Feshbach resonances in an ultracold ^{7}Li and ^{87}Rb mixture

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We report on the observation of five Feshbach resonances in collisions between ultracold ^{7}Li and ^{87}Rb atoms in the absolute ground-state mixture where both species are in their $|f,m_f\rangle=|1,1\rangle$ hyperfine states. The resonances appear as trap losses for the ^{7}Li cloud induced by inelastic heteronuclear three-body collisions. The magnetic field values where they occur are important quantities for an accurate determination of the interspecies interaction potentials. Results of coupled channels calculations based on the observed resonances are presented and refined potential parameters are given. A very broad Feshbach resonance centered around 649 G should allow for fine-tuning of the interaction strength in future experiments.

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Feshbach spectroscopy has enabled physicists to gather high-precision data on interaction potentials that made it possible to significantly increase the knowledge of the potential curves, since the location of Feshbach resonances is very sensitive to the shape of the long-range part of the interatomic potentials. Their experimental observation therefore sets tight constraints on them and fixes the scattering lengths. This works also for mixtures of different atomic species, where Feshbach resonances have been found in a range of alkali-metal mixtures. To date these include Fermi-Bose mixtures such as ^{6}Li+^{23}Na [1] and ^{40}K+^{87}Rb [2,3], Bose-Bose mixtures such as ^{85}Rb+^{87}Rb [4] and ^{39}K+^{87}Rb [5] as well as very recently Fermi-Fermi mixtures such as ^{6}Li+^{40}K [6].

Until a few months ago, in the absence of spectroscopic data for the Li-Rb mixtures, the interaction potentials were unknown to an extent that not even the signs of the background scattering lengths were known [7,8]. Recently, this has changed with the observation of heteronuclear Feshbach resonances in the Fermi-Bose mixture of ^{6}Li and ^{87}Rb atoms in the absolute ground state [9]. In parallel to our own running analysis, the group of Madison (UBC, Vancouver) has been able to determine the closed channels underlying the resonances by means of theoretical coupled channel calculations based on *ab initio* interaction potentials [10]. But they constructed artificial potentials, with which extrapolation to other isotope combinations by mass scaling is normally not reliable. At the same time we did a similar analysis applying potential curves of the singlet and triplet states from the $2s+5s$ atomic asymptote of Li+Rb, which were obtained by Fourier transform spectroscopy [11], with which predictions are meaningful for searches of Feshbach resonances for other isotopic combinations.

Furthermore, for the ^{7}Li+^{87}Rb system, there is a discrepancy between the experimentally determined absolute value of triplet scattering length [8] and the calculations described in Ref. [10]. Now, with the observation of heteronuclear Feshbach resonances in the purely bosonic system of ^{7}Li+^{87}Rb, data becomes available that allows for precise calculations of the Bose-Bose interaction potentials by also incorporating the spectroscopic results by Pashov *et al.* [11].

Accurate knowledge of potential curves is crucial for the efficient production of ultracold polar molecules. Here, the Li-Rb system is of particular interest, as the significant difference in electronegativity of Li compared to Rb leads to a large electric dipole moment as predicted in Ref. [12]. Usually, Feshbach or rf-associated molecules are highly excited and exhibit no significant dipole moment. Different possible routes to lower lying vibrational levels include direct population by means of photoassociation [13]. Huge increases in the molecule production rates have been predicted for both homonuclear [14] and heteronuclear photoassociation [15] performed in the vicinity of a Feshbach resonance. For homonuclear photoassociation this increase has already been shown experimentally [16,17].

In a Feshbach resonance, the scattering length changes as a function of magnetic field [18], which allows tuning the strength of interactions in atomic model systems for many-body physics for a wide range of applications in quantum gas experiments as studied in homonuclear systems, but heteronuclear mixtures will open a wide window to different model systems. Further, the recent observation of Efimov resonances in ultracold collisions of Cs atoms [19] pave the way for studying higher order bound state systems. Possible observations of the predicted universal properties are of particular interest [20]. Studies with three identical bosons are hampered by a large scaling factor for the appearance of these resonances. The strong mass dependence of the scaling factor in favor of large mass ratios of the collision partners together with the newly found very broad Feshbach resonances make the Li+Rb system an ideal candidate for studying this field.

