Observation of a Feshbach Resonance in Cold Atom Scattering

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We probe s-wave collisions of laser-cooled ^{85}Rb($f = 2, m_f = -2$) atoms with Zeeman-resolved photoassociation spectroscopy. We observe that these collisions exhibit a magnetically tunable Feshbach resonance, and determine that this resonance tunes to zero energy at a magnetic field of 164 ± 7 G. This result indicates that the self-interaction energy of an ^{85}Rb Bose-Einstein condensate can be magnetically tuned. We also demonstrate that Zeeman-resolved photoassociation spectroscopy provides a useful new tool for the study of ultracold atomic collisions. [S0031-9007(98)06510-7]

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The observation of Bose-Einstein condensation (BEC) in dilute, magnetically trapped alkali gases has created exciting new opportunities for studies of macroscopic quantum phenomena [1–7]. An important aspect of dilute gas BEC is that two-body interactions dominate, and give rise to a condensate self-energy proportional to the two-body scattering length a. The self-energy strongly influences most of the important properties of a condensate, including its stability, formation rate, size and shape, and collective excitations. There has been considerable interest in finding ways to experimentally modify the scattering length, because that could make possible studies of a BEC with a very strong, very weak, positive, negative, or even time-dependent interaction strength, all within a single experiment. One promising proposal to do this relies on the strong variation of a that occurs if a Feshbach collision resonance is tuned through zero energy [8]. Such a tunable resonance could be induced optically, but this method introduces undesired effects of optical spontaneous emission into the condensate [9,10]. Magnetically tunable Feshbach resonances that arise from the coupling between different spin channels in an atomic collision can also result in a tunable value of a [8,11,12]. A previous search for this type of resonance [13] did not detect one. Interest in this topic increased with a prediction of a zero-energy Feshbach resonance in collisions of ^{85}Rb($f = 2, m_f = -2$) atoms [12]. In this paper, we report the observation of this resonance, which we find tunes to zero energy at a magnetic field of 164 ± 7 G. From the observed position and width of the resonance, we are able to precisely determine ^{85}Rb interaction parameters. Our work, along with a recent report of a similar resonance in an atomic ^{23}Na BEC [14], constitute the first observations of this important cold collision phenomenon.

In order to detect this resonance, we use photoassociation spectroscopy [15] to probe the collisions of laser-cooled ^{85}Rb atoms in a magnetic field. The concept of the experiment is illustrated in Fig. 1. To be concrete, we specialize to our particular case. Free, ground-state ^{85}Rb atoms collide in the $|f = 2, m_f = -2\rangle + |f = 2, m_f = -2\rangle$ entrance channel. Here, $f = 2$ or 3 is the hyperfine state (combined electron and nuclear spin) of an atom and m_f is the spin projection quantum number of that atom. The entrance channel has a total angular momentum projection quantum number $M_F = -4$, equal to the sum of the two atomic m_f values. It is coupled to other $M_F = -4$ channels at a small internuclear distance by

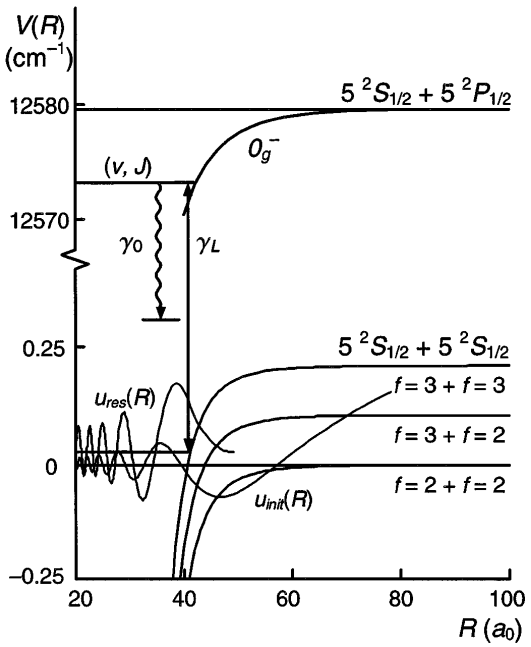

FIG. 1. Photoassociation method for detecting a Feshbach resonance in collisions of ultracold ^{85}Rb($f = 2, m_f = -2$) atoms. The entrance channel wave function $u_{\rm init}(R)$ couples to a quasibound state with wave function $u_{\rm res}(R)$. A laser field induces photoassociation of this state to an excited, bound $0_g^-(v, J)$ molecular state at a rate γ_L, which then decays back to free atoms at a rate γ_0. As a magnetic field is varied, the quasibound state tunes through zero energy, producing a Feshbach resonance for ultracold collisions. The resulting enhancement of $u_{\rm res}(R)$ produces an enhancement of γ_L that we detect with a trap loss method.

the electronic exchange interaction. The other $M_F = -4$ potential curves all correlate to the higher energy $f = 2 + f = 3$ or $f = 3 + f = 3$ dissociation limits. They support multichannel quasibound states at positive energies, where we take the zero of energy to be the threshold of the entrance channel. If the energy of the incoming atoms matches the energy of one of these states, a Feshbach resonance occurs in which a large wave-function amplitude builds up in the quasibound state. The resonance energy can be tuned to zero with a magnetic field because the quasibound state and threshold energy Zeeman shift at different rates. In that case the resonance strongly affects ultracold collisions. In order to detect the resonance, we drive photoassociation transitions to the excited $^{85}Rb_2$ 0_g^- bound molecular vibrational state at an energy 5.9 cm^{-1} below the $5^2S_{1/2} + 5^2P_{1/2}$ dissociation limit [16]. As discussed below, we are able to isolate a single component of the spectrum which originates from the s-wave, $M_F = -4$, collisional resonance state. Its transition rate is proportional to the square of the wave-function overlap between the collisional state and the excited state, and therefore shows an enhancement when the Feshbach resonance is tuned near zero energy.

We detect the photoassociation with a trap loss method [16–19]. About 10^4 ^{85}Rb atoms are transferred from a magneto-optical trap into a far-off resonance optical dipole force trap (FORT) [20], created by a 1.7 W, 835 nm wavelength laser beam focussed to a waist of 20 μm. The atoms are laser cooled to a temperature between 30 and 100 μK, and have a density between 10^{11} and 10^{12} cm^{-3}. We then switch on a magnetic field B and allow it to stabilize for 300 ms. After this, we continuously illuminate the atoms with a near-resonance laser beam that optically pumps them into their $f = 2$ ground hyperfine state, and with a tunable probe (PA) laser beam which induces the photoassociation transitions. In some cases we also apply an additional near-resonance σ^--polarized (OP) laser to pump the atoms into their $m_f = -2$ state. After an additional 700 to 1000 ms, we switch off these laser beams and the magnetic field, and probe the atoms remaining in the trap with laser-induced fluorescence. The photoassociation rate is detectable as reduced atomic fluorescence, because most pairs of atoms which absorb a PA laser photon return to the ground state by spontaneous emission as free atoms with a kinetic energy that is too high to remain in the trap. In the plots below, we show this measured fluorescence signal vs PA laser frequency, inverted so that photoassociation-induced trap loss produces upward going peaks.

A typical spectrum, recorded with the OP laser beam off and with no magnetic field, is shown in Fig. 2. We observe a simple spectrum that arises from the 0_g^- excited state $J = 0$, 1, and 2 rotational levels. Figure 2 also shows the spectrum with the OP laser beam off and with $B \approx 195$ G. In this case, the $f = 2 + f = 2$ dissociation limit Zeeman splits into 15 different limits for the even partial waves, and 10 different limits for the odd partial

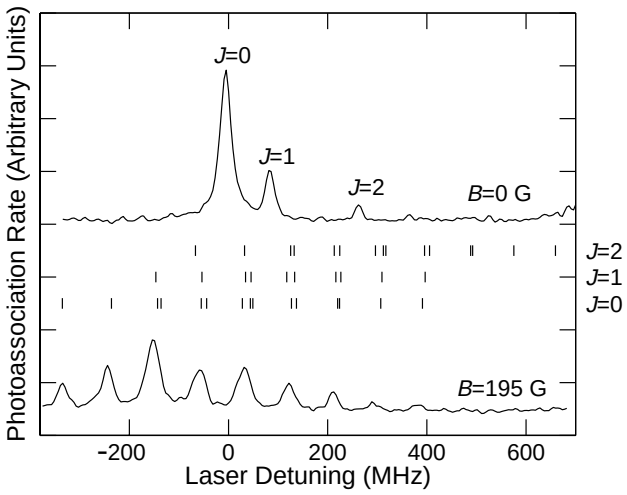

FIG. 2. $^{85}Rb_2$ photoassociation spectra for excitation from lower ($f = 2 + f = 2$) hyperfine state collisions to a single excited vibrational level, at a laser intensity of 20 W/cm^2. Upper curve: spectrum at zero magnetic field. Lower curve: spectrum at a magnetic field of 195 G. Each of the zero field components splits into 10 or 15 distinct components due to Zeeman splitting of the ground state atoms; calculated splittings are shown by the vertical dashed marks. The successive peaks in the lower spectrum correspond mainly to $J = 0$, and (from left) $M_F = -4$, -3, -2, -1, 0, 1, and 2.

waves, which correspond to the various possible combinations of the two atomic m_f quantum numbers. Without optical pumping all of these combinations are populated. The excited state does not show a significant Zeeman splitting. Because some of the splittings are not resolved, the $J = 0$ rotational peak splits into nine Zeeman components corresponding to $M_F = -4, \ldots, +4$. The leftmost peak in the spectrum arises only from $|f = 2, m_f = -2\rangle + |f = 2, m_f = -2\rangle$ ($M_F = -4$) collisions. Further, this peak arises only from s-wave collisions because the selection rule $J = l$ is obeyed for this transition, where l is the orbital angular momentum of the initial state [16]. Therefore the leftmost peak probes exclusively the desired collision channel.

In Fig. 3, we show repeated scans over the $J = 0$, $M_F = -4$ peak at many different field values. The data clearly show the effect of the Feshbach resonance. For these scans we also turn on the OP laser beam, which enhances the intensity of the $M_F = -4$ peak by a factor of 5. The PA laser intensity $I = 0.1$ W/cm^2. As the magnetic field is increased, the signal emerges from the noise, reaches a maximum strength near 167 G, and then disappears again into the noise. The field magnitude is calibrated using the Zeeman-resolved spectra. Our interpretation of this enhancement as a Feshbach resonance is supported by several factors. First, previous studies of ultracold Rb collisions have fairly strongly constrained its ground state interaction potentials [4,13,16–19,21,22], and allowed for predictions of this resonance [12,22]. We observe a resonance in the correct channel near the predicted field. Finally, we observe these photoassociation

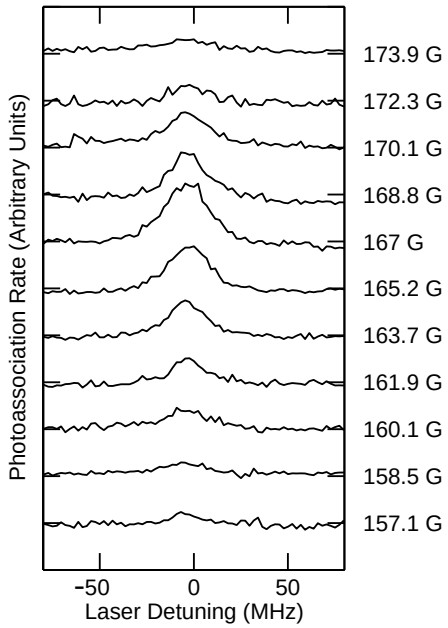

FIG. 3. Photoassociation spectra showing the $J = 0$, $M_F = -4$ peak at a succession of magnetic field values, with a laser intensity of 0.1 W/cm^2. The relative Zeeman shift of the successive peaks is removed so that they appear at the same laser tuning.

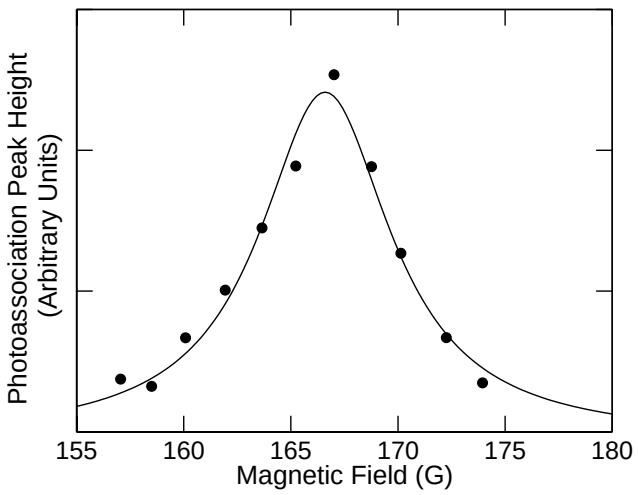

FIG. 4. Height of the photoassociation peaks shown in Fig. 3, as a function of magnetic field, showing clearly the Feshbach resonance. The solid curve shows a Lorentzian fit to the data.

peaks at an anomalously low laser intensity, at which other features in the spectrum are not visible. This can occur only with resonance enhancement of the rate γ_L due to the enhanced wave-function amplitude.

