Investigation of Feshbach Resonances in ultra-cold $^{40}\text{K}$ spin mixtures

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Magnetically-tunable Feshbach resonances are an indispensable tool for experiments with atomic quantum gases. We report on twenty thus far unpublished Feshbach resonances and twenty one further probable Feshbach resonances in spin mixtures of ultracold fermionic $^{40}\text{K}$ with temperatures well below 100 nK. In particular, we locate a broad resonance at $B = 389.6\text{ G}$ with a magnetic width of 26.4 G. Here $1\text{ G} = 10^{-4}\text{ T}$. Furthermore, by exciting low-energy spin waves, we demonstrate a novel means to precisely determine the zero crossing of the scattering length for this broad Feshbach resonance. Our findings allow for further tunability in experiments with ultracold $^{40}\text{K}$ quantum gases.

Ultracold fermionic atomic gases are ideally suited for the study of many-body quantum phenomena owing to the unrivaled control over experimental parameters such as the spatial geometry of confining potentials and the interaction strength between the atoms. The interaction strength is controlled using magnetically-tunable Feshbach resonances and typically characterized by the scattering length, which can be set to a wide range of values, either negative or positive. Feshbach resonances have been found in many bosonic as well as fermionic atomic systems (see [1–5] and references therein). The isotope $^{40}\text{K}$ constitutes one of the work horses in current experiments with ultracold fermions and provides a rich ground-state structure allowing for the realization of binary and multi-component spin mixtures [6–23] as well as several Bose-Fermi [24–30] and Fermi-Fermi mixtures [31–35]. In the energetically-lowest hyperfine manifold with total angular momentum $f = 9/2$ ten magnetic spin states are available ranging from $m = -9/2, \ldots, +9/2$ and 45 binary spin mixtures can be realized [36]. So far, only three Feshbach resonances have been reported, one for each of collision channels $\{m_1, m_2\} = \{-9/2, -7/2\}$ [37], $\{-7/2, -7/2\}$ [38, 39] and $\{-9/2, -5/2\}$ [40].

Here, we report on the experimental observation of 20 theoretically confirmed and 22 further probable magnetic Feshbach resonances in different spin mixtures of ultracold $^{40}\text{K}$. Their positions are determined from the enhanced, resonant loss of atoms near the resonance. In addition, we introduce a novel method for precisely determining the sign changes of the scattering length around the Feshbach resonance by exciting low-energy spin waves. In particular, this approach enables us to measure the zero crossing with high accuracy. We also find that the measured positions of the assigned Feshbach resonances agree well with theoretical calculations based on multi-channel quantum defect theory using the best available Born-Oppenheimer potentials for $^{40}\text{K}$ [41].

A Feshbach resonance occurs when two atoms in well-defined spin states collide and couple to a virtual molecular state with a different spin configuration [1–5]. As these configurations have different magnetic moments their relative Zeeman energy can be tuned with a magnetic field. This leads to a magnetic-field-dependent complex scattering length $a(B) = a(B) - ib(B)$, where real-valued $a(B)$ and $b(B) > 0$ describe elastic and inelastic two-body processes, respectively. Here, we have allowed for inelastic transitions to spin configurations whose Zeeman energy is below that of the entrance configuration. In fact, near a resonance and in the limit of zero collision energy

$$a(B) = a_{\text{bg}} \left( 1 - \frac{\Delta B (B - B_{\text{res}})}{(B - B_{\text{res}})^2 + (\gamma_2/2)^2} \right), \quad (1)$$

with resonance position $B_{\text{res}}$, magnetic width $\Delta B$, and background scattering length $a_{\text{bg}}$. Finally $\gamma_2$ describes two-body decay to other spin-channels (expressed in units of the magnetic field). Similarly, we have

$$b(B) = 2a_{\text{res}} \frac{(\gamma_2/2)^2}{(B - B_{\text{res}})^2 + (\gamma_2/2)^2}, \quad (2)$$

with resonance length $a_{\text{res}} = a_{\text{bg}} \Delta B / \gamma_2$. Atom loss, quantified by the two-body rate coefficient $K_2(B) = 4\pi h b(B)/\mu$, is largest in the vicinity of the resonance position $B_{\text{res}}$. Here, $h$ is the reduced Planck constant, $\mu = m/2$, and $m$ is the atomic mass.

We begin our experiments by preparing a spin mixture of $m_1 = +9/2$ and $m_2 = +7/2$ atoms with about $N = 5 \times 10^4$ atoms per spin state in an optical dipole trap. The trap is harmonic and nearly isotropic with
mean trapping frequency \( \tilde{\omega} = 2\pi \times 50\,\text{Hz} \) and temperature \( T \approx 0.3\,\text{T}_{\text{F}} \), where \( T_{\text{F}} = \hbar \tilde{\omega}/(6N)^{1/3}/k \approx 170\,\text{nK} \) is the Fermi temperature and \( k \) is the Boltzmann constant. For the investigation of different collision channels, the corresponding spin mixture is prepared at a magnetic field of \( B = 45\,\text{G} \) using radio-frequency sweep protocols optimized for each mixture. After this preparation, the magnetic field is ramped to its final value and the ensemble is held for a time of 100 ms. The magnetic field is switched off and the remaining atoms are counted after a time-of-flight in a Stern-Gerlach gradient field. The field value where atom loss is maximal, \( B_{\text{loss}} \), is assigned as the resonance position \( B_{\text{res}} \). The full-width-half-maximum magnetic width of the experimental loss feature is denoted by \( \sigma_{\text{loss}} \).

We have located 41 resonant loss features in this manner. Based on multi-channel quantum defect theory [14, 12], we find that nineteen of these features are Feshbach resonances with \( s \) partial-wave character and one has \( p \)-wave character. In addition, there is qualitative agreement between the location of these experimental loss maxima and the theoretical resonance location. Table I lists these twenty assigned resonances. The remaining loss features are probable Feshbach resonances. They are listed in Table II. For these features we have no corresponding theoretical calculations. Parallel to this work, groups in Munich and Amsterdam have measured other \( ^{40}\text{K} \) Feshbach resonances in different collision channels [44].

Note that the position of a resonance determined from atom loss measurements contains systematic deviations as reported previously, i.e. \( B_{\text{res}} \neq B_{\text{loss}} \) [16]. Similarly \( \sigma_{\text{loss}} \) does not coincide with the calculated \( \gamma_{2} \). Atom loss is not only due to two-body collisions but is also caused by three-body recombinations, where three colliding atoms react to produce a hot molecule. The field-dependent recombination rate coefficient \( K_{3}(B) \), does not need to peak at the same \( B \)-field or have the same width as \( K_{2}(B) \). In addition, for quantum degenerate Fermi gases of \( ^{40}\text{K} \) atoms, collective phenomena can modify the resonance feature especially when the scattering length \( a(B) \) is large compared to \( 1/k_{\text{F}} \), where the Fermi wavevector \( k_{\text{F}} \) is defined by \( h^{2}k^{2}/(2m) = kT_{\text{F}} \) [51]. Finally, lineshapes can also be distorted when a large fraction of the atoms is lost.

The collision channel \( \{+1/2, -1/2\} \) is of particular interest. It is the magnetic ground state of the spin subspace with zero magnetization \( M = m_{1} + m_{2} = 0 \) and, hence, losses due to inelastic two-body collisions can only occur by spin-relaxation from the weak magnetic dipole-dipole interactions [23]. In this mixture, we have located a Feshbach resonance at \( B_{\text{res}}^{\text{calc}} = 389.6\,\text{G} \) with a width of \( \Delta B_{\text{res}}^{\text{calc}} = 26.4\,\text{G} \), which is about three times larger than the width of the commonly used Feshbach resonances in the channels \( \{-9/2, -7/2\} \) and \( \{-9/2, -5/2\} \).

From an experimental point of view, a broad resonance is desirable as it lowers the technical demands for setting a stable value of the interaction strength close to resonance. Hence, the accurate determination of the resonance position \( B_{\text{res}} \) and the zero crossing, where \( a(B) \) has a node as a function of \( B \), are of particular importance.

The latter occurs when \( B_{\text{zero}} = B_{\text{res}} + \Delta B \) as can be seen from Eq. [4] when \( \gamma_{2} \to 0 \). At this zero crossing atom loss tends to be small. Recently, detection methods such as radio-frequency spectroscopy [17, 44], collective excitations [15, 16], Bloch oscillations [17], and spin segregation [18] have been used to determine the resonance position or the zero crossing. Here, we report on a method based on creating spin-wave excitations near a Feshbach resonance. These excitations are sensitive to the sign of the scattering length \( a(B) \) [20] and, in particular, the phase of the spin-wave changes sign as the sign of \( a(B) \) changes. Spin waves are an interaction-induced phenomenon and cannot be excited at the zero crossing. For strong interactions close to the pole in \( a(B) \) where the sign of \( a(B) \) also changes many-body effects induce additional corrections [51]. Therefore, spin waves are particularly suited for finding the zero crossing of Feshbach resonances.

