We report on the observation of a mixed spin channel Feshbach resonance at the low magnetic field value of $(9.09 \pm 0.01) \text{ G}$ for a mixture of $|2, -1\rangle$ and $|1, +1\rangle$ states in $^{87}\text{Rb}$. This mixture is important for applications of multi-component BECs of $^{87}\text{Rb}$, 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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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.

| Action         | Mixture            | State 1 | State 2 |
|----------------|--------------------|---------|---------|
| Sweep 1        |                    | $|2,+2\rangle$ | $|2,0\rangle$ |
| Raman $\pi/2$  |        | $|2,0\rangle$ | $|1,0\rangle$ |
| Sweep 2        |        | $|2,-1\rangle$ | $|1,-1\rangle$ |
| Sweep 3        |        | $|2,-2\rangle$ | $|1,+1\rangle$ |
| Sweep 4        |        | $|2,-1\rangle$ | $|1,+1\rangle$ |

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 $\mu$s. The mixture of the $|2,0\rangle$ and $|1,0\rangle$ states obtained after the Raman pulse is transferred to the final mixture by 3 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 10G. 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 1d 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 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 presence of a two-particle loss process.

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

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 root-mean-square-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 and allows the introduction of a loss coefficient, $C$, characterizing particle losses until time $t_0$. Variable separation of eq. 1 yields

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

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

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

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

$$C(B) = C_0 + \frac{A}{1 + 4((B - B_0)/\Delta B)^2}. \quad (4)$$
extracting the parameters shown in table I. 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.  

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 4 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 ($\approx 5$ mGrms) and AC stray magnetic fields in the laboratory (on the order of 5 mGrms 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 $3 \times 10^{-3}$, 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 short hold times (as observed for $t_0=10$ ms, compare fig. 2 and table I). Numerical integration of the current-switching curve however yields a shift of the resonance of less than 2 mG for $t_0 \geq 18$ 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 $\tilde{\gamma} \approx -2.8/s$, 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

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**FIG. 2:** Loss coefficients for a mixture of $|2, -1\rangle$ and $|1, +1\rangle$ states as 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 $\tilde{\gamma}$ multiplied by the hold time (see text for further explanation).

**FIG. 3:** Final population of $m_F$ states after a Landau-Zener sweep starting at 6326 kHz versus 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 $2\pi \times (6353.13 \pm 0.08)$ kHz.

**TABLE II:** Fitting parameters for the experimental data shown in figure 2 using eq. 14 and calculated loss rates $\tilde{\gamma} = A/(t_0 - 6$ ms) taking into account the initial ringing of the magnetic field (see text).

| Hold time $t_0$ [ms] | $\tilde{\gamma}(B_0)$ [1/s] | $B_0$ [G] | $\Delta B$ [G] |
|----------------------|-----------------------------|-----------|----------------|
| 10                   | -3.5                        | 9.084     | 0.013          |
| 18                   | -2.8                        | 9.091     | 0.023          |
| 25                   | -2.7                        | 9.089     | 0.017          |
lower loss rate than expected \cite{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$\pm$0.01 G. The line width is consistent with theoretical predictions \cite{22, 30}, but there remain a slight line shift of $\approx 30$ mG and a discrepancy in loss rates to be resolved. \note{Recently, observation of this resonance using entanglement interferometry with pairs of atoms in an optical lattice has been reported \cite{52}.}

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