In Fig. 4, we plot the heights of the photoassociation peaks, determined from Lorentzian fits, as a function of magnetic field. We find that this curve is also well fit by a Lorentzian line shape, which yields a resonance field $B_{0,\mathrm{PA}}(I)$ and a width (FWHM) $\Delta B_{\mathrm{PA}}(I)$. Theoretical calculations [23] show that departures from Lorentzian line shapes should be small for our conditions. We find that optical power broadening is significant. In order to account for this, we repeat the measurements at laser intensities I ranging from 0.1 to 0.54 W/cm^2, and plot $B_{0,\mathrm{PA}}(I)$ and $\Delta B_{\mathrm{PA}}(I)$ vs I. $B_{0,\mathrm{PA}}(I)$ varies by less than 1.5 G over this range, and $\Delta B_{\mathrm{PA}}(I)$ varies from about 8 to about 15 G. By fitting these data, we determine zero-intensity intercepts of $B_{0,\mathrm{PA}} = 166.6 \pm 6$ G and $\Delta B_{\mathrm{PA}} = 5.9 \pm 2.1$ G. The error in $B_{0,\mathrm{PA}}$ is mainly due to errors in the magnetic field calibration. We searched for and did not find any additional Feshbach resonances in the field range between 100 and 195 G.

In order to further analyze these results, we have calculated the resonance field $B_{0,\mathrm{PA}}$ and width ΔB_{PA} using an accurate model for the atomic Rb interaction potential [23]. These quantities depend most sensitively on the Rb_2 ground state Van der Waals interaction coefficient C_6, and the two parameters $\upsilon_{\mathrm{DS}}(\mathrm{mod}\,1)$ and $\upsilon_{\mathrm{DT}}(\mathrm{mod}\,1)$. υ_{DS} and υ_{DT} correspond to the (fractional) number of bound states in the lowest singlet and triplet $^{85}Rb_2$ molecular potential wells, respectively. Further, near our parameter range the position of the resonance depends mostly on C_6 and on the sum $\upsilon_{\mathrm{DS}}(\mathrm{mod}\,1) + \upsilon_{\mathrm{DT}}(\mathrm{mod}\,1)$, whereas its width depends mostly on the difference $\upsilon_{\mathrm{DS}}(\mathrm{mod}\,1) - \upsilon_{\mathrm{DT}}(\mathrm{mod}\,1)$. Taking a fixed $C_6 = 4550$ a.u. [18] we determine from our measured value of $B_{0,\mathrm{PA}}$ that $\upsilon_{\mathrm{DS}}(\mathrm{mod}\,1) + \upsilon_{\mathrm{DT}}(\mathrm{mod}\,1) = -0.082 \pm 0.011$. Allowing for a 50 a.u. uncertainty in C_6 increases the uncertainty of $\upsilon_{\mathrm{DS}}(\mathrm{mod}\,1) + \upsilon_{\mathrm{DT}}(\mathrm{mod}\,1)$ to ± 0.016. From the measured value of ΔB_{PA}, we determine $\upsilon_{\mathrm{DS}}(\mathrm{mod}\,1) - \upsilon_{\mathrm{DT}}(\mathrm{mod}\,1) = 0.058 \pm 0.016$. (We rule out an opposite sign for $\upsilon_{\mathrm{DS}} - \upsilon_{\mathrm{DT}}$ because it conflicts with previous measurements [19].) Combining these results, we determine $\upsilon_{\mathrm{DS}}(\mathrm{mod}\,1) = -0.012$ and $\upsilon_{\mathrm{DT}}(\mathrm{mod}\,1) = -0.070$, with uncertainties for both their sum and difference of ± 0.016.

