Feshbach spectroscopy of a K-Rb atomic mixture

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We perform extensive magnetic Feshbach spectroscopy of an ultracold mixture of fermionic $^{40}$K and bosonic $^{87}$Rb atoms. The magnetic-field locations of 14 interspecies resonances is used to construct a quantum collision model able to predict accurate collisional parameters for all K-Rb isotopic pairs. In particular we determine the interspecies $s$-wave singlet and triplet scattering lengths for the $^{40}$K-$^{87}$Rb mixture as $(-111 \pm 5)a_0$ and $(-215 \pm 10)a_0$ respectively. We also predict accurate scattering lengths and position of Feshbach resonances for the other K-Rb isotopic pairs. We discuss the consequences of our results for current and future experiments with ultracold K-Rb mixtures.

Quantum degenerate atomic mixtures\cite{1,2,3,4,5,6,7} are promising for the study of a variety of novel physical phenomena, such as production of quantum gases of polar molecules\cite{7}, boson-induced superfluidity of fermions\cite{8}, and quantum phases of matter in optical lattices\cite{8} or random potentials\cite{10}. The study of these phenomena requires the use of magnetically tunable Feshbach resonances\cite{11} to control the interaction. A detailed knowledge of resonances and collisional parameters is however necessary to achieve such control. Feshbach resonances have been deeply investigated in homonuclear systems, and recently observed also in some heteronuclear mixtures\cite{12,13,14,15,16,17}. However, accurate Feshbach spectroscopy, has been performed so far only on homonuclear systems\cite{15,16,17}. We report here an extensive experimental study of Feshbach resonances in a $^{40}$K-$^{87}$Rb mixture. This is used to construct a quantum collisional model able to predict the relevant parameters for all K-Rb isotopic pairs, including both boson-fermion and boson-boson pairs of great experimental interest.

In particular this study allows us to determine univocally the scattering lengths for the $^{40}$K-$^{87}$Rb mixture, for which contrasting determinations have been reported. The values we find for the singlet $a_s$ and triplet $a_t$ scattering lengths are $(-111 \pm 5)a_0$ and $(-215 \pm 10)a_0$, respectively. We also determine high-accuracy values for inter-isotope triplet and singlet scattering lengths for all other K-Rb pairs. In addition, we determine all relevant parameters of Feshbach resonances in the $^{40}$K-$^{87}$Rb mixture and demonstrate the presence of several Feshbach resonances in other K-Rb isotopic pairs. Our findings have important consequences for both ongoing and future experiments with K-Rb mixtures.

The apparatus and techniques used have already been presented in detail elsewhere\cite{7} and are only briefly summarized here. We prepare samples of typically $10^9$ K fermions and $5 \times 10^9$ Rb bosons at ultralow temperatures using two successive phases of laser and evaporative cooling. The mixture is magnetically trapped in the states $|F = 9/2, m_F = 9/2\rangle$ for K and $|2, 2\rangle$ for Rb. The atomic sample is then adiabatically transferred to a purely optical trap, created by two off-resonance laser beams, at a wavelength of 830 nm, crossing in the horizontal plane. The typical density of the Rb (K) sample in the optical trap throughout this experiment was $5 \times 10^{12}$ cm$^{-3}$ (1$\times$10$^{12}$ cm$^{-3}$), while the common temperature of the two gases was about 1 $\mu$K. At this temperature the two samples are still out of the quantum regime.

