Efimov Resonance and Three-Body Parameter in a Lithium-Rubidium Mixture

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We study collisional heating in a cold ^{7}Li-^{87}Rb mixture near a broad Feshbach resonance at 661 G. At the high field slope of the resonance, we find an enhanced three-body recombination rate that we interpret as a heteronuclear Efimov resonance. With improved Feshbach spectroscopy of two further resonances, a model for the molecular potentials has been developed that now consistently explains all known Feshbach resonances of the various Li-Rb isotope mixtures. The model is used to determine the scattering length of the observed Efimov state. Its value of $-1870a_0$ Bohr radii supports the currently discussed assumption of universality of the three-body parameter also in heteronuclear mixtures.

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Investigating the collision properties of cold atomic gases has turned out to be a powerful tool for understanding fundamental few-body interactions. A prominent example is the experimental observation of the long-predicted Efimov trimers [1]. Such bound states between three particles exist near scattering resonances, where the pair interaction between the particles depends only on the interparticle scattering length a, and thus exhibit a so-called universal behavior [2]. Since, in cold atomic gases, the scattering length can be tuned by applying an external magnetic field, such gases are regarded as a nearly ideal test environment for investigating Efimov-related fundamental physics [3]. In the experiment, the existence of a bound trimer is observed as an increase of the inelastic three-body collision rate at specific values of the scattering length. The intriguing property of Efimov trimers is the scaling law of their energy eigenstates, which can be constructed by applying integer multiples of a universal scaling factor to a first state, defined as that with the lowest energy. For negative scattering length, this scaling rule has recently been confirmed in a homonuclear cesium gas [4] and in a heteronuclear mixture of cesium and lithium [5,6]. In heteronuclear mixtures with atoms of very different masses [7–10], the scaling factor may be significantly smaller than for homonuclear gases. This helps to observe more Efimov states in the regime of experimentally controllable magnetic fields and temperatures.

Besides the scaling law, the absolute energy of the Efimov states is discussed to show universal behavior. Recent experimental observations and theoretical investigations seem to indicate that the position of the Efimov states in homonuclear gases is determined only by the van der Waals radius and the strength parameter of the Feshbach resonance [11–13]. In heteronuclear mixtures, the situation is more complicated [10]. For large mass imbalance with two heavy atoms each resonantly coupled to one light atom, it is predicted that the position of the first Efimov state only depends on the mass ratio, the van der Waals length, and the scattering length of the two heavy atoms [14]. However, comparison with the available experimental observations is not yet conclusive and experiments with a larger variety of suitable mixtures are highly desirable, because so far results are only available for K-Rb [8,10] and Li-Cs [5,6].

A promising candidate for studying the universality of Efimov physics in heteronuclear mixtures is the $^{6/7}$Li-^{87}Rb system. In comparison with the above mentioned Li-Cs system, it has the specific advantage that the scattering length between the two heavy ^{87}Rb atoms has a moderate value of $a \approx 100a_0$ and does not vary due to the external magnetic field in the range of the heteronuclear Feshbach resonance. For Li-Rb mixtures a number of Feshbach resonances have been observed in various isotope combinations. However, a model for the molecular potentials that consistently describes the experimental data was missing.

In this Letter, we present the observation of a first Efimov resonance in the Li-Rb mixture and determine the related scattering length by means of an improved model for the molecular potential curves. The Efimov resonance is observed by monitoring the temperature of the mixture that increases on resonance because of enhanced three-body collisional heating [15]. For developing the improved model, we have recorded the Feshbach resonances near 535, 570, and 661 G with enhanced quality. In combination with already published data for ^{6}Li-^{85}Rb [16], ^{6}Li-^{87}Rb [17], and ^{7}Li-^{87}Rb [18], molecular potentials that consistently describe all known Feshbach resonances in the Li-Rb systems can now be derived. Furthermore, the yet unassigned resonance near 535 G [18] can be identified as a d-wave resonance.

The experimental setup has already been described elsewhere [18]. In brief, ^{7}Li and ^{87}Rb atoms are collected in overlapping magneto-optical traps. After optical pumping both atom species into the Zeeman state $F = 2$, $m_F = 2$

they are transferred into a magnetic Ioffe-Pritchard trap. There, the rubidium gas is cooled by microwave-induced forced evaporation while the lithium gas thermalizes with rubidium by elastic collisions. Near the end of the cooling procedure, the trap frequencies are lowered such that the two gases decouple. The rubidium gas is further cooled alone. This allows for the preparation of the two gases at different temperatures before they are transferred into an optical dipole trap. It is formed by two horizontally crossed laser beams each with a wavelength of 1070 nm and a power of 7 W. The angle between the beams amounts to 36°. The x axis of the trap is defined as the bisector of this angle. The beam waist is manually adjustable to a fixed value between $w_0 = 50$–$200\ \mu$m. The dipole trap is loaded by slowly turning on the laser power. Then, the magnetic field is turned off. At the end of this adiabatic transfer, temperatures amount to values in the low microkelvin range. Lowest temperatures are obtained for the dipole traps with the largest beam waist. The adiabatic temperature change is slightly different for the two species since the trapping potential for lithium is more shallow than for rubidium. The preadjusted temperature difference in the magnetic trap is used to compensate for this effect such that final temperature difference is well controlled. With the coils of the Ioffe-Pritchard trap, a moderate homogeneous magnetic field is now generated in which the atoms are transferred to their ground states ($F = 1$, $m_F = 1$) by means of rapid adiabatic microwave passages. Finally, the magnetic field is increased to the values where Feshbach resonances are observed.

The trap coils are located inside the vacuum chamber with symