

Observation of Feshbach resonances in a Bose–Einstein condensate

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It has long been predicted that the scattering of ultracold atoms can be altered significantly through a so-called ‘Feshbach resonance’. Two such resonances have now been observed in optically trapped Bose–Einstein condensates of sodium atoms by varying an external magnetic field. They gave rise to enhanced inelastic processes and a dispersive variation of the scattering length by a factor of over ten. These resonances open new possibilities for the study and manipulation of Bose–Einstein condensates.

Bose–Einstein condensates of atomic gases offer new opportunities for studying quantum-degenerate fluids^{1–5}. All the essential properties of Bose condensed systems—the formation and shape of the condensate, the nature of its collective excitations and statistical fluctuations, and the formation and dynamics of solitons and vortices—are determined by the strength of the atomic interactions. In contrast to the situation for superfluid helium, these interactions are weak, allowing the phenomena to be theoretically described from ‘first principles’. Furthermore, in atomic gases the interactions can be altered, for instance by employing different species, changing the atomic density, or, as in the present work, merely by varying a magnetic field.

At low temperatures, the interaction energy in a cloud of atoms is proportional to the density and a single atomic parameter, the scattering length a which depends on the quantum-mechanical phase shift in an elastic collision. It has been predicted that the scattering length can be modified by applying external magnetic^{6–10}, optical^{11,12} or radio-frequency¹³ (r.f.) fields. Those modifications are only pronounced in a so-called ‘Feshbach resonance’¹⁴, when a quasibound molecular state has nearly zero energy and couples resonantly to the free state of the colliding atoms. In a time-dependent picture, the two atoms are transferred to the quasibound state, ‘stick’ together and then return to an unbound state. Such a resonance strongly affects the scattering length (elastic channel), but also affects inelastic processes such as dipolar relaxation^{6,7} and three-body recombination. Feshbach resonances have so far been studied at much higher energies¹⁵ by varying the collision energy, but here we show that they can be ‘tuned’ to zero energy to be resonant for ultracold atoms. The different magnetic moments of the free and quasibound states allowed us to tune these resonances with magnetic fields, and as a result, minute changes in the magnetic field strongly affected the properties of a macroscopic system.

Above and below a Feshbach resonance, the scattering length a covers the full continuum of positive and negative values. This should allow the realization of condensates over a wide range of interaction strengths. By setting $a \approx 0$, one can create a condensate with essentially non-interacting atoms, and by setting $a < 0$ one can make the system unstable and observe its collapse. Rapid tuning of an external magnetic field around a Feshbach resonance will lead to sudden changes of the scattering length. This opens the way to studies of new dynamical effects such as novel forms of collective oscillations or the sudden collapse of a large condensate when the scattering length is switched from positive to negative¹⁶.

Theoretical predictions

Calculations for Feshbach resonances in external magnetic fields have been reported for the lower hyperfine states of the atoms Li (ref. 8), K (ref. 10), Na (ref. 8), Rb (ref. 9) and Cs (refs 6, 7). They are typically spaced by several hundred gauss, and for Li and Na occur outside the range where states in the lower hyperfine manifold are weak-field-seeking and can be magnetically trapped. Recent experimental efforts to observe Feshbach resonances have concentrated on ⁸⁷Rb (ref. 17) and on ⁸⁵Rb (ref. 18 and C. E. Wieman, personal communication) where Feshbach resonances have been predicted at relatively low magnetic fields⁹. However, our recently demonstrated all-optical confinement of a Bose condensate¹⁹ opened the possibility of observing Feshbach resonances for strong-field-seeking states which cannot be trapped in a d.c. magnetic trap. The optical trapping potential is unaffected by magnetic fields and is independent of the hyperfine ground state. We report here the observation of two Feshbach resonances of sodium in a strong-field-seeking state.

Several Feshbach resonances in sodium are caused by quasibound hyperfine states of the second highest vibrational level, $\nu = 14$, of the triplet potential of the sodium dimer. The lowest magnetic field value B_0 for a strong Feshbach resonance in sodium was predicted to lie in the range $760 < B_0 < 925$ G (B. J. Verhaar and F. A. van Abeelen, personal communication). It occurs in collisions between atoms in the lowest hyperfine state $|m_s = -1/2, m_l = +3/2\rangle$, which correlates with the $|F = 1, m_F = +1\rangle$ state at low fields (S, I and F are the usual quantum numbers for the electronic, nuclear and total spin, respectively). This Feshbach resonance is due to a quasibound molecular state $|S = 1, m_s = +1, I = 1, m_l = +1\rangle$. A much weaker resonance due to a $|S = 1, m_s = +1, I = 3, m_l = +1\rangle$ state (which is almost degenerate with the other quasibound state) was predicted to occur 50 to 75 G below.

Near a Feshbach resonance, the scattering length a should vary dispersively as a function of magnetic field B (ref. 8):

$$a = \bar{a} \left(1 - \frac{\Delta}{B - B_0} \right) \quad (1)$$

where Δ parametrizes the width of the resonance at $B = B_0$, and \bar{a} is the scattering length outside the resonance. For sodium, \bar{a} was found spectroscopically to be 2.75 nm at zero field, and increases to the triplet scattering length of 4.5 nm (ref. 20) at high magnetic fields. The widths Δ for the strong and weak resonance were predicted to be 1 G and 0.01 G, respectively (B. J. Verhaar and F. A. van Abeelen, personal communication).

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Experimental set-up

Bose–Einstein condensates in the $|F = 1, m_F = -1\rangle$ state were produced as in our previous work by laser cooling, followed by evaporative cooling in a magnetic trap²¹. The condensates were transferred into an optical dipole trap formed at the focus of an infrared laser beam¹⁹. Atoms were then spin-flipped with nearly 100% efficiency to the $|F = 1, m_F = +1\rangle$ state with an adiabatic r.f. sweep while applying a 1 G bias field. Without large modifications of our magnetic trapping coils, we could provide bias fields of up to $\sim 1,200$ G, but only by using coils producing axial curvature²¹, which for high-field-seeking states generated a repulsive axial potential. At the highest magnetic fields, this repulsion was stronger than the axial confinement provided by the optical trap. To prevent the atoms from escaping, two ‘end-caps’ of far-off-resonant blue-detuned laser light were placed at the ends of the condensate, creating a repulsive potential, and confining the atoms axially (Fig. 1a). For this, green light at 514 nm from an argon-ion laser was focused into two sheets about 200 μm apart. The focus of the optical trap was placed near the minimum of the bias field in order to minimize the effect of the destabilizing magnetic field curvature. The axial trapping potential at high fields was approximately ‘W’-shaped (Fig. 1b), and had a minimum near one of the end-caps as observed by phase-contrast imaging²² (Fig. 1c, d).

The calibration factor between the current (up to ~ 400 A) in the coils and the magnetic bias field was determined with an accuracy of 2% by inducing r.f. transitions within the $|F = 1\rangle$ ground-state hyperfine manifold at about 40 G. Additionally, an optical resonance was found around 1,000 G, where the Zeeman shift equalled the probe light detuning of about 1.7 GHz and led to a sign-reversal of the phase-contrast signal. These two calibrations agreed within their uncertainties.

The condensate was observed in the trap directly using phase-contrast imaging²² or by using time-of-flight absorption imaging^{1,2,21}. In the latter case, the optical trap was suddenly switched off, and the magnetic bias field was shut off 1–2 ms later to ensure that the high-field value of the scattering length was responsible for the acceleration of the atoms. After ballistic expansion of the condensate (either 12 or 20 ms), the atoms were optically pumped into the $|F = 2\rangle$ ground state and probed using resonant light driving the cycling transition. The disk-like expansion of the

cloud and the radial parabolic density profile were clear evidence for the presence of a Bose condensed cloud.

Locating the resonances

When the magnetic field is swept across a Feshbach resonance one would expect to lose a condensate due to an enhanced rate of inelastic collisions (caused either by the collapse in the region of negative scattering length or by an enhanced rate coefficient for inelastic collisions). This allowed us to implement a simple procedure to locate the resonances: we first extended the field ramp until the atoms were lost and then used successively narrower field intervals to localize the loss. This procedure converged much faster than a point-by-point search. As we could take many non-destructive phase-contrast images during the magnetic field ramp, the sharp onset of trap loss at the resonance was easily monitored (Fig. 1c, d).