The best previous determination of these quantities followed from our measurements of the highest bound levels of the $^{85}Rb_2$ molecule [19]. Taking again a fixed $C_6 = 4550$ a.u., those measurements yield $\upsilon_{\mathrm{DS}}(\mathrm{mod}\,1) = -0.006 \pm 0.008$ and $\upsilon_{\mathrm{DT}}(\mathrm{mod}\,1) = -0.047 \pm 0.006$. Plotting the allowed regions in the $\upsilon_{\mathrm{DS}} - \upsilon_{\mathrm{DT}}$ plane at fixed C_6 for both the Feshbach and the bound state measurements, we find that they nearly contact each other near the point corresponding to the lower limits for both the Feshbach resonance width and resonance field. The difference between the parameters derived from the two experiments is somewhat larger than would be expected from their respective uncertainties; a possible explanation is that errors in the bound state measurements due to line-shape effects were underestimated. The uncertainty in C_6 also increases the uncertainties of the parameters derived from the bound state experiment [19], but it does not significantly change the level of agreement between the two experiments because their allowed υ_{DS}-υ_{DT} regions display similar shifts with C_6.

Based on our Feshbach resonance measurements, we calculate the scattering length $a_{2,-2}$ for collisions

of $^{85}\mathrm{Rb}(f = 2, m_f = -2)$ atoms as a function of field strength shown in Fig. 5. The resonance in the scattering length has the dispersive form $a_{2,-2} = a^0_{2,-2}[1 - \Delta/(B - B_0)]$. For the same parameters that yield the observed values of $B_{0,\mathrm{PA}}$ and ΔB_{PA}, we find that $a^0_{2,-2} = -295 \pm 80\ a_0$, $\Delta = 8.2 \pm 3.8$ G, and $B_0 = 164 \pm 7$ G. B_0 is a few Gauss lower than $B_{0,\mathrm{PA}}$ due to the fact that close to the crossing of the Rb_2 bound state and the $|f = 2, m_f = -2\rangle + |f = 2, m_f = -2\rangle$ threshold, the PA phenomenon is influenced to a significant extent by interference of the Feshbach resonance and the strong background (potential) scattering associated with the large background value of $a_{2,-2}$. The measured resonance field is in moderate disagreement with our previous prediction of 142 ± 10 G [12], which was based on the bound state measurements [19], for the reasons discussed above.

In summary, we have detected a zero-energy Feshbach resonance in collisions of $^{85}\mathrm{Rb}(f = 2, m_f = -2)$ atoms at a magnetic field of 164 ± 7 G. Our method, based on Zeeman-resolved photoassociation spectroscopy of ultracold atoms, allows us to search for resonances in any hyperfine, Zeeman, and partial wave channel by simply looking for an enhancement of the appropriate spectral component as the magnetic field is tuned. This method may therefore prove more generally useful as a new probe of ultracold atomic collisions. $^{85}\mathrm{Rb}(f = 2, m_f = -2)$ atoms can be magnetically trapped, and are expected to exhibit a very low two-body inelastic collision rate [22]. Evaporative cooling of this isotope is somewhat difficult due to a suppression of its elastic cross section at temperatures above 10 μK [22,24,25], but it is feasible [25]. Therefore it should be possible to study a magnetically trapped ^{85}Rb BEC with an adjustable scattering length. One attractive feature of this resonance is that its ratio Δ/B_0, which governs the degree of magnetic field control needed to stably produce a very large scattering length, is relatively large. Two and three body collisional loss rates are also enhanced by a Feshbach resonance [14,22], and this may limit the tuning range achievable in practice. A further interesting possibility is that it should be possible to form a mixed ^{87}Rb-^{85}Rb condensate, with the ^{87}Rb and cross-species scattering length positive [17,22], and the ^{85}Rb scattering length tunable. Other Feshbach resonances in both single and multicomponent gases could play important roles in many future BEC and coherent atom optics experiments.

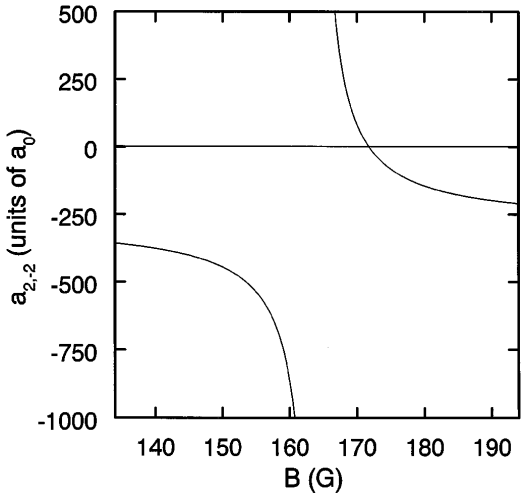

FIG. 5. Calculated field dependence of scattering length $a_{2,-2}$, corresponding with the resonance field value and width observed in this experiment.

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