Measurement of a mixed-spin-channel Feshbach resonance in ^{87}Rb

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We report on the observation of a mixed-spin-channel Feshbach resonance at the low magnetic field value of 9.09 ± 0.01 G for a mixture of $|2,-1\rangle$ and $|1,+1\rangle$ states in ^{87}Rb. This mixture is important for applications of multicomponent Bose-Einstein condensates of ^{87}Rb, e.g., in spin mixture physics and for quantum entanglement. Values for position, height, and width of the resonance are reported and compared to a recent theoretical calculation of this resonance.

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Feshbach resonances are a versatile tool to alter the scattering properties of atomic ensembles in a controlled way, which opens fascinating possibilities for Bose-Einstein condensates (BECs) as well as ultracold Fermi gases. In the vicinity of a Feshbach resonance the atom-atom interaction characterized by the *s*-wave scattering length can typically be tuned over a wide range of negative and positive values by simply varying an applied magnetic field. Feshbach resonances have been observed for various alkali-metal atoms [1–12]. The tunability of the interatomic interactions has been used to alter the mean-field energy of a BEC leading to a collapse of the condensate [13]. Furthermore the possibility of coherently coupling atomic and molecular states has sparked recent interest in atomic Feshbach resonances resulting in a series of cold molecule experiments based on BEC and cold Fermi gases [14–21]. For ^{87}Rb, the element most commonly used in Bose-Einstein condensation experiments, no Feshbach resonances have been found for the magnetically trappable states $|F,m_F\rangle=|1,-1\rangle$ and $|F,m_F\rangle=|2,+2\rangle$. In a recent precision experiment on the $|1,+1\rangle$ state and a mixture of the $|1,+1\rangle$ and $|1,0\rangle$ states more than 40 Feshbach resonances have been observed [10]. Most of them are in excellent agreement with theory, which makes ^{87}Rb one of the elements with the most precisely known collisional parameters. The observed Feshbach resonances are mostly relatively narrow and at high magnetic field values of several 100 G, making their exploitation a difficult task.

In this paper we report on the observation of an easily accessible mixed-spin-channel Feshbach resonance between the $|2,-1\rangle$ and $|1,+1\rangle$ states of ^{87}Rb at a low magnetic-field value. This resonance has been predicted theoretically based on recent experimental data by van Kempen *et al.* [22].

The knowledge of atom-atom interaction parameters between different spin states is fundamental for a deeper understanding of so called spinor condensates. Lifetimes of spin mixtures in the $F=2$ manifold as well as collective spin dynamics leading to nanomagnetic effects are governed by the atom-atom interactions. A tunability of spin interactions in dilute quantum gases may, e.g., improve the experimental feasibility of spin-squeezing scenarios [23] leading to future applications in quantum optics and quantum computation.

Our experimental apparatus is based on a double-MOT (magneto-optical trap) system which can produce magnetically trapped Bose-Einstein condensates of 10^6 atoms in the $|2,+2\rangle$ state every 30–45 s. These are subsequently transferred into a far detuned optical dipole trap operated at 1064 nm with trapping frequencies of $\approx 2\pi\times 890$ Hz vertically, $2\pi\times 160$ Hz horizontally, and $2\pi\times 20$ Hz along the beam direction. The experiments reported were performed typically with initially 10^5 optically trapped atoms. The confining potential is independent of the spin and hyperfine states and is therefore well suited for examinations of arbitrary spin and hyperfine states and mixtures of those [24]. For detection, the atoms are released from the dipole trap and separated by a Stern-Gerlach gradient of ≈ 26 G/cm at an offset field of ≈ 157 G applied for 7.5 ms. After a further time of flight of typically 7 ms an absorption image is taken. The linear Zeeman effect leads to a separation of 650 μm between m_F states. An additional separation of 85 μm between F states occurs due to the quadratic Zeeman effect. Therefore each absorption image provides population numbers for each of the m_F components of the $F=2$ and $F=1$ states separately and simultaneously.

For the experiment reported here, a mixture of the $|2,-1\rangle$ and $|1,+1\rangle$ states is prepared. We use a Landau-Zener crossing technique [25] to transfer populations between the m_F states. An offset field of 25 G during all Landau-Zener processes leads to a significant difference of the m_F-transition frequencies due to the quadratic Zeeman effect and therefore allows specific addressing of the individual transitions. Slowly sweeping the radio frequency allows for an adiabatic following of the eigenstate.

In order to prepare the desired spin mixture, we first transfer the atoms initially in the $|2,+2\rangle$ state adiabatically into the $|2,0\rangle$ state. Subsequently the magnetic field is lowered to 10 G and $\pi/2$-Raman pulse is used to transfer 50% of the population into the $|1,0\rangle$ state resulting in the distribution shown in Fig. 1(a).

The Raman laser system consists of two phase-locked diode lasers similar to Ref. [26]. The master laser is operated in a free-running mode ≈ 16 GHz above the $F=2\leftrightarrow F'=3$-transition resonance. The slave laser is phase locked to the master at a difference frequency of 6.8 GHz above the master laser frequency taking into account the quadratic Zeeman shifts of 47 kHz between the $|2,0\rangle$ and $|1,0\rangle$ states. The intensities of the two equally and circularly polarized Raman laser beams at the position of the condensate are on the order of 30 mW/cm^2 each and the pulse duration is 100 μs. The mixture of the $|2,0\rangle$ and $|1,0\rangle$ states obtained after the Raman pulse is transferred to the final mixture by

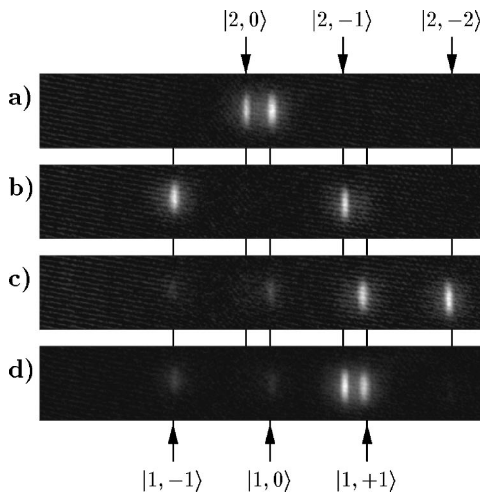

FIG. 1. Absorption images after different preparation steps. The corresponding sweeps and states are summarized in Table I.

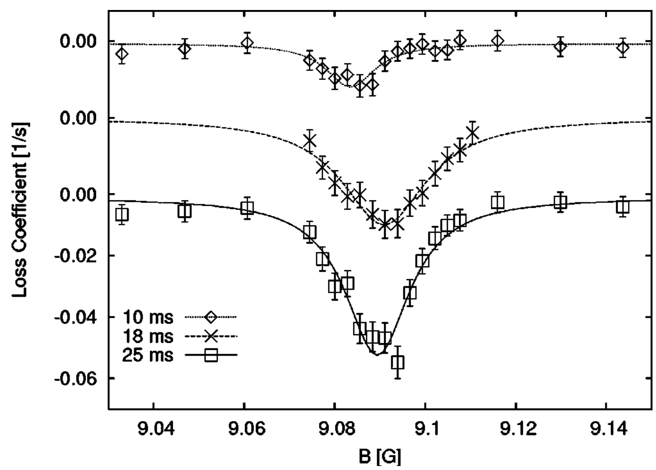

FIG. 2. Loss coefficients for a mixture of $|2,-1\rangle$ and $|1,+1\rangle$ states as a function of the magnetic field for hold times of 10, 18, and 25 ms. The loss coefficient is proportional to the two-body loss rate $\overline{\gamma}$ multiplied by the hold time (see text for further explanation).

three further Landau-Zener sweeps. Table I summarizes these steps and corresponding absorption images are shown in Fig. 1. We would like to note at that point that the absence of linear Zeeman shifts during the Raman passage made us favor the implemented scheme in comparison to a simpler sequence (e.g., using a Landau-Zener passage to $|2,-1\rangle$ and a $\pi/2$ pulse of appropriately polarized Raman lasers to transfer half of the population directly to the $|1,+1\rangle$). This way we achieve a good reproducibility of the preparation.

In order to observe the Feshbach resonance, the prepared mixture of $|2,-1\rangle$ and $|1,+1\rangle$ is held for a variable hold time in the dipole trap, while a precise current is applied to Helmholtz coils inducing magnetic fields up to 10 G. Then the dipole trap is switched off and after Stern-Gerlach separation an absorption image is taken. The number of atoms in the condensate fractions for the $|2,-1\rangle$ and $|1,+1\rangle$ states are determined by performing a one-dimensional fit to the column sums of the processed absorption images. For every value of the magnetic field the number of atoms in the condensates for both states is determined for negligible hold time as $N_1(0)$ and $N_2(0)$ and subsequently for hold time t_0 as $N_1(t_0)$ and $N_2(t_0)$.

Note that for the Feshbach resonance investigated in this paper the atoms in the incoming channels differ not only in their m_F but also in their F quantum number leading to a

TABLE I. Steps for the preparation of the $|2,-1\rangle$, $|1,+1\rangle$ mixture, starting with a $|2,2\rangle$ sample in the optical dipole trap.

		Mixture		
Action		State 1	State 2	Picture
		$|2,+2\rangle$		
Sweep 1	$\rightarrow$	$|2,0\rangle$		
Raman $\pi/2$	$\rightarrow$	$|2,0\rangle$	$|1,0\rangle$	(a)
Sweep 2	$\rightarrow$	$|2,-1\rangle$	$|1,-1\rangle$	(b)
Sweep 3	$\rightarrow$	$|2,-2\rangle$	$|1,+1\rangle$	(c)
Sweep 4	$\rightarrow$	$|2,-1\rangle$	$|1,+1\rangle$	(d)

significant extension of the number of outgoing and loss channels as compared to single-spin-channel resonances. For all channels not conserving the hyperfine state or total spin the released hyperfine or Zeeman energy leads to an instantaneous loss of atoms from the trap. In the following we analyze the loss dynamics in order to determine position and width of the resonance in a well-defined way. Loss during the hold time is evaluated assuming the following differential equation which describes the particle number $N(t)$ in a harmonic trap as a function of time t in the presence of a two-particle loss process [27]

$$\dot{N} = \gamma(B(t))N^{7/5}. \tag{1}$$

The loss rate, $\gamma(B(t))$ depends on the s-wave scattering length, introducing a magnetic-field dependence in order to allow for temporally varying values (as the magnetic field rms noise is comparable to the resonance width). It is important to annotate at this point that the equation above assumes an adiabatic following of the trapping volume during the decay process and therefore is not strictly valid for our considered process due to the fact that the decay is fast compared to the axial trapping frequency. Nevertheless the equation is a reasonable approximation [28] and allows the introduction of a loss coefficient C characterizing particle losses until time t_0. Variable separation of Eq. (1) yields

$$C = \overline{\gamma}(B)t_0 := \int_0^{t_0} dt\,\gamma(B(t)) = \frac{5}{2}\left(\frac{1}{N(0)^{2/5}} - \frac{1}{N(t_0)^{2/5}}\right), \tag{2}$$

defining a time averaged loss rate $\overline{\gamma}$. The loss coefficient is determined from the experiment as

$$C = \frac{5}{2}\left(\frac{1}{[N_1(0)+N_2(0)]^{2/5}} - \frac{1}{[N_1(t_0)+N_2(t_0)]^{2/5}}\right). \tag{3}$$

This equation can be applied due to $N_1 \approx N_2$ [29]. Figure 2 shows the according curves for hold times of 10, 18, and

TABLE II. Fitting parameters for the experimental data shown in Fig. 2 using Eq. (4) and calculated loss rates $\overline{\gamma}=A/(t_0-6\text{ ms})$ taking into account the initial ringing of the magnetic field (see text).

Hold time t_0(ms)	$\overline{\gamma}(B_0)$(1/s)	B_0(G)	ΔB(G)
10	−3.5	9.084	0.013
18	−2.8	9.091	0.023
25	−2.7	9.089	0.017

25 ms. The data have been fitted by a Lorentzian function

$$C(B) = C_0 + \frac{A}{1 + 4[(B - B_0)/\Delta B]^2}, \tag{4}$$

extracting the parameters shown in Table II. The C_0 value turns out to be small compared to the resonance depth and is consistent with two-body loss rates of other experiments [24].

