Observation of Feshbach resonances in an ultracold gas of $^{52}\text{Cr}$

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With the development of laser cooling and trapping techniques, atomic collisional properties in the ultracold regime have become directly accessible. Today, these properties play a crucial role in experiments with quantum degenerate bosonic and fermionic gases. In the ultracold regime, elastic collisions between most neutral atoms are dominated by isotropic interaction potentials, which only depend on the internuclear separation $R$ and can be characterized by a single length, the $s$-wave scattering length $a$. This type of interaction is responsible for many of the fascinating phenomena observed in Bose-Einstein condensates (BEC’s) (for a review see [1]) and degenerate Fermi gases [2].

In alkali-metal gases, the effect of the isotropic potentials and, consequently, the value of the scattering length can be controlled by magnetically tunable Feshbach resonances [2]. Feshbach resonances appear when the energy of the incoming atoms equals the energy of a bound molecular level of a higher-lying molecular potential and are used to change sign and magnitude of $a$ [4]. Recently, Feshbach resonances have been exploited to study the strong interaction regime in ultracold atomic gases or even to produce molecular Bose-Einstein Condensates [5]. Feshbach resonances between different atomic species have also been theoretically predicted [2], and experimentally observed [2,7].

The spins of the six electrons in the 3d and 4s valence shells of the $^7\text{S}_3$ ground state of $^{52}\text{Cr}$ are aligned. This gives rise to a magnetic moment as large as $\mu = 6 \mu_B$, where $\mu_B$ is the Bohr magneton. This large magnetic moment is responsible for a very strong anisotropic spin-spin dipole interaction between two $^7\text{S}_3$ $^{52}\text{Cr}$ atoms. In fact, when compared to alkali-metal atoms, which have a maximum magnetic moment of 1 $\mu_B$, it is 36 times stronger. This difference has limited hopes of Bose condensing $^{52}\text{Cr}$ in a state where the electron spins are aligned parallel to an external magnetic field by severely restricting its lifetime [5].

For atomic $^{52}\text{Cr}$ in spin state anti-parallel to the magnetic field the spin-spin dipole interaction, however, does not lead to atom losses. Instead, the effects of the anisotropic and long-range spin-spin dipole interaction can add a new twist to the field of ultracold quantum gases. In particular, the expansion and the stability of a dipolar BEC is expected to depend on the trapping geometry [3]. A roton is expected to develop in the dispersion relation and new quantum phases in optical lattices have been predicted for dipolar gases [10]. The anisotropic interaction can be changed by time-varying magnetic fields [11], while the isotropic interaction can be tuned using a Feshbach resonance. This allows one to arbitrarily adjust the ratio of the isotropic and anisotropic interactions.

Isotropic interactions between two ground-state $^{52}\text{Cr}$ atoms are due to Hund’s case (a) $^{2S+1}\Sigma_g^+$ Born-Oppenheimer potentials. The large number of valence electrons leads to seven Born-Oppenheimer potentials instead of two for ground-state alkali-metal atoms. Here, $S$ is the total electron spin of the two atoms and $g/u$ is gerade/ungerade for inversion symmetry of the electron wavefunction around the center of charge. For $^{52}\text{Cr}$ even (odd) $S$ implies $g$ ($u$) symmetry, respectively. Conventional spectroscopic data only exists for the ground-state $^1\Sigma_g^+$ potential. Theoretical ab-initio calculations [12,13] exist but are extremely challenging for $^{52}\text{Cr}$.

Chromium has been trapped using buffer gas cooling techniques [14], in magneto-optical traps [15,16], and in magnetic traps [17,18]. Using a cross-dimensional relaxation technique, our group was able to determine the decaplet $^{13}\Sigma_g^+$ $s$-wave scattering length of $^{52}\text{Cr}$ to be 170(39) $a_0$ and of $^{50}\text{Cr}$ to be 40(15) $a_0$ [18]. The uncertainty in parenthesis is a one-standard deviation uncertainty combining statistical and systematic errors.

In this Letter, we report the observation of magnetic Feshbach resonances in a gas of ultracold $^{52}\text{Cr}$ atoms. We locate 14 resonances through inelastic loss measurements...
between magnetic field values of 0 mT and 60 mT. The broadest observed feature has a 1/√*C*-width of 68 µT. By comparing the experimental data with theoretical multi-channel calculations, we are able to identify the resonances and to determine the scattering lengths of the \( ^{13,9,5}Σ_g^+ \) Born-Oppenheimer potentials, the Van der Waals dispersion coefficient \( C_6 \), and \( C_8 \), which are the same for all seven Born-Oppenheimer potentials.

The details of our cooling scheme are presented in Refs. [19, 20]. After Doppler-cooling in a clover-leaf type magnetic trap and evaporative cooling we load the atoms into a crossed optical dipole trap. The dipole trap is realized using an Yb-fiber laser with a wavelength of 1064 nm. The two trapping beams have a waist of 30 µm and a power of 11 W and 6 W, respectively. To suppress dipolar relaxation, we optically pump the atoms from the \( m_s = +3 \) Zeeman sublevel of the \( ^7S_3 \) state to the energetically lowest \( m_s = -3 \) level. To achieve this, we use a frequency-doubled master-slate diode laser system, which is resonant with the \( ^7S_3 \rightarrow ^7P_j \) transition at 427.6 nm. Using 250 µW of \( σ^- \) polarized light and an optical pumping time of 1.2 ms, we achieve a transfer efficiency close to 100%. The lifetime in the optical dipole trap increases from 7 s in the \( m_s = +3 \) state to 140 s in the \( m_s = -3 \) state and is limited by dipolar relaxation in the former and by the finite background gas pressure in the latter case. The optical pumping field of about 9 G is left on, in order to prevent thermal re-occupation of higher \( m_s \)-levels through dipolar collision processes. During the first 5 s after optical pumping, we see a fast initial decay in the atom number and a decrease in temperature, which we ascribe to plain initial evaporation in the optical dipole trap. To prepare a sample of up to 120 000 atoms at a temperature of 6 µK and a density of \( 5 \times 10^{19} \text{m}^{-3} \) in a crossed optical dipole trap, we continue the evaporation by ramping down the intensity of the stronger of the two laser beams to 5 W.

We look for an increase of atom loss by three-body recombination to locate the Feshbach resonances [21]. This is done by first sweeping the magnetic field strength in coarse steps on the order of 0.1 mT–3 mT from 0 mT to 60 mT. Smaller sweep ranges are then used in regions where atom loss is observed. To find the precise location of the resonances a different method is used. The magnetic field is ramped up to a value close to the resonance in about 5 ms. We hold the magnetic field for 2 s to let the current settle and to give our magnetic coils time to thermalize. Then the magnetic field is quickly ramped to the desired value and held there for a variable amount of time. The holding time is chosen to clearly resolve the resonance and lies between 100 ms and 10 s. Finally, the magnetic field is switched off and an absorption image is taken.

The magnetic field is calibrated both slightly below and above each resonance using RF-spectroscopy. We are able to determine the value of the magnetic field with an one-standard deviation uncertainty of 10 µT.

![Figure 1: Inelastic loss measurement of the Feshbach resonances at 28.66 mT and 29.03 mT. The dashed lines are gaussian fits to the data and determine the position and width of the loss features.](image-url)
terms. The connection point \( R_x = 17.5 \, a_0 \) is chosen such that each \( V_S \) can be well represented by its long range form beyond \( R_x \) and its value at \( R_x \) is much larger than the collision and bound-state energies of interest here. The inner wall and dissociation energy of the model potentials approximately agree with Ref. [13]. We allow for variation of \( C_n \) and Include short-range corrections near the minimum of each potential curve. This allows us to independently tune \( C_n \) and the \( s \)-wave scattering lengths \( a_S \) of \( V_S \) to fit the experimental data. The number of bound states of \( V_S \) is uncertain to \( \pm 10 \) for the deeper potentials.

When the atoms are far apart, the eigenstates of the dimer are \( |SM_S; ℓm_ℓ⟩ \), in which \( M_S \) and \( m_ℓ \) are projections of \( \vec{S} \) and \( \vec{ℓ} \) along \( \vec{B} \). The total projection \( M = m_ℓ + M_S \) and parity \((-1)^{S+ℓ} = 1 \) must hold. In absence of the spin-spin interaction, the Hamiltonian conserves \( ℓ \) and \( S \) as well. The anisotropic spin-spin dipole interaction couples states with \( ∆S = 0, 2 \) and \( ∆ℓ = 0, 2 \) with \( ℓ = 0 \to ℓ' = 0 \) transitions forbidden.