We excite spin waves with spatially-dependent mag-

| \{m_{1}, m_{2}\} | M | pw | \( B_{\text{calc}} \) | \( \sigma_{\text{loss}} \) | \( \Delta B_{\text{phase}}^{\text{calc}} \) |
|-----------------|-----|----------|-------------|-------------|-----------------|
| \{+1/2, −1/2\} | 0   | s        | 15 (4)      | 4           | 17.3            | 0.1             |
|                 | 0   | s        | 31 (4)      | 5           | 30.9            | 0.2             |
|                 | 0   | s        | 53 (4)      | 5           | 53.4            | 0.4             |
|                 | 0   | s        | 88 (4)      | 4           | 87.1            | 0.4             |
|                 | 0   | s        | 246 (0.8)   | 2.4         | 246.6           | 2.0             |
|                 | 0   | s        | 389 (1)     | 5.5         | 389.6           | 26.4            |
| \{+3/2, −3/2\} | 0   | s        | 95 (4)      | 23          | 93.8            | 1.8             |
|                 | 0   | s        | 182 (4)     | 12          | 181.5           | 2.2             |
| \{+5/2, −5/2\} | 0   | s        | 61 (4)      | 21          | 61.5            | 4.2             |
| \{+7/2, −7/2\} | 0   | s        | 34.3 (0.8)  | 10.8        | 35.0            | 3.4             |
|                 | 0   | s        | 147.1 (3.0) | 0.8         | 145.8           | 0.2             |
| \{+9/2, −9/2\} | 0   | s        | 17.6 (0.3)  | 5.4         | 18.8            | 1.8             |
| \{+9/2, −7/2\} | +1  | s        | 13.9 (0.2)  | 1.3         | 14.5            | 0.4             |
|                 | +1  | s        | 28.4 (0.3)  | 6.1         | 30.2            | 2.9             |
| \{+9/2, −5/2\} | +2  | s        | 27.3 (0.3)  | 4.8         | 27.1            | 1.4             |
| \{+9/2, −3/2\} | +3  | s        | 63.4 (0.7)  | 30          | 63.3            | 6.0             |
| \{+9/2, −1/2\} | +4  | s        | 53 (4)      | 14          | 52.4            | 3.1             |
|                 | +4  | s        | 137 (8)     | 53          | 140.5           | 14.0            |
| \{+9/2, 1/2\}  | +4  | s        | 114 (8)     | >40         | 113.5           | 7.8             |

**TABLE I. Twenty assigned Feshbach resonances in \(^{40}\text{K}\).** The first five columns represent the collision channel \( \{m_{1}, m_{2}\} \) in the \( f = 9/2 \) manifold, the total spin quantum number \( M = m_{1} + m_{2} \), the partial wave (pw), the experimental maximum loss position \( B_{\text{loss}} \) and the observed magnetic width \( \sigma_{\text{loss}} \); respectively. The uncertainty of \( B_{\text{loss}} \), given in parenthesis, is one standard deviation uncertainty with combined systematic and statistical error. The last two columns show the calculated resonance position \( B_{\text{res}}^{\text{calc}} \) and the magnetic width \( \Delta B_{\text{phase}}^{\text{calc}} \). Magnetic fields and widths are in Gauss.
magnetic fields that induce spatially-dependent relative phase evolution between the two spin components (for details see [21]). For this purpose, we first prepare a single-component Fermi gas in spin state $m = +1/2$ in an elongated dipole trap with trapping frequencies $\omega = 2\pi \times (70, 70, 12)$ Hz along the three independent spatial directions. At a magnetic field near the $\{+1/2, -1/2\}$ Feshbach resonance at $B_{\text{res}}^{\text{calc}} = 389.6$ G, we subsequently apply a radio-frequency pulse with a duration of $10\,\mu$s to create a coherent and equal superposition of the spin states $m = +1/2$ and $-1/2$. We then excite a spin wave by using one of the two types of field inhomogeneities along the weakest trapping direction. Close to the zero crossing, where the interaction strength is small, we apply a linear magnetic gradient and excite linear spin waves leading to dipole oscillations. For larger interaction strengths small field inhomogeneities are sufficient. Here, even the small residual magnetic quadrupole component originating from the Helmholz coils excite quadrupole spin waves and spatial breathing modes. Examples of the spatial breathing and dipole modes are shown in Figs. 1b) and b). In both cases counterflow spin currents between the two spin components are induced, even though the overall density remains constant. While the dipole mode induced near the zero crossing of the resonance is long lived [21], the breathing mode quickly decays due to incoherent collisions in the vicinity of $B_{\text{res}}$ [19].