The magnetic field is calibrated by performing Landau-Zener sweeps within the $F=2$ manifold at the approximate magnetic field of the Feshbach resonance. Figure 3 shows measured atom numbers in the BEC fraction for different end frequencies of the Landau-Zener sweep starting at 6326 kHz. The data is compared to a theoretical model of the m_F populations taking into account a m_F-dependent particle loss and Landau-Zener parameters during the sweeps. The positions of the m_F transition frequencies are evaluated by a simultaneous fit of the theoretically calculated populations for each of the m_F components. Due to symmetry this calibration method is first-order insensitive to ac-Stark shifts connected to the coupling field. The conversion to magnetic field values is based on a Landé-factor of $g_F=0.49945$ for ^{87}Rb. We want to mention that the difference between measured resonance positions and the calibration field of 9.088 G leads to relative errors of the order of 10^{-5} taking into account our offset field compensation. A detailed error budget estimating higher-order terms of the Breit-Rabi formula and ac-Stark shifts leads to an overall calibration error of <1 mG.

Nevertheless, the observed width is likely to be significantly broadened by current noise of the power supply ($\hat{=}5\text{ mG}_{rms}$) and ac stray magnetic fields in the laboratory (on the order of 5 mG_{rms} in the vicinity of the trapped atoms). The observed width of the Feshbach resonance is thus consistent with the theoretically predicted value of 1–2 mG [22,30], while we find a slight shift of its offset on the order of 3×10^{-3}, i.e., 30 mG (theoretical value 9.12 G [22]). Note that the initial ringing of the current in the Helmholtz coils when switched on at the beginning of the hold time inhibits the observability of the resonance for short hold times <6 ms and leads to slight shifts of the resonance mainly for

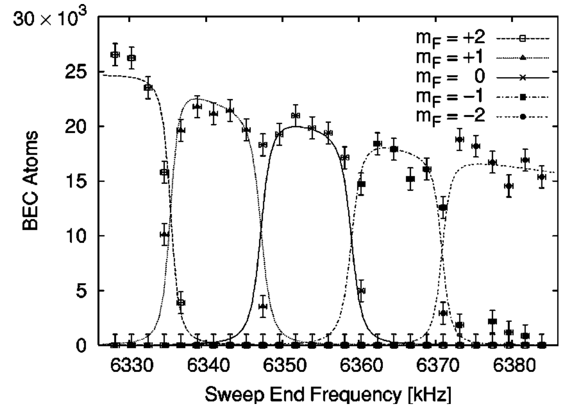

FIG. 3. Final population of m_F states after a Landau-Zener sweep starting at 6326 kHz vs sweep end frequency. The horizontal errors represent the accuracy of the used sweeping generator. A theoretical model is fitted to the data to determine a magnetic-field calibration yielding a linear Zeeman splitting frequency of $2\pi\times(6353.13\pm0.08)$ kHz.

short hold times (as observed for $t_0=10$ ms, compare Fig. 2 and Table II). Numerical integration of the current-switching curve however yields a shift of the resonance of less than 2 mG for $t_0\geqslant18$ ms, which thus cannot account for the shift we observe versus the theoretical prediction. Nevertheless additional eddy currents may be present. This conclusively explains the shift of the observed resonance for $t_0=10$ ms. Concerning longer hold times we observe no shift between the resonance curves for $t_0=18$ ms and $t_0=25$ ms and therefore shifts due to magnetic-field switching and eddy currents seem to be unlikely for these hold times.

A major difference is found concerning the loss rate $\overline{\gamma}\approx-2.8/\text{s}$, which is nearly two orders of magnitude lower than predicted [31]. This can be explained in part by broadening of the resonance due to technical noise. In addition, our estimation is based on a homogeneous mixture, but spacial separation effects of the two immiscible spin components may reduce the overlap and lead to a lower loss rate than expected [30].

In conclusion we have measured a mixed-spin-channel Feshbach resonance in ^{87}Rb between the states $|2,-1\rangle$ and $|1,+1\rangle$ at an easily accessible magnetic field of 9.09 ± 0.01 G. The line width is consistent with theoretical predictions [22,30], but there remain a slight line shift of ≈30 mG and a discrepancy in loss rates to be resolved.

Note added. Recently, observation of this resonance using entanglement interferometry with pairs of atoms in an optical lattice has been reported [32].

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[29] The used preparation scheme fulfills the requirement $N_1 \approx N_2$ with an accuracy of 20%. The preparation asymmetry can be determined and compensated for each measurement regarding the actual asymmetry and assuming losses by pairs of $F=2$ and $F=1$ atoms. Nevertheless this procedure leads only to changes of 20% in initial loss rates and has negligible effects on position and width of the resonance.
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