The experimental sequence for producing ultracold mixtures of ^{7}Li and ^{87}Rb is similar to that described in Ref. [8]. In short, ^{7}Li and ^{87}Rb atoms are loaded in a magneto-optical

trap and are then transferred via several intermediate magnetic traps into a Ioffe-Pritchard type trap characterized by the secular frequencies $\tilde{\omega}/2\pi=(206\times200\times50)^{1/3}$ Hz (for Rb) and the magnetic field offset 3.5 G. Both species are in their stretched spin states $|f,m_f\rangle=|2,2\rangle$. The rubidium cloud is selectively cooled by microwave-induced forced evaporation, whereas the ^{7}Li cloud is cooled sympathetically by interspecies thermalization to temperatures around 3 μK. After the cooling ramp, the magnetic trap is slightly decompressed and moved exactly into the center of the trap coils. This is important because the magnetic field gradients due to the small size of the trap coils, which are also used for the Feshbach search, would otherwise strongly limit the magnetic field resolution. The atoms are then transferred into a horizontally crossed dipole trap operating at 1064 nm. The light is divided into two horizontal laser beams having powers of 2.9 and 3.2 W, respectively, which intersect at right angles at the center of the magnetic trap. Both beams are focused down to 58 μm resulting in trap depths of 130 μK (^{87}Rb) and 44 μK (^{7}Li) and trap frequencies of $\tilde{\omega}_{\mathrm{Rb}}/2\pi=(610\times440\times430)^{1/3}$ Hz and $\tilde{\omega}_{\mathrm{Li}}/2\pi=(1250\times900\times870)^{1/3}$ Hz. The mixture thermalizes in the dipole trap at temperatures of 10 μK (^{87}Rb) and 8 μK (^{7}Li) with about 5×10^5 Rb atoms and a few times 10^4 Li atoms. The temperature difference is due to permanent evaporative cooling of the ^{7}Li cloud in the dipole potential which is shallower for Li than for Rb.

For the search of Feshbach resonances, the atoms are prepared in their absolute ground states $|f,m_f\rangle=|1,1\rangle$ by means of rapid adiabatic passage on their respective hyperfine transition $|2,2\rangle\rightarrow|1,1\rangle$ at 6.835 GHz (^{87}Rb) and 803 MHz (^{7}Li). Each of these sweeps is performed over a range of 3 MHz in 4 ms in the presence of a homogeneous 4 G magnetic field. We obtain nearly 100% transfer efficiency in each case. Residual Rb $|2,2\rangle$ is removed by means of a resonant light pulse. Then the homogeneous magnetic field is quickly increased with fast ramping speeds between 100 and 600 G/ms to a variable final value B, where it is either scanned over a limited field interval or it is held at a fixed value for a certain amount of time. Then the magnetic field is ramped down again, the dipole trap laser is turned off, and both clouds are absorption imaged after a free expansion time of 300 μs for ^{7}Li and 5 ms for ^{87}Rb. Atom numbers are determined from these images and measured as a function of magnetic field. Feshbach resonances are identified by a dramatic increase in inelastic collision rates showing up in a reduction of atom numbers. Here, interspecies Feshbach resonances enhance the three-body loss rate coefficients $K_{\mathrm{Li,Rb,Rb}}$ and $K_{\mathrm{Li,Li,Rb}}$. Furthermore, since the Rb atom number exceeds the Li atom number by more than an order of magnitude, losses are visible specifically on the Li component. We searched the magnetic field range between 0 and 750 G for increased trap losses. The range is divided into intervals of 6 G, and the intervals are swept in subsequent experimental runs by magnetic field ramps of 200 ms duration. Intervals with sudden atom loss are analyzed in more detail. Several Feshbach resonances are identified at the locations listed in Table I. For resolving the individual resonances, different hold times with fixed magnetic fields (given as t_{hold}, i.e., time on resonance for the individual cases in Table I) are used in order to get an optimal saturation. The profiles are then fitted with Lorentzian functions to extract the center locations and the widths of the loss features. For the broad resonance at 649 G, the fit function is altered to take atom loss while scanning across the resonance into account. It consists of two Lorentzians with different offsets and amplitudes but the same width that are joined together at the resonance position. In order to resolve this resonance, crossing over to the high magnetic field side has to be done very quickly. But still a significant fraction of atoms is lost during the ramp across the resonance point as shown in Fig. 1. The asymmetry of the line shape due to the losses is apparent.