The initial phase and amplitude of the breathing and dipole oscillation depends on the magnetic field strength. To extract this behavior from our data we analyze the time-dependence of the variance of the spatial density profile along the weak trapping direction for the breathing mode and of the displacement of each of the spin components for the dipole mode. The time evolution of the difference in the variance of the two spin clouds is shown in Fig. 2a) for two magnetic fields on either side of the $B_{\text{res}} = 389.6$ G resonance position. Initially, the differential width grows up to a maximum value and then slowly decays to zero indicative of strongly damped motion. Figure 2b) depicts the time evolution of the difference in the displacement of the two spin components for two magnetic fields on either side of the zero crossing. The dipole oscillations remain visible over several periods. The measurements in Figs. 2a) and b) also reveal a strong magnetic field dependence. Figures 2c) and d) summarize this dependence as a function of magnetic field. Using a linear fit, we can accurately determine the magnetic field at which the spin waves change their oscillation phase. This yields $B_{\text{sw}}^{\text{calc}} = 389.5$ (0.1) G and $B_{\text{sw}}^{\text{calc}} = 416.1$ (0.1) G, respectively. The quoted one standard deviation uncertainty follows from the fit. We estimate a systematic error due to an uncertainty in the magnetic field calibration of $\Delta B_{\text{sys}} = 0.2$ G.

| $\{m_1, m_2\}$ | $M$ | $\delta E$ | $|B_{\text{loss}}|$ | $\sigma_{\text{loss}}$ |
|-----------------|-----|----------|-----------------|------------|
| $\{+5/2, -9/2\}$ | -2 s | 24.0(0.5) | 4.2             |
| $\{-1/2, -1/2\}$ | -1 p | 373(2)   | 2               |
| $\{+1/2, -1/2\}$ | 0 s  | 61(4)    | 4               |
| $\{+3/2, -3/2\}$ | 0 s  | 31(4)    | 6               |
| $\{+5/2, -5/2\}$ | 0 s  | 46(4)    | 4               |
| $\{+7/2, -7/2\}$ | 0 s  | 53(4)    | 4               |
| $\{+9/2, -9/2\}$ | 0 s  | 31(4)    | 6               |
| $\{+7/2, -5/2\}$ | 0 s  | 65.5(1.3)| 11              |
| $\{+5/2, -3/2\}$ | 0 s  | 35.9(0.4)| 5.6             |
| $\{+9/2, -7/2\}$ | 0 s  | 93.6(1.3)| 17.3            |
| $\{+7/2, -5/2\}$ | 0 s  | 66.3(0.7)| 14.5            |
| $\{+5/2, -3/2\}$ | 0 s  | 61(8)    | 29              |
| $\{+7/2, -3/2\}$ | 0 s  | 23(8)    | 8               |
| $\{+5/2, -5/2\}$ | 0 s  | 53(8)    | 8               |
| $\{+9/2, -7/2\}$ | 0 s  | 120(8)   | >40             |
| $\{+3/2, +3/2\}$ | 0 s  | 150(3)   | 40              |
| $\{+9/2, -1/2\}$ | 0 s  | 76(4)    | 4               |
| $\{+7/2, +7/2\}$ | 0 s  | 140(4)   | 4               |
| $\{+5/2, -1/2\}$ | 0 s  | 61(8)    | 9               |
| $\{+9/2, -3/2\}$ | 0 s  | 105(3)   | 11              |
| $\{+7/2, +5/2\}$ | 0 s  | 182(2)   | 12              |

**TABLE II.** Further measured loss resonances in $^{40}$K. Columns represent collision channel $\{m_1, m_2\}$ in the $f = 9/2$ manifold, quantum number $M = m_1 + m_2$, the partial wave, the maximum loss position $|B_{\text{loss}}|$, and the magnetic width $\sigma_{\text{loss}}$. For these loss features no corresponding theoretical value exists. Magnetic fields and widths are in Gauss. The partial wave for each resonance has been assigned s-wave for equal losses in both components and p-wave if losses occur in only one component.

![FIG. 1. Breathing and dipole mode resulting from a quadrupole and linear spin wave.](image-url)
Spin waves for different magnetic fields. (a) Time evolution of the differential variance for a breathing-mode spin wave at two magnetic fields close the broad \((+1/2,-1/2)\) Feshbach resonance. (b) Time evolution of the differential displacement for a dipole-mode spin wave at two magnetic fields close to the zero crossing of this same resonance. In (a) and (b) the solid lines are only guides to the eye. (c) Maximum amplitude of the differential variance as a function of magnetic field around the resonance position. (d) Amplitude of the differential displacement as a function of magnetic field near the zero crossing. The amplitude is extracted by fitting a damped sine oscillation to data similar to \([2]b\). The positions of the sign change of the scattering length are determined from a linear fit.

The measured value \(B_{\text{zero}} = 416.1\) (0.1) G should coincide with the zero crossing of the scattering length. In fact, our measured value is in very good agreement with the theoretical value of 416.0 G. In contrast, the field value \(B_{\text{res}}\) is affected by many-body effects and does not serve as a precise measure for the Feshbach resonance position. In future experiments, this could be overcome by using thermal gases, where these effects are negligible [51].

In conclusion, we have observed twenty new Feshbach resonances in \(^{40}\text{K}\) over a broad range of magnetic field values, as well as twenty one further loss resonances whose origin has not yet been theoretically determined. Nineteen of the theoretically confirmed resonances have \(s\)-wave character and one is a \(p\)-wave resonance. Most of these resonances are accompanied by losses. In fact, these losses as well as the elastic interactions can be tuned for each Feshbach resonance. This allows for various future applications, such as the study of a quantum Zeno insulator in optical lattices [52, 53]. Furthermore, a broad Feshbach resonance in the collision channel \(\{+1/2,-1/2\}\) has been identified at a magnetic field of \(B = 389.6\) G with a width of 26.4 G, which constitutes an ideal candidate for two-component studies with accurate control over the interaction strength. In addition, we demonstrated the creation of spin waves around this Feshbach resonance, which allowed for a precise determination of the zero crossing. Furthermore, we observed a phase shift of the spin waves near the Feshbach resonance position, which might allow for the study of many-body effects in strongly interacting Fermi gases in the future.

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[1] E. Timmermans, P. Tommasini, M. Hussein, and A. Ker- man, Feshbach resonances in atomic Bose-Einstein con- densates, Physics Reports 315, 199 (1999).
[2] R. A. Duine and H. T. C. Stoof, Atom-molecule coher- ence in Bose gases, Physics Reports 396, 115 (2004).
[3] T. Köhler, K. Göral, and P. S. Julienne, Production of cold molecules via magnetically tunable Feshbach reso- nances, Rev. Mod. Phys. 78, 1311 (2006).
[4] C. Chin, R. Grimm, P. Julienne, and E. Tiesinga, Fesh- bach resonances in ultracold gases, Phys. Rev. A 79, 1225 (2010).
[5] C. Chin, R. Grimm, P. Julienne, and E. Tiesinga, Quan- tum chaos in ultracold collisions of gas-phase erbium atoms, Nature 507, 475 (2014).
[6] C. A. Regal, M. Greiner, and D. S. Jin, Observation of Resonance Condensation of Fermionic Atom Pairs, Phys. Rev. Lett. 92, 040403 (2004).
[7] C. Chin et al., Observation of the Pairing Gap in a Strongly Interacting Fermi Gas, Science 305, 1128 (2004).
[8] G. B. Partridge, K. E. Strecker, R. I. Kamar, M. W. Jack, and R. G. Hulet, Molecular Probe of Pairing in the BEC-BCS Crossover, Phys. Rev. Lett. 95, 020404 (2005).
[9] M. W. Zwierlein, J. R. Abo-Shaeer, A. Schirotzek, C. H. Schunck and W. Ketterle, Vortices and superfluidity in a strongly interacting Fermi gas, Nature 435, 1047 (2005).
[10] R. Jordens, N. Strohmaier, K. Günter, H. Moritz, and T. Esslinger, A Mott insulator of fermionic atoms in an optical lattice, Nature 455, 204 (2008).
[11] U. Schneider et al., Metallic and Insulating Phases of...
Induces Correlations in Cold Molecular Gases, Science 320, 1329 (2008).

[53] J. J. García-Ripoll et al., Dissipation-induced hard-core boson gas in an optical lattice, New J. Phys. 11, 013053 (2009).