The most robust performance was obtained by operating the optical dipole trap at 10 mW laser power focused to a beam waist of 6 μm , resulting in tight confinement of the condensate and therefore rather short lifetimes owing to three-body recombination¹⁹. This required that the magnetic field be ramped up in two stages: a fast ramp at a rate of ~ 100 G ms^{-1} to a value slightly below that expected for a Feshbach resonance, followed by a slow ramp at a rate between 0.05 and 0.3 G ms^{-1} to allow for detailed observation. Near 907 G, we observed a dramatic loss of atoms, as shown in Figs 1c and 2a. This field value was reproducible to better than 0.5 G and had a calibration uncertainty of ± 20 G.

To distinguish between an actual resonance and a threshold for trap loss, we also approached the resonance from above. Fields above the Feshbach resonance were reached by ramping at a fast rate of 200 G ms^{-1} , thus minimizing the time spent near the resonance and the accompanying losses. The number of atoms above the resonance was typically three times smaller than below. Approaching the resonance from above, a similarly sharp loss phenomenon was observed about 1 G higher in field than from below (Fig. 2a), which roughly agrees with the predicted width of the resonance. A second resonance was observed 54 ± 1 G below the first one, with the observed onset of trap loss at least a factor of ten sharper than for the first. As the upper resonance was only reached by passing through the lower one, some losses of atoms were unavoidable; for example, when the lower resonance was crossed at 2 G ms^{-1} ,

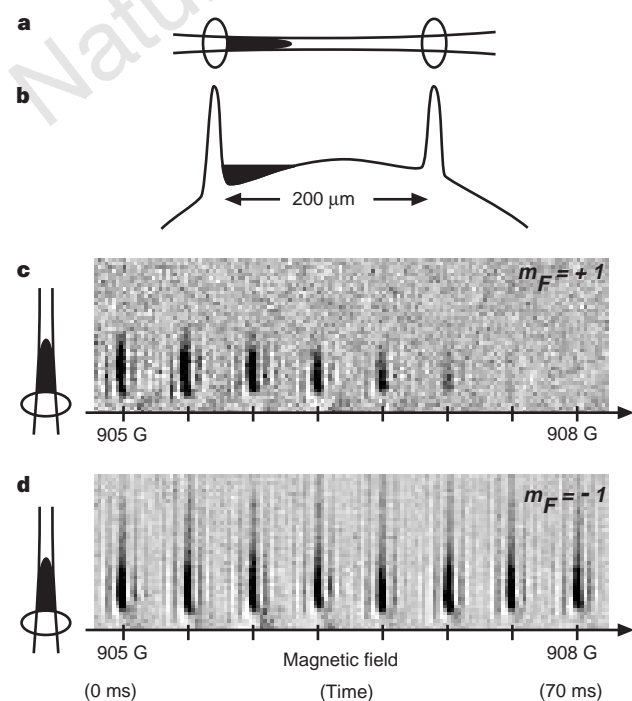


Figure 1 Observation of the Feshbach resonance at 907 G using phase-contrast imaging in an optical trap. A rapid sequence (100 Hz) of non-destructive, *in situ* phase-contrast images of a trapped cloud (which appears black) is shown. As the magnetic field was increased, the cloud suddenly disappeared for atoms in the $|m_F = +1\rangle$ state (see images in **c**), whereas nothing happened for a cloud in the $|m_F = -1\rangle$ state (images in **d**). The height of the images is 140 μm . A diagram of the optical trap is shown in **a**. It consisted of one red-detuned laser beam providing radial confinement, and two blue-detuned laser beams acting as end-caps (shown as ovals). The minimum of the magnetic field was slightly offset from the centre of the optical trap. As a result, the condensate (shaded area) was pushed by the magnetic field curvature towards one of the end-caps. The axial profile of the total potential is shown in **b**.

about 80% of the atoms were lost. This, coupled with the stability and finite programming speed of the power supplies, limited the ramp rates to those given above.

The observation of twin resonances separated by 54 ± 1 G, with the weaker one at lower field, exactly matches the theoretically predicted pattern and thus strongly confirms our interpretation. No resonance phenomena were observed in the $|m_F = -1\rangle$ state at any field up to 1,000 G, in agreement with theory which predicted resonances for this state only at much higher fields.