The atoms are then transferred in selected states by means of a series of radio-frequency (RF) and microwave (\muw) adiabatic rapid passages. As already noted in\cite{22}

![Figure 1: Relative inelastic losses of potassium atoms in a $^{40}$K-$^{87}$Rb mixture in its absolute ground state at interspecies Feshbach resonances. The two features near 456 G and 515 G are $p$-wave resonances, the others are $s$-wave resonances.](image)
any combination of states in which one species is in its absolute ground state and the other is in any magnetic sublevel of its ground hyperfine state, is stable against spin-exchange collisions. In this work we have studied in particular the combinations with Rb in \( |1, 1 \rangle \) and K in: a)\( |9/2, -9/2 \rangle \); b)\( |9/2, -7/2 \rangle \); c) \( |9/2, 7/2 \rangle \). In a first phase we apply a homogeneous magnetic field of about 10 G and then transfer Rb to the \( |1, 1 \rangle \) state and K to the \( |9/2, -9/2 \rangle \) (for cases a and b) by means \( \mu \omega \) and RF sweeps, respectively. The field is then raised to 100 G to perform the additional K transfer \( |9/2, -9/2 \rangle \rightarrow |9/2, -7/2 \rangle \) (\( |9/2, 9/2 \rangle \rightarrow |9/2, 7/2 \rangle \)) for case b(c) with another RF sweep. The homogeneous field is then changed in few ms to any value in the range 0-900 G and actively stabilized there with an accuracy of about 200 mG. The field is calibrated by means of RF spectroscopy of the \( |2, 2 \rangle - |2, 1 \rangle \) transition of Rb.

To look for Feshbach resonances we record the fraction of K atoms lost through inelastic collisions after about 1 s of permanence in the magnetic field. The typical experimental signature of interspecies resonance is shown in Fig. 11 for the absolute ground state of the mixture (\( |9/2, -9/2 \rangle + |1, 1 \rangle \)): due to the lower abundance of K in our sample, we usually observe a complete loss of K atoms at resonance. To avoid any possible confusion with homonuclear resonances we also check the absence of losses after removing either K or Rb from the mixture before applying the magnetic field.

The first theoretical study on this system \cite{22} predicted the presence of several resonances around 500 G for most hyperfine states. In this experiment we have detected 14 of such resonances, including the four in the ground state already investigated in Ref. \cite{13}. The measured positions and widths are summarized in Tab. \ref{tab:1}. While our measurements confirm the magnetic-field positions of the four resonances reported in \cite{13}, most of the newly observed resonance pattern cannot be reproduced using the collision model proposed in \cite{13, 22}, indicating the need for an alternative interpretation.

Our theoretical quantum collision model is constructed as described in Ref. \cite{18, 22}. The isotropic singlet \( X^1 \Sigma^+ \) and triplet \( e \Sigma^+ \) interaction potentials are parameterized in terms of the \( \alpha_s \) and \( \alpha_t \) scattering lengths, respectively. Few sample experimental features are compared to maxima in the two-body elastic cross section computed for different \( \alpha_s, \alpha_t \), until a good agreement is found. A global least square fit is then performed, leading to the best fit parameters with one standard deviation \( \alpha_s = (-111 \pm 5) a_0 \) and \( \alpha_t = (-215 \pm 10) a_0 \). In the fit also the van der Waals coefficient \( C_6 \) is let free to vary, obtaining \( C_6 = (4292 \pm 19) \text{ a.u.} \), which agrees to better than one standard deviation with the high precision \textit{ab initio} calculation of \cite{24}. Error bars also include a typical \( \pm 10\% \) uncertainty in \( C_6 \). The average theory-experiment deviation for the resonance positions is about 0.3 G only.

The nature of the molecular states associated to the resonances can be better understood through multichannel bound state calculations. Since \( \alpha_s \) and \( \alpha_t \) are comparable the spacing between singlet and triplet vibrational levels is small compared to the hyperfine interaction. Strong singlet/triplet mixing then occurs at least for the two vibrational states closest to dissociation, resulting in molecular levels labeled as \( (F_a F_b F_\ell) \) in zero magnetic field, where \( F_\ell \) is the rotational quantum number and \( \vec{F} = \vec{F}_a + \vec{F}_b \). The features below \( \approx 600 \text{ G} \) arise from these strongly mixed levels. At such magnetic fields however the Zeeman magnetic energy is comparable to the smaller hyperfine splitting in the system, that of \( ^{40}\text{K} \). Therefore \( F_a \) is not a good quantum number to label the resonances, whereas \( F_b \) is approximately good and equal to 2. Resonances at higher magnetic field correlate with more deeply-bound states and tend to assume singlet or triplet character. In all cases \( \ell \) is an almost exact quantum number and is also shown in Tab. \ref{tab:1}.