Our sample is spin polarized, so that the incoming state has quantum numbers \( S = −M_S = 6 \) by straightforward angular momentum addition. Moreover, the temperature of the sample, \( T \approx 6 \, \mu \text{K} \), is small compared to the \( ℓ \geq 2 \) centrifugal barrier such that incoming \( ℓ_i = 0 \) collisions dominate the scattering cross sections. We find that, in addition to the incoming state, states with \( ℓ = 2 \) and 4 (\( d \) and \( g \)) partial waves and \( S = 2, 4, \) and 6 have to be coupled together in order to explain the 11 strongest observed features of Table 1. Even though, no term in the molecular Hamiltonian directly couples \( ℓ = 4 \) states to the \( ℓ_i = 0 \) state, second order mixing in the spin-spin dipole interaction via \( ℓ = 2 \) states is relevant in \( ^{52}\text{Cr} \). All these states have a total projection \( M' = −6 \). Two of the weakest \( B < 1 \, \text{mT} \) resonances in the table must be explained with incoming \( ℓ_1 = 2 \) \( d \)-wave collisions and \( M ≠ −6 \).

The locations of the maxima in the experimental three-body loss rate are compared with locations of peaks in the elastic two-body cross section calculated by full quantum-scattering methods. We perform a global \( χ^2 \)-minimization with parameters \( a_{2,4,6} \), \( C_6 \) and \( C_8 \). Our best-fit parameters with one standard deviation are \( a_2 = −7(20) \, a_0 \), \( a_4 = 58(6) \, a_0 \), \( a_6 = 112(14) \, a_0 \), \( C_6 = 733(70) \, \text{a.u.} \), and \( C_8 = 75^{+90}_{−75} \cdot 10^3 \, \text{a.u.} \). Here \( 1 \, \text{a.u.} \) is \( E_ha_0^2 \) for \( C_n \) and \( E_h = 4.359744 \cdot 10^{-18} \) is a Hartree. The minimization procedure provides only a weak upper bound on the \( C_8 \). The \( ^{13}\Sigma_0^+ \) scattering length \( a_6 \) is in reasonable agreement with Ref. [13] and the \( C_6 \) coefficient is consistent with that of Ref. [13]. The average difference between theoretical and experimental resonance positions is only \( ≈ 0.06 \, \text{mT} \).

Figure 2 shows the experimentally accessible \( s \)-wave scattering length \( a_{S,M_S} \) of two colliding \( s = 3 \), \( m_s = −3 \) \( (S = −M_S = 6) \) atoms as a function of magnetic field for our best fit parameters. Unlike the \( a_S \), this scattering length depends on the spin-spin dipole interaction. Near each Feshbach resonance, the scattering length both diverges and crosses zero. The difference in magnetic field between these two locations defines the resonance width \( ∆R \) and is given in Table 1.

The nature of \( ^{52}\text{Cr} \) Feshbach resonances can be understood through approximate calculations of molecular bound states. We find that calculations of eigenstates of a reduced Hamiltonian limited to a single basis state \( |SM_S; ℓm_ℓ⟩ \) locates the resonances to within \( 0.25 \, \text{mT} \) from the scattering calculation. Our assignment \( S, M_S, ℓ, \) and \( m_ℓ \) from this approximate model is shown in Table 1. An alternative assignment in which the quantum numbers of the nearly degenerate pair near \( 29.0 \, \text{mT} \) are interchanged is consistent with our best-fit parameters.

In the limit of vanishing spin-spin dipole interaction a simple resonance-pattern is expected. Scattering is then independent of \( m_ℓ \) and the resonances occur at \( B_{res} = E_B/(g_sμ_B (M_S + 6)) \), where \( E_B \) is one of the zero-field binding energies of the potential \( V_S(R) + \hbar^2(ℓ + 1)/(2μR^2) \). Inclusion of the spin-spin dipole interaction gives rise to observable deviations from this pattern, as large as \( ≈ 1 \, \text{mT} \). Such shifts are an order of magnitude larger than the 0.06 mT discrepancies that remain after
our least-squares fit. Moreover, the 0.06 mT agreement strongly suggests that the spin-spin dipole interaction is the dominant relativistic interaction in ultracold $^{52}$Cr.