TABLE I. List of experimentally observed Feshbach resonances in both the Fermi-Bose mixture ^{6}Li-^{87}Rb [9] and the Bose-Bose mixture ^{7}Li-^{87}Rb with the resonances positions B_0 and full width at half maximum δB of the trap loss features for the used magnetic hold time t_{hold}. The numbers in brackets indicate the respective experimental uncertainty in units of the last digit shown for the measured field values.

Open Channel	B (G)	δB (G)	t_{hold} (ms)
$^6\mathrm{Li}\left\|\frac{1}{2},\frac{1}{2}\right\rangle^{87}\mathrm{Rb}\left\|1,1\right\rangle$	882.02(27)	1.27(27)	75
	1066.92(27)	10.62(27)	20
$^7\mathrm{Li}\left\|1,1\right\rangle^{87}\mathrm{Rb}\left\|1,1\right\rangle$	389.5(2)	0.9(2)	30
	447.4(2)	1.1(2)	10
	535.4(3)	1.1(4)	20
	565(1)	6(1)	90
	649(5)	70(10)	20

To model the Feshbach resonances we use the Hamiltonian for the two electronic states $X\,^1\Sigma^+$ and $a\,^3\Sigma^+$ of a pair of atoms A and B with electron and nuclear spin s and i, respectively, but no orbital angular momentum (see, for example, Refs. [21–23]):

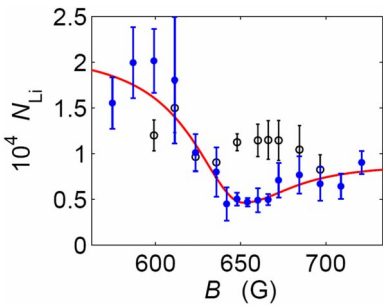

FIG. 1. (Color online) A very broad Feshbach resonance has been found located at B_0=649 G. Due to the tight confinement in the optical dipole trap, atom losses are observed even for fast ramping across the resonance position. The broad resonance should allow for precise tuning of the interaction strength in future experiments. The magnetic field was held for 20 ms at each value. The (black open) circles represent the ^{7}Li atom number in the absence of ^{87}Rb while the (blue) dots represent ^{7}Li with ^{87}Rb present in the trap. The (red) line is a fit based on two Lorentzian curves of same widths but different amplitudes and offsets connected at the resonance position. It takes atom losses during the fast sweep across the resonance when probing the high-field side into account.

$$H = T_n + U_X(R)P_X + U_a(R)P_a + a_A\vec{s}_A\vec{i}_A + a_B\vec{s}_B\vec{i}_B + [(g_{sA}s_{zA} - g_{iA}i_{zA}) + (g_{sB}s_{zB} - g_{iB}i_{zB})]\mu_B B_z + \tfrac{2}{3}\lambda(R)(3S_Z^2 - S^2). \quad (1)$$

The first line shows the kinetic energy T_n and the potential energy U_X and U_a for the internal nuclear motion of the atom pair; P_X and P_a are projection operators on the uncoupled singlet state X and triplet state a, respectively, for atoms with electron spin 1/2. The second line shows the hyperfine interaction, determined mainly by the Fermi contact term, for which we take the magnetic hyperfine parameters of the atomic ground state of the Li and Rb isotopes from the report in Ref. [24]. Feshbach resonances probe mainly the interaction at the atomic asymptote, thus effects by chemical bonds in the hyperfine interaction are very small and cannot be identified in our analysis. The coupling of nucleus A with the electron spin of atom B is neglected. The third line gives the Zeeman energy from the electron spin and the nuclear spin by an external homogeneous magnetic field B in z direction. Again the g factors determined for the isolated atoms [24] are applied. The last line contains the spin-spin interaction represented by the total molecular spin S and its direction to the molecule fixed axis Z. The parameter λ is a function of R, mainly as $1/R^3$ from the magnetic dipole-dipole interaction, but it contains also contributions from second order spin-orbit interactions. The atomic masses for the kinetic energy operator are taken from the recent tables by Audi *et al.* [25].

