that although we did not observe any other loss features between 18 and 635 G, we cannot rule out the presence of other more narrow resonances, or resonances with highly suppressed inelastic losses.

Figure 4 shows the elastic cross section for collisions between $|9/2, -9/2\rangle$ ^{40}K atoms and $|1, 1\rangle$ ^{87}Rb atoms, calculated using the parameters obtained from the position of the three observed Feshbach resonances. We expect the inelastic loss peaks to coincide with the elastic peaks to within the experimental uncertainty [20]. The

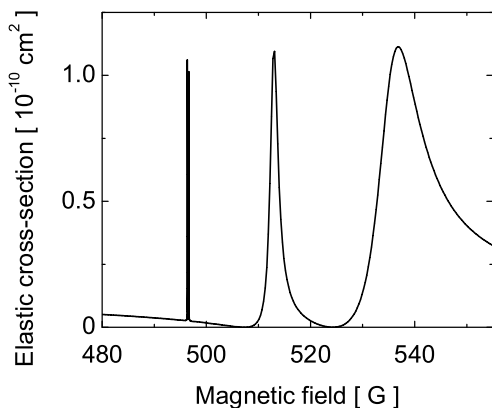


FIG. 4. Calculated elastic cross section for a fixed collision energy of $10 \mu\text{K}$ between ^{87}Rb atoms in the $|1, 1\rangle$ state and ^{40}K atoms in the $|9/2, -9/2\rangle$ state as a function of magnetic field. The triplet (singlet) scattering length used for producing this result was $-281a_0$ ($-54a_0$).

scattering Hamiltonian was constructed in the field-dressed hyperfine basis, by standard methods [21]. This Hamiltonian uses the *ab initio* singlet and triplet potentials from Ref. [22], smoothly matched to the long-range dispersion potentials of the form $V_{\text{long}} = -C_6/R^6 - C_8/R^8 - C_{10}/R^{10} \pm V_{\text{ex}}$. The C_6 coefficient is given by Ref. [23] and the C_8 and C_{10} coefficients are found in Ref. [24]. The exchange potential V_{ex} is estimated using the analytic form of Ref. [25]. These potentials are consistent with the ones used in the calculations of Refs. [8,13]. In addition, the singlet and triplet potentials can be varied at short internuclear separation (shorter than their equilibrium separation) to allow fine-tuning of their scattering lengths.

To fit the data, the singlet and triplet scattering lengths (a_s and a_t , respectively) were varied until all three resonances corresponded with the experimentally measured positions. This analysis demonstrates that the two higher-field resonances are *s* wave in character, while the narrow feature at 492 G represents a *p*-wave resonance. This resonance was predicted in Ref. [26], based on earlier estimates of scattering lengths. The position of a narrow nearby *s*-wave resonance, predicted in Ref. [8], is refined by this analysis; we now expect this resonance to lie at 444 ± 8 G. The result of this assignment of the features establishes the interspecies scattering lengths to be $a_t = (-281 \pm 15)a_0$ and $a_s = (-54 \pm 12)a_0$. Here the error bars have been determined from the range of a_s and a_t that doubles the chi-squared of a simultaneous fit to all three resonance locations. We found that changing C_6 had a negligible effect on the error bars.

The resulting values for the triplet and singlet scattering lengths are in good agreement with collisional measurements of the elastic collision cross section [8,13,15]. Note that there is a serious disagreement when comparing our result with the value of $a_t = (-395 \pm 15)a_0$ determined from comparing theory predictions and experimental observation of collapse phenomena [27]. These results suggest a need for further investigation of the behavior of the mixture close to the collapse. The control over interactions afforded by an interspecies Feshbach resonance should greatly facilitate studies of such interaction-driven phenomena.

In conclusion, we have observed three interspecies Feshbach resonances in a boson-fermion mixture. The resonances were located by observing an inelastic loss of ^{40}K atoms from a ^{87}Rb - ^{40}K mixture in the lowest energy spin states. The location and widths of the loss features are in reasonable agreement with a recent prediction [8] and enable us to make a more precise determination of the singlet and triplet scattering lengths. Future work exploiting these Feshbach resonances to control the interactions in a boson-fermion mixture opens up a number of exciting possibilities such as controlled collapse due to mechanical instability, creation of hetero-

nuclear, fermionic molecules with anisotropic dipole-dipole interactions, fermion-mediated bright solitons in a BEC [28], complex phase diagrams in optical lattices [29], and a proposed p -wave Cooper pairing mechanism [9], where the effective attraction between fermions is generated by a mutual interaction with phonons in the condensate.

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Note added.—Since submission of this manuscript we have observed a loss feature at 453 ± 3 G, which we identify as the s -wave resonance predicted to lie at 444 ± 8 G.

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