In Tab. \ref{tab:1} we also show the theoretical width \( \Delta_{th} \) of the resonances, defined as the difference between the magnetic-field locations of maximum and minimum of the elastic cross section. The \( \ell=0 \) molecules tend to give rise to broad resonances due to strong spin-exchange coupling to incoming \( s \)-wave atoms. We also observe two narrow resonances due to coupling of an \( \ell=2 \) molecule to incoming \( s \)-wave atoms through weaker anisotropic spin-spin interactions \cite{13, 17}. The two resonances associated with \( \ell=1 \) molecules couple by spin-exchange to incoming \( p \)-wave atoms. These resonances have an energy-

| \( m_{F_a} \) + \( m_{F_b} \) | \( B_{\text{exp}} \) (G) | \( \Delta_{\text{exp}} \) (G) | \( B_{\text{th}} \) (G) | \( \Delta_{\text{th}} \) (G) |
|---|---|---|---|---|
| \( |9/2⟩ + |1⟩ \) | 456.0 ± 0.2 | 456.5 ± 2 \( \times 10^{-3} \) | 1 |
| \( |9/2⟩ + |1⟩ \) | 495.6 ± 0.5 | 495.7 ± 0.16 | 0 |
| \( |9/2⟩ + |1⟩ \) | 515.7 ± 0.5 | 515.4 ± 0.25 | 1 |
| \( |9/2⟩ + |1⟩ \) | 546.7 ± 0.7 | 546.8 ± 2.9 | 2 |
| \( |9/2⟩ + |1⟩ \) | 558.9 ± 0.6 | 569.2 ± 1.0 | 0 |
| \( |9/2⟩ + |1⟩ \) | 563.7 ± 0.6 | 563.9 ± 0.018 | 1 |
| \( |7/2⟩ + |1⟩ \) | 469.2 ± 0.4 | 469.2 ± 0.16 | 0 |
| \( |7/2⟩ + |1⟩ \) | 584.0 ± 0.2 | 584.1 ± 0.67 | 0 |
| \( |7/2⟩ + |1⟩ \) | 591.0 ± 0.3 | 591.0 ± 2 \( \times 10^{-3} \) | 2 |
| \( |7/2⟩ + |1⟩ \) | 598.3 ± 0.6 | 598.2 ± 2.5 | 0 |
| \( |7/2⟩ + |1⟩ \) | 697.3 ± 0.3 | 697.3 ± 1.6 | 0 |
| \( |7/2⟩ + |1⟩ \) | 705.0 ± 0.6 | 704.5 ± 0.78 | 2 |

\[ \Delta_{\text{th}} \text{ (G)} = (4292 \pm 19) \text{ a.u.}, \]
dependent width $\Delta_{\text{exp}}$ of the highest-field $p$-wave feature is larger, as expected because of its larger $\Delta_{\text{Rb}}$. Tab. 1 also shows two narrow not yet observed resonances. We find that several stable states of the mixture present at least one broad resonance, analogous to that in the ground state near 545 G. Any of these resonances can be very well suited for control of the interaction and molecule formation.

The optimized $^{40}\text{K}-^{87}\text{Rb}$ model can now be used to determine singlet and triplet scattering lengths $\tilde{a}_{s,t}$ for any K-Rb isotopic pair, see Tab. 1. Within the Born-Oppenheimer approximation this can be simply achieved by using the appropriate reduced mass in the Hamiltonian. We note that such mass-scaling procedure depends in a sensitive way on the actual number of bound states supported by the potentials. They are nominally $N_t^b = 98$ and $N_t^s = 32$ for the singlet and triplet $ab$ initial potentials we use, with an expected uncertainty of $\pm 2$. In fact, we find that the error in $\tilde{a}_{s,t}$ due to variation $\delta N_t^{s,t}$ (for fixed $a_{s,t}$) dominates that due to $a_{s,t}$ (for fixed $N_t^{s,t}$) for all the isotopic combinations. This shift can be expressed to a few percent accuracy through

$$\frac{2}{\pi} \frac{\delta \text{arctan} \tilde{a}_{s,t}}{L} = \beta_{s,t} \delta N_t^{s,t}$$

(1)

where $L = 72 \mu_0 \approx \frac{1}{2} (2\mu \mathcal{C}_0)^{1/4}$ is the typical length scale of a van der Waals potential, with $\mu$ the K-Rb reduced mass. The value of the $^{41}\text{K}-^{87}\text{Rb}$ triplet scattering length in Tab. 1 confirms the direct collisional measurements reported in Ref. [13]. The comparison is not conclusive about the number of bound states, though an optimal agreement is found for our nominal $N_t^s$. However, a limited amount of Feshbach spectroscopy on a different pair might be sufficient to determine $N_t^{s,t}$.

Another quantity of general interest for experiments with K-Rb mixtures is the effective elastic scattering length $a$ for the absolute ground state. The $a$ for all isotopes are reported in Tab. 1 together with the location of Feshbach resonances for the systems we judge most interesting for future experiments, the three boson-boson pairs $^{39}\text{K}-^{87}\text{Rb}$, $^{41}\text{K}-^{85}\text{Rb}$, and $^{44}\text{K}-^{87}\text{Rb}$.

Let us now discuss the results presented so far, beginning with the $^{40}\text{K}-^{87}\text{Rb}$ system for which a comparison with existing determination of the scattering lengths is due. The values of $a_{s,t}$ determined here differ from the results $a_s = (-54 \pm 12) a_0$ and $a_t = (-281 \pm 15) a_0$ of the analysis in Ref. [13], which was based on an incorrect resonance assignment. The present $a_s$ value is consistent with Ref. [22]. The $a_t$ is consistent with the value of Ref. [18], which however bears large error bars, and it is in reasonable agreement with Ref. [21]. It is otherwise neither consistent with the determination of [13] nor with the observation of a collapse instability in this mixture [27, 28]. Comparison of the collapse observations reported so far with current mean-field models indicated $a_t = (-395 \pm 15) a_0$ for [27] (see the analysis in [5]) and $(-281 \pm 15) a_0$ for [28]. These discrepancies with the current determination could be in principle explained by a low-field Feshbach resonance in the magnetically trappable state $|9/2, 9/2, +2, 2\rangle$ used in those experiments, which however seems to be excluded by our collisional model. Further investigation is therefore necessary in order to understand the observed phenomenology. In particular, use of Feshbach resonances to control the effective interaction should allow the current theories of instabilities to be tested.

The Fermi-Bose system is also interesting to study boson-induced fermion pairing [8], due to its large and attractive background interaction. However, the new value of the ground state scattering length is considerably smaller than the one considered in Ref. [22] and the optimal conditions for $s$-wave pairing described therein seem to be difficult to reach. Moreover, the present investigation shows that no overlapping resonances which could be used to favor the pairing [22] exist in collisions between the two lower Zeeman states of K and the ground state of Rb. The most promising direction seems therefore to be the $p$-wave boson-induced pairing of fermions [37] at an interspecies $p$-wave Feshbach resonance.

Concerning the other isotopic pairs, the simultaneous determination of scattering lengths and Feshbach resonances is of invaluable help in devising future experiments. For example, sympathetic cooling of $^{39}\text{K}$ using $^{87}\text{Rb}$ is interesting to create a Bose-Einstein condensate with zero-field negative scattering length in the ground state and a rather broad Feshbach resonance available at low field in the $|1, -1\rangle$ hyperfine state [29]. In spite of a rather small interspecies scattering length the broad resonance near 320 G predicted in this work could be used in order to enhance thermalization between the two components. A sample of $^{41}\text{K}$ could instead be used to

| K-Rb | $\tilde{a}_s (a_0)$ | $\beta_s$ | $\tilde{a}_t (a_0)$ | $\beta_t$ |
|------|------------------|--------|------------------|--------|
| 39-85 | 26.5 ± 0.9 | -2.8(-2) | 63.0 ± 0.5 | -1.3(-2) |
| 39-87 | 824^{+90}_{-70} | -1.5(-2) | 35.9 ± 0.7 | -1.6(-2) |
| 40-85 | 64.5 ± 0.6 | -3.9(-3) | -28.4 ± 1.6 | -1.8(-2) |
| 40-87 | -111 ± 5 | -215 ± 10 | - | - |
| 41-85 | 106.0 ± 0.8 | 3.6(-3) | 348 ± 10 | 6.5(-3) |
| 41-87 | 14.0 ± 1.1 | 2.6(-2) | 163.7 ± 1.6 | 7.7(-3) |
TABLE III: Predicted zero-field $s$-wave scattering lengths for the absolute ground state of K-Rb isotopes. Feshbach resonance positions and widths are also provided for three selected isotopic pairs. The quoted uncertainties do not include the uncertainty on the number of bound states.

| K-Rb | $a$ ($a_0$) | $B_{th}$ (G) | $\Delta_{th}$ (G) |
|------|-------------|--------------|-----------------|
| 39-85 | 56.6 $\pm$ 0.4 | 248.8 $\pm$ 1.6 | 0.26 |
| 39-87 | 27.9 $\pm$ 0.9 | 320.1 $\pm$ 1.6 | 7.9 |
|       |              | 531.9 $\pm$ 1.2 | 2.7 |
|       |              | 616.2 $\pm$ 1.5 | 0.10 |
| 40-85 | $-21.3 \pm 1.6$ |                |          |
| 40-87 | $-185 \pm 7$ |                |          |
| 41-85 | 283 $\pm$ 6 | 132.5 $\pm$ 0.6 | 0.19 |
|       |              | 141.2 $\pm$ 1.1 | 2.10$^{-4}$ |
|       |              | 147 $\pm$ 2 | 0.025 |
|       |              | 184.6 $\pm$ 1.0 | 2.9 |
|       |              | 191.4 $\pm$ 1.0 | 0.81 |
|       |              | 660 $\pm$ 3 | 3.4 |
|       |              | 687 $\pm$ 2 | 16 |
| 41-87 | 1667$^{+720}_{-406}$ | 17 $\pm$ 5 | 45 |
|       |              | 67 $\pm$ 3 | 8.9 |
|       |              | 516 $\pm$ 7 | 82 |
|       |              | 688 $\pm$ 8 | 0.059 |

optimize the evaporation of $^{85}$Rb atoms which is typi-}

cally very inefficient in a pure homonuclear sample due to occurrence of the first zero in the $^{85}$Rb cross-section already at temperatures on the order of 100 $\mu$K. On the other hand, we have checked that the large magnitude of the zero energy interspecies cross section persists even up to the mK regime. The availability of several Feshbach resonances at relatively low field could also prove to be useful for the production of binary Bose-Einstein condensates where both the self- and the interspecies interaction are tunable. Finally, in the $^{41}$K-$^{87}$Rb pair, a system for which the production of a stable binary condensate has already been reported, availability of very broad resonances will allow the mutual interaction to be precisely tuned. The availability of heteronuclear resonances in these mixtures could also be exploited for the formation of bosonic polar molecules.

In conclusion, we have performed extensive Feshbach spectroscopy in the heteronuclear $^{40}$K-$^{87}$Rb system and constructed an accurate collisional model capable of predicting scattering lengths and Feshbach resonances for all K-Rb isotopic pairs. This will serve as invaluable input to future experiments on these mixtures. In particular, our accurate characterization of Feshbach resonances in K-Rb mixtures will be useful to investigate the formation of both fermionic and bosonic heteronuclear molecules.

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