The calculations incorporate Born-Oppenheimer potentials for U_X and U_a according to Hund's coupling case b, because the total electronic spin is taken as good quantum number. As start of the analysis we apply directly the results of the Fourier transform spectroscopy at Hannover [11] and simulate the Zeeman pattern of the closest molecular levels just below those asymptotes studied by the Feshbach resonances given in Table I. Through the crossings of these patterns as function of the magnetic field with the level of separated atoms we obtain a first approximation of the expected Feshbach resonances. These calculations were initially done for ^{6}Li and ^{87}Rb to assign the results reported in Ref. [9]. Because of the good starting potentials it was almost straightforward to conclude that the resonance at 1066.92 G is a s-wave resonance and that at 882.02 G is a p-wave resonance. This agrees with the results in Ref. [10]. We made slight adjustments to the potentials at the short range branches to bring the calculated Feshbach resonances close to the observed positions. With these results predictions of Feshbach resonances for the isotope combination ^{7}Li and ^{87}Rb were made and s-wave resonances were observed fairly close to these predictions. During this study other resonances were found which could be immediately assigned to be p-wave resonances. Only the resonance around 535 G could not be identified up to now. This will be discussed later.

With this set of data a fit of the asymptotic form of the potentials was performed, in which we fitted the long range behavior with the van der Waals coefficient C_6 and C_8, to bring the rotational barrier for the p resonances to the right position, and the short range branch. The fit identifies as resonance the maximum of the rate constant of the corresponding elastic two-body collision at an average temperature of 4 and 9 μK for ^{6}Li+^{87}Rb and ^{7}Li+^{87}Rb, respectively. Because the spectroscopy analysis [11] showed that for the singlet state a correction to the Born-Oppenheimer potential has to be introduced to describe the data set with ^{6}Li and ^{7}Li, this was also kept during the present long-range analysis. The adiabatic correction function goes asymptotically for large R to zero as the normal long-range function does, and makes the total potential U_X mass dependent. The detailed ansatz is described in a recent paper on K_2 [26]. For the triplet state a the spectroscopic data set from Ref. [11] is poor and thus in that analysis we did not get a clear answer if a correction term would be needed. But here the influence is also expected to be smaller because the variation of the binding energy within the triplet potential is more than a factor 20 less than within the singlet potential. Additionally, both correction functions vanish when R goes to infinity, which follows from the infinitely slow relative motion of the two nuclei at such nuclear separations, and thus the asymptotic behavior of the two states is not altered compared to the pure Born-Oppenheimer potentials.

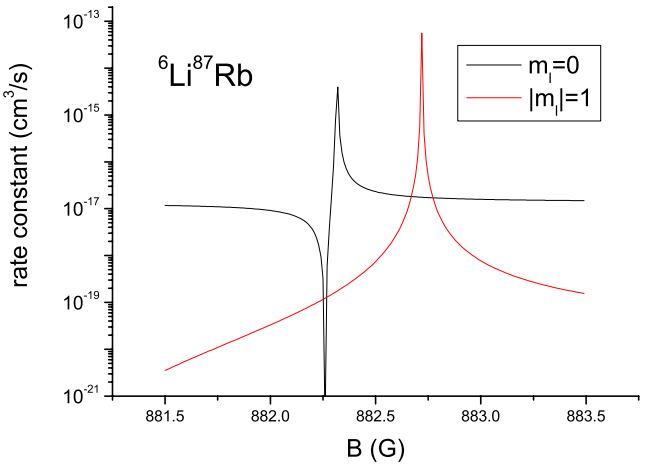

FIG. 2. (Color online) Splitting of p-wave resonance around 882 G for ^{6}Li+^{87}Rb at a collision energy of 4 μK, predicted from pure spin-spin interaction.

Because the splitting of the p-wave resonances [27] between the possible projections of the molecular rotation $m_l = 0$ and $m_l = \pm 1$ onto the space fixed axis was not observed, we included in the fit each p resonance two times assigning $m_l = 0$ and +1 to both cases ($m_l = -1$ is coinciding with +1) and increased their uncertainty to obtain the proper weighting of these observations for the fit. If one knew this splitting one could get a direct measure of the spin-spin coupling according to Eq. (1). We used the theoretical function $\lambda(R)$ assuming pure spin-spin coupling of free electron spins of the atoms. Figure 2 shows the expected splitting for the case ^{6}Li+^{87}Rb, the rates were calculated for a collision temperature of 4 μK. The splitting of about 0.5 G is fairly large but was not observed in the present experiment and also no asymmetry of the profile. These two aspects probably indicate that the contribution by the second-order spin-orbit interaction compensates the pure spin-spin interaction to a large extent, as it was already found for Rb_2 [28]. We

TABLE II. Calculated Feshbach resonances for the two models in both the Fermi-Bose mixture ^{6}Li+^{87}Rb and the Bose-Bose mixture ^{7}Li+^{87}Rb. We plot the resonance positions B_0, and for the s-wave resonances the distances from the resonance positions to the lower lying zero crossings of the scattering length Δ_0^∞ as well as the widths ΔB from fits to dispersion functions. In the case of model I, the resonance position $B_{0,\mathrm{rate}}$ refers to the maximum of the elastic scattering rate at finite temperature while $B_{0,\mathrm{fit}}$ is the resonance position for the dispersion fit at zero temperature. For the overlapping resonances of ^{7}Li+^{87}Rb, the formula $a(B)=a_{\mathrm{bg}}\,[1+\Delta B_1/(B-B_{0,\mathrm{fit},1})+\Delta B_2/(B-B_{0,\mathrm{fit},2})]$ was used. The fit interval and a_{bg} (unit Bohr radius) are indicated in the corresponding column. The quantum numbers of the coupling molecular state are given in the last column.

	Model I				Model II			Assignment
Open Channel	$B_{0,\mathrm{rate}}$ (G)	Δ_0^∞ (G)	$B_{0,\mathrm{fit}}$ (G)	ΔB (G)	$B_{0,\mathrm{fit}}$ (G)	Δ_0^∞ (G)	ΔB (G)	$\tilde{v}$, G, f, m_f, l
^{6}Li$\vert\frac{1}{2},\frac{1}{2}\rangle$+^{87}Rb$\vert 1,1\rangle$	882.42				882.04			-1, $\frac{3}{2}$, $\frac{5}{2}$, $\frac{3}{2}$, 1
	1066.54	−6.5	1066.51	7.4	1066.93	−10.5	10.5	-1, $\frac{3}{2}$, $\frac{5}{2}$, $\frac{3}{2}$, 0
			$a_{\mathrm{bg}}=-14.3\ a_B$		$a_{\mathrm{bg}}=-17.7\ a_B$			
			1000–1100 G		1010–1140 G			
^{7}Li$\vert 1,1\rangle$+^{87}Rb$\vert 1,1\rangle$	390.2				388.9			-1, $\frac{3}{2}$, 3, 2, 1
	445.6				446.2			-1, $\frac{3}{2}$, 2, 2, 1
	568.8	−120	568.6	7.9	570.3	−115	7.4	-1, $\frac{3}{2}$, 3, 2, 0
	650.6	−73	650.7	175	663.0	−87	194.23	-1, $\frac{3}{2}$, 2, 2, 0
			$a_{\mathrm{bg}}=-36\ a_B$		$a_{\mathrm{bg}}=-43\ a_B$			
			400–800 G		400–800 G			
	$\sigma=2.27$				$\sigma=2.64$			

checked that thermal averaging broadens both resonances only slightly, resolving them could be possible in future experiments if two-body effects determine the resonance profiles.

Table II shows in column labeled model I the results of this fit, where the resonances are described by the magnetic field value $B_{0,\mathrm{rate}}$ of the maximum of the two-body rate constants and in cases of s resonances the difference Δ_0^∞ for the field where the rate goes to zero. We also fit dispersion functions, in the case of the two overlapping resonances of ^{7}Li+^{87}Rb of the form $a(B)=a_{\mathrm{bg}}\,[1+\Delta B_1/(B-B_{0,\mathrm{fit},1})+\Delta B_2/(B-B_{0,\mathrm{fit},2})]$, to obtain the widths of the individual resonances. The latter method is strictly only valid for $T=0$ K, whereas the former gives the values in between which the scattering length has its full dynamical range. Neither of the two reported widths is equivalent to the width of the loss features reported in Table I.

The assignment is described by the vibrational quantum number $\tilde{v}$, counted from the asymptote, and angular momenta with quantum number G, from the coupling of the electronic spin with the nuclear spin of Rb $\vec{G}=\vec{S}+\vec{i}_{\mathrm{Rb}}$, with quantum number f of the total atomic angular momentum and its projection of the space fixed axis m_f and the rotation l of the atomic pair. Because the hyperfine structure of Rb is much larger than that of Li, G is in most cases a good quantum number, whereas the separated atom angular momenta lose their meaning. For the level just below the asymptote both assignments could have comparable quality, but we choose the quantum number G which becomes certainly the better one when going to more deeply bound states. The assignment also shows directly that the p resonances correspond to the same hyperfine levels as the s resonances. Thus the difference of the magnetic field between both groups reflect the Zeeman energy which is about equal to the rotational energy. The vibrational assignment $\tilde{v}=-1$ corresponds to the conventional vibrational states counted from the bottom $v_a=13$ and $v_X=48$ for the mixed singlet and triplet states, respectively, for ^{6}Li+^{87}Rb and 14 or 52 for the case ^{7}Li+^{87}Rb. The obtained values for the long-range potential function, namely, $C_6=2550.0$ a.u. and $C_8=2.3416\times10^5$ a.u. are almost equal to the ones reported by theoretical estimates in Refs. [29,30] $C_6=2545(7)$ a.u. and $C_8=2.34(4)\times10^5$ a.u.