Changing the scattering length

The trap loss measurements easily located the Feshbach resonances. To measure the variation of the scattering length around these resonances, we determined the interaction energy of a trapped condensate. This was done by suddenly switching off the trap, allowing the stored interaction energy to be converted into the kinetic energy of a freely expanding condensate and measuring it by time-of-flight absorption imaging^{1,2,21}. The interaction energy is proportional to the scattering length and the average density of the condensate $\langle n \rangle$:

$$E_I/N = \frac{2\pi\hbar^2}{m} a \langle n \rangle \quad (2)$$

where N is the number of condensed atoms of mass m . For a large condensate the kinetic energy in the trap is negligible (Thomas–Fermi limit), and E_I is equal to the kinetic energy E_K of the freely expanding condensate $E_K/N = mv_{\text{rms}}^2/2$, where v_{rms} is the root-mean-square velocity of the atoms. For a three-dimensional har-

monic oscillator potential one finds $\langle n \rangle \propto N(Na)^{-3/5}$ (ref. 23) (We note that, for a general power-law potential $\sum_i c_i x_i^{\beta_i}$, one obtains $\langle n \rangle \propto N(Na)^{k-1}$, where $k = 1/(1 + \sum_i 1/\beta_i)$). Thus, the value of the scattering length scales as:

$$a \propto \frac{v_{\text{rms}}^5}{N} \quad (3)$$

Both v_{rms} and N can be directly evaluated from absorption images of freely expanding condensates. For a cigar-shaped condensate the free expansion is predominantly radial, and so the contribution of the axial dimension to v_{rms} could be neglected. The quantity v_{rms}^5/N (equation (3)), normalized to unity outside the resonance, should be identical to a/\bar{a} (equation (1)). This quantity was measured around the resonance at 907 G and is shown in Fig. 2b together with the theoretical prediction of a resonance with width $\Delta = 1$ G. The data clearly displays the predicted dispersive shape and shows evidence for a variation in the scattering length by more than a factor of ten.

We now discuss the assumptions for equation (3) and show that it is approximately valid for our conditions. (1) We assumed that the condensate remains in equilibrium during the magnetic field ramp. This is the case if the adiabatic condition $\dot{a}/a \ll \omega_i$ holds for the temporal change of the scattering length¹⁶, and a similar condition for the loss of atoms (the ω_i are the trapping frequencies). For the condensate's fast radial dynamics ($\omega_r \approx 2\pi \times 1.5$ kHz) this condition is fulfilled, whereas for the slower axial motion ($\omega_z \approx 2\pi \times 0.1$ kHz) it breaks down close to or within the resonance. In this case the density would approach the two-dimensional scaling $N(Na)^{-1/2}$, but the values for a/\bar{a} (Fig. 2b) would differ by at most 50%. (2) The second assumption was a three-dimensional harmonic trap. If the axial potential has linear contributions, the density scales instead like $N(Na)^{-2/3}$ resulting in at most a 50% change for a/\bar{a} . (3) We assumed that contributions of collective excitations to the released energy were small. Axial striations were observed in free expansion for both $|m_F = +1\rangle$ and $|m_F = -1\rangle$ atoms (probably created by the changing potential during the fast magnetic field ramp). However, the small scatter of points outside the resonance in Fig. 2b, which do not show any evidence of oscillations, suggests that the contribution of excitations to the released energy is negligible. (4) We assumed a sudden switch-off of the trap and ballistic expansion. The inhomogeneous bias field during the first 1–2 ms of free expansion accelerated the axial expansion, but had a negligible effect on the expansion of the condensate in the radial direction, which was evaluated for Fig. 2b.

None of the corrections (1)–(4) discussed above affect our conclusion that the scattering length varies dispersively near a Feshbach resonance. More accurate experiments should be done with a homogeneous bias field. In addition, an optical trap with larger volume and lower density would preclude the need to ramp the field quickly because three-body recombination would be reduced.

The trap losses observed around the Feshbach resonances merit further study as they might impose practical limits on the possibilities for varying the scattering length. An increase of the dipolar relaxation rate near Feshbach resonances has been predicted^{6,7}, but for atoms in the lowest hyperfine state no such inelastic binary collisions are possible. Therefore, the observed trap loss is probably due to three-body collisions. In this case the loss rate is characterized by the coefficient K_3 , defined as $\dot{N}/N = -K_3 \langle n^2 \rangle$. So far, there is no theoretical work on K_3 near a Feshbach resonance. An analysis based on Fig. 2 shows that K_3 increased on both sides of the resonance, because the loss rate increased while the density decreased or stayed constant. In any case, the fact that we observed Feshbach resonances at high atomic densities ($\sim 10^{15} \text{ cm}^{-3}$) strongly enhanced this loss process, which can be avoided with a condensate at lower density in a modified optical trap. Control of the bias field with a precision better than $\sim 10^{-4}$ will be necessary to achieve negative or extremely large values of the scattering length in a stable way.

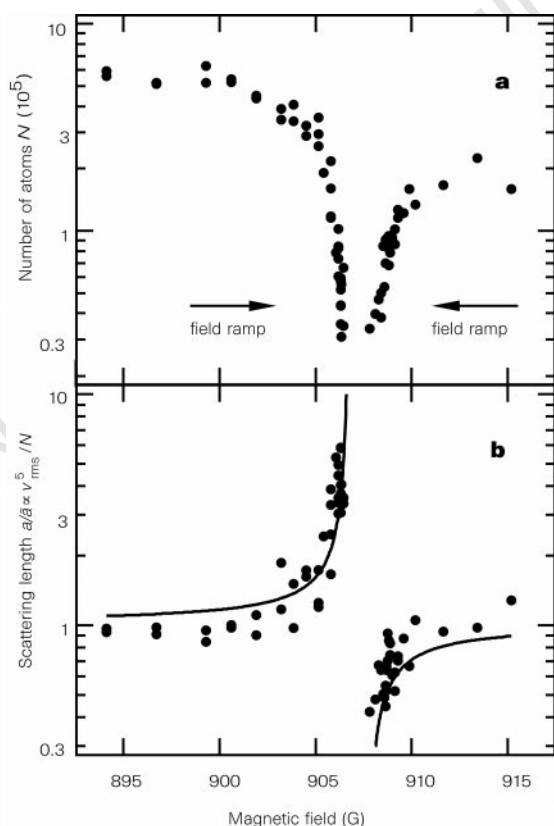


Figure 2 Observation of the Feshbach resonance at 907 G using time-of-flight absorption imaging. **a**, Number of atoms in the condensate versus magnetic field. Field values above the resonance were reached by quickly crossing the resonance from below and then slowly approaching from above. **b**, The normalized scattering length $a/\bar{a} \propto v_{\text{rms}}^5/N$ calculated from the released energy, together with the predicted shape (equation (1), solid line). The values of the magnetic field in the upper scan relative to the lower one have an uncertainty of <0.5 G.

A tunable condensate

We have observed two Feshbach resonances for Bose–Einstein condensates of sodium through the abrupt loss of atoms, and obtained strong evidence for a dispersive variation of the scattering length by a factor of more than ten. ‘Tuning’ of the scattering length should become an important tool for ‘designing’ atomic quantum gases with novel properties; for example, to create ideal Bose–Einstein condensates with nearly zero scattering length, and to obtain a detailed picture of the collapse of a condensate with negative scattering length, which is so far not fully understood. Tuning the scattering length can also be used to vary interactions between different species²⁴ and thus control the phase diagram of multi-component condensates, possibly switching from interpenetrating superfluids to phase separation²⁵. Feshbach resonances may also be important in atom optics, for modifying the atomic interactions in an atom laser, or more generally, for controlling nonlinear coefficients in atom optics with coherent beams of atoms. □

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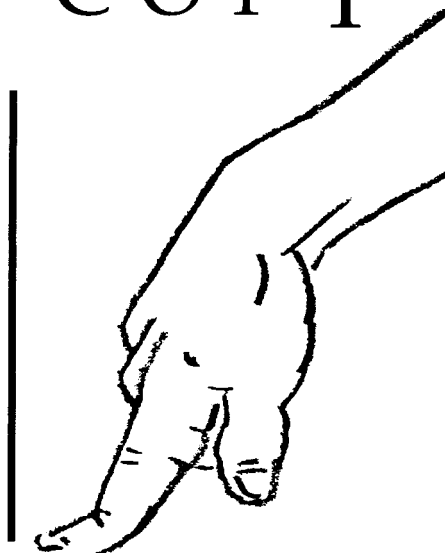
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