So far, we have focused on incoming $\ell_\ell = 0$ $s$-wave scattering and thus assumed $M = -6$. We do observe resonances due to collisions from $\ell = 2$ partial waves with $M = -4, \ldots, -8$ corresponding to different orientations of the internuclear axis. The pair near 0.4 mT and 0.8 mT is due to such collisions. These additional features are strongly suppressed at our temperatures and we are only able to detect them at fields $B < 2$ mT where we have larger atom numbers and an optimal control of the magnetic field strength. We are not able to infer from our data a conclusive assignment of the weakest observed resonance at 0.61 mT.

In conclusion, we have observed Feshbach resonances in an ultracold gas of $^{52}$Cr atoms held in an optical dipole trap. Resonances were located by measuring the inelastic loss of $^{52}$Cr in the energetically lowest Zeeman sublevel. Positions and widths extracted from quantum scattering calculations are in good agreement with the experimental data. The spin-spin dipole interaction is essential for a quantitative understanding of the experimental spectrum. We have improved the accuracy of the previous collisional measurements [18] and provided a determination of the $9^+5^5_{Sg}$ scattering lengths.

The resonances can be used to control the relative strength of isotropic and anisotropic interactions. Together with the BEC of $^{52}$Cr we recently realized [24], this makes the spin-spin dipole interaction in degenerate quantum gases experimentally accessible. Moreover, the formation of $^3$He$_2$ molecules via Feshbach resonances is now possible.

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| Exp. Pos. [mT] | Theo. Pos. [mT] | Theo. $\Delta$ [μT] | Exp. $L_3$ [μT/s] | Assignment $\ell_\ell$; $SM_\ell$; $\ell_m$ |
|----------------|-----------------|-----------------------|--------------------|---------------------------------|
| 0.41           | 0.40            | -                     | $3 \cdot 10^{-40}$ | 2; 6, -4; 0, 0                   |
| 0.61           | -               | -                     | $8 \cdot 10^{-41}$ | -                               |
| 0.82           | 0.81            | -                     | $4 \cdot 10^{-39}$ | 2; 6, -5; 0, 0                   |
| 5.01           | 5.01            | $< 1 \cdot 10^{-4}$   | $2 \cdot 10^{-38}$ | 0; 6, -2; 4, 4                   |
| 6.51           | 6.49            | $6 \cdot 10^{-4}$     | $5 \cdot 10^{-38}$ | 0; 6, -3; 4, -3                  |
| 9.89           | 9.85            | 0.030                 | $1 \cdot 10^{-36}$ | 0; 6, -4; 4, -2                  |
| 14.39          | 14.32           | 0.012                 | $1 \cdot 10^{-38}$ | 0; 4, -2; 4, -4                  |
| 18.83          | 18.79           | 0.022                 | $4 \cdot 10^{-38}$ | 0; 4, -3; 4, -3                  |
| 20.58          | 20.56           | 1.2                   | $4 \cdot 10^{-36}$ | 0; 6, -5; 4, -1                  |
| 28.66          | 28.80           | 1.2                   | $6 \cdot 10^{-37}$ | 0; 4, -4; 4, -2                  |
| 29.03          | 29.07           | 5.1                   | $1 \cdot 10^{-37}$ | 0; 6, -4; 2, -2                  |
| 37.92          | 37.92           | 0.042                 | $1 \cdot 10^{-37}$ | 0; 2, -2; 4, -4                  |
| 49.99          | 49.92           | 8.1                   | $1 \cdot 10^{-36}$ | 0; 4, -4; 2, -2                  |
| 58.91          | 58.92           | 170                   | $3 \cdot 10^{-36}$ | 0; 6, -5; 2, -1                  |

Table I: Compendium of positions and strengths of the observed loss features, the theoretical positions, widths, initial partial wave, and assignment of the resonances. Theoretical calculations use a collision energy of $E = k_B T$ and parameters as in Fig. 2 The one standard deviation uncertainty of the experimental resonance position is 10 μT (See text)

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