Comparing the experimental resonance positions with the results of the fit we get significant deviations, sometimes outside the range of experimental uncertainty. However, there is no obvious systematic trend. The resonances were observed by trap losses thus shifts by three-body effects can be a concern. Studies in this direction are planned.

In Table II a different fit labeled "model II" is presented, which was obtained completely independently by the group in Berlin, using as starting potentials results from *ab initio* calculations and fitting as above the long- and short-range

behavior. This fit reproduces the resonances of the isotope pair ^{6}Li+^{87}Rb almost exactly but shows larger deviations for the other isotope combination. In the last line of Table II the normalized standard deviations are given for both models applying the same weights for the individual observations, and both are statistically only slightly different. The deviation of σ from a healthy value of about 1 signals the existing problems in the present theoretical models such as the assumption of two-body collisions for describing trap loss features. The long-range parameters for model II are C_6 =2543.0 a.u. and $C_8=2.2825\times10^5$ a.u. If one considers the correlation of these parameters expected from the data analysis, the two sets derived in this work are probably not really different.

We were unable to assign the resonance found at 535 G for ^{7}Li+^{87}Rb. For the experimentally prepared atomic pairs ^{7}Li$|1,1\rangle$+^{87}Rb$|1,1\rangle$ we checked the case of further resonances by s and p waves and by a s wave coupled to bound states with $l=2$ through spin-spin interaction. Nothing was found in the desired vicinity. Sharp s resonances by the l =2 states are expected at magnetic fields below 150 G. For the other cases all expected resonances of the lowest atomic asymptote for fields below 1.2 kG are observed in this work. Only very sharp resonances for p waves with the selection rule $\Delta m_l=-\Delta m_f\neq0$ in the neighborhood of the much stronger p resonances $\Delta m_l=\Delta m_f=0$ are predicted, but they are still too far from the observed one, namely, 535 G, and are too weak to be detected with experimental conditions in our present experiment, mainly the observation time on resonance and the sweep speed. Thus the question arises if the theory allows an overall different assignment. This is clearly not the case, because for the LiRb molecule, in which the small mass of the Li atom vibrates with respect to the heavy Rb atom close to the center-of-mass, the vibrational spacing is large. The next level is about 30 GHz below the last one at the asymptote. Thus the hyperfine structure in LiRb is small compared to this spacing and Feshbach resonances originating for these levels will only appear above 5 kG.

We also considered several other atomic asymptotes assuming that the preparation of the atomic states by the rf field ramps might be not pure enough. s-wave resonances for projection $m_f=0$ of the total angular momentum [with possible combinations $m_f(\mathrm{Rb})=\pm1$ or 0 and $m_f(\mathrm{Li})=\mp1$ or 0] are expected for fields larger than 700 G and for $m_f=1$ [$m_f(\mathrm{Rb})=1$ or 0 and $m_f(\mathrm{Li})=0$ or 1] larger than 600 G (see Table V below). Thus, these predictions are too far from the observed 535 G to try a fit with such an assumption. Only p resonances of those collision channels come close to the observed value 535 G, but then we have to accept two weak points: First, the impure preparation of the collision pair and second, the weakness of p resonances. We might speculate that this resonance does not originate from a two-body collision. We already tried to study the collision pair ^{7}Li$|1,0\rangle$ +^{87}Rb$|1,1\rangle$, but the stability of such prepared mixture was too short, less than 100 ms, to allow a search for Feshbach resonances. The collision pair ^{7}Li$|2,2\rangle$+^{87}Rb$|1,1\rangle$, could be prepared with good stability and we did not find a resonance in the range of 12 to 1095 G, which agrees with the expectations from our theoretical results.

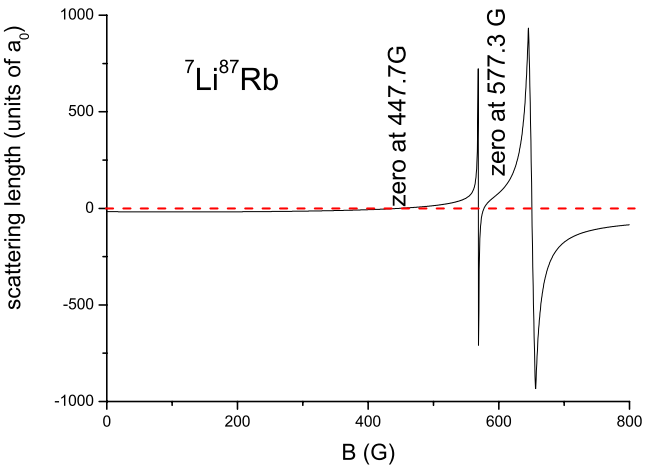

FIG. 3. (Color online) Scattering length of s-wave resonances calculated for ^{7}Li$|1,1\rangle$+^{87}Rb$|1,1\rangle$ as a function of the magnetic field.

For future experiments the tuning of interspecies interactions by the two s-wave resonances in ^{7}Li^{87}Rb is very promising. Figure 3 shows the calculated scattering length as function of the magnetic field. At low magnetic fields the scattering length is very small and negative until the crossing around 438 G and is increasing slowly to the resonance at 566 G. The long left tail of the upper resonance almost overlaps with the lower one thus the zero crossing between both is very close to the lower. From the fit result in Table II one sees, as mentioned already earlier, that the observations are not completely reproduced for these resonances, thus additional measurements especially for the zero crossing would be desirable for preparing the applicability of such interaction tuning. But independent of this fact the convenient tunability of the interspecies interaction with the help of these resonances remains valid.

With the analysis we computed the scattering length of the uncoupled singlet and triplet states for the different isotopic combinations. The results are given in Table III with an estimation of uncertainty limits (in units of the last digit shown for the scattering length) for the observed isotope combinations with ^{87}Rb using the variability of the long-range behavior obtained during the fit series due to correlations between C_6 and C_8 considering both models. The scattering length of the singlet state for ^{6}Li+^{87}Rb is almost zero, thus the sign is not yet determined, model I gives negative values whereas model II would favor values with the opposite sign.

TABLE III. Calculated scattering lengths for the uncoupled singlet and triplet states for different isotopic combinations of Li and Rb in units of Bohr radius ($a_0=0.529\times10^{-10}$ m).

State	Model	^{6}Li^{85}Rb	^{6}Li^{87}Rb	^{7}Li^{85}Rb	^{7}Li^{87}Rb
$X\,^1\Sigma^+$	I	7.6	0.5(30)	60.5	53.9(20)
	II	10.46	2.25	61.94	54.92
$a\,^3\Sigma^+$	I	−14.3	−18.6(30)	−51.5	−63.5(50)
	II	−15.50	−19.81	−55.08	−67.82

TABLE IV. Binding energies and vibrational quantum number v for the last bound state in the triplet and singlet potentials for varying isotope combinations as computed in the two different models. In the lower third of the table, the differences in binding energies between the two models are given for convenient comparison.

		$X\,^1\Sigma^+$		$a\,^3\Sigma^+$	
Model		v	E (cm^{-1})	v	E (cm^{-1})
I	^{6}Li^{87}Rb	48	0.113358	13	0.133654
	^{7}Li^{87}Rb	52	0.019722	14	0.134255
	^{6}Li^{85}Rb	48	0.099217	13	0.129054
	^{7}Li^{85}Rb	52	0.014744	14	0.128979
II	^{6}Li^{87}Rb	48	0.107631	13	0.136385
	^{7}Li^{87}Rb	52	0.018126	14	0.138009
	^{6}Li^{85}Rb	48	0.093908	13	0.131792
	^{7}Li^{85}Rb	52	0.013400	14	0.132689
I–II	^{6}Li^{87}Rb		0.005727		−0.002731
	^{7}Li^{87}Rb		0.001596		−0.003754
	^{6}Li^{85}Rb		0.005309		−0.002738
	^{7}Li^{85}Rb		0.001344		−0.003710

The values for the triplet case are consistent with absolute values determined by thermalization experiments on ^{6}Li $+^{87}$Rb [7] and ^{7}Li$+^{87}$Rb [8]. The value of the triplet scattering length for ^{7}Li$+^{87}$Rb from the work by Li *et al.* [10] is inconsistent with the present result; this is not surprising because these authors used constructed potentials for which they did not know the true depth and thus the number of vibrational levels each potential would accommodate. It is important to note that all triplet scattering lengths are small but have negative values, thus attractive interspecies interaction will determine ultracold ensembles at low magnetic fields. In order to estimate the sensitivity of the present models with respect to the binding energies, the energies of the least bound states that govern the scattering behavior are shown in Table IV along with the corresponding vibrational quantum number v for the different isotope combinations. Singlet and triplet binding energies for both models are given together with the difference of the values obtained in both models. The size of these differences indicates, that rf spectroscopy close to Feshbach resonances [31] could be of great value to derive the asymptotic potentials.

In conclusion, we detected five collision resonances in a two species ultracold mixture of ^{7}Li and ^{87}Rb gases with both species in their respective absolute ground state $|1,1\rangle$. Four of them could be unambiguously assigned to *s*- or *p*-Feshbach resonances. We combined these data with the existing observations on ^{6}Li and ^{87}Rb [9] to derive until now only unsatisfactorily known interspecies interaction potentials of the Bose-Bose and Fermi-Bose mixtures. For experiments employing the broad resonance at 649 G, low densities have to be used in order to decrease the large losses associated with this resonance and to obtain a better profile for determining the position of this resonance with higher accuracy.

TABLE V. Calculated Feshbach resonances for different collision channels in ^{7}Li$+^{87}$Rb, positions given in *G*.

Atomic Channels ^{7}Li$\|f,m_f\rangle+^{87}$Rb$\|f,m_f\rangle$	Model I	Model II
$\|1,0\rangle+\|1,1\rangle$	634	644
	663	667
	748	763
$\|1,1\rangle+\|1,0\rangle$	786	807
$\|1,-1\rangle+\|1,1\rangle$	717	730
	772	773
	854	865

Because of the slightly different theoretical results we calculated Feshbach resonances for other atomic collision channels, for which further measurements could help to obtain a converging analysis. Table V shows predictions for the pair ^{7}Li$+^{87}$Rb for some of the lowest atomic asymptotes. Searching for the resonances of channel ^{7}Li$|1,0\rangle+^{87}$Rb$|1,1\rangle$ one should prepare the atomic pair at fields higher than 18 G, because at lower fields the losses to channel ^{7}Li$|1,1\rangle$ $+^{87}$Rb$|1,0\rangle$ will be significant and for the case ^{7}Li$|1,-1\rangle$ $+^{87}$Rb$|1,1\rangle$ the preparation should be above 174 G to avoid inelastic losses to ^{7}Li$|1,1\rangle+^{87}$Rb$|1,-1\rangle$ and ^{7}Li$|1,0\rangle$ $+^{87}$Rb$|1,0\rangle$. The predictions of the two models largely agree, but show a significant difference for the Feshbach resonance in the channel ^{7}Li$|1,1\rangle+^{87}$Rb$|1,0\rangle$. Studying this resonance could thus facilitate the discrimination between the two models or their convergence. But this might be hampered by the fact that the resonance will also be broadened by inelastic processes.

For the pair ^{6}Li$+^{87}$Rb calculations were already done by Li *et al.* [10] giving few *s*-wave resonances around 1000 G or above, thus not in a convenient region for experiments. Our own calculations show only small shifts for these predictions, e.g., for the entrance channel ^{6}Li$|1/2,1/2\rangle$ $+^{87}$Rb$|1,1\rangle$ we get 1292 G instead of the reported value of 1278 G in Ref. [10], no additional listing of these cases seems to be necessary at present.

Future research could include formation of heteronuclear molecules as mentioned earlier. For the population of vibrationally highly excited states, such molecules could be formed by either adiabatically sweeping the magnetic field over an interspecies Feshbach resonance from high to low fields [4] or by radio-frequency association [31]. In the case of the very desirable low lying states, preferably the absolute ground state, Feshbach-assisted photoassociation schemes [14,15] could be the method of choice. The molecular spectroscopy started by Pashov *et al.* [11] will lead to the needed knowledge of the rovibrational structure of electronically excited states. Advancing to three-body effects, the scaling

factor for Efimov resonances [19] is dependent on the mass ratio of the collision partners [20]. For Li-Rb a much smaller scaling factor is predicted than for three identical bosons, making this system particularly interesting for possibly uncovering universal properties of Efimov resonances. Further, by fine-tuning the interspecies interaction in the Bose-Bose mixture, mean-field induced stabilization of intrinsically unstable ^{7}Li condensates could be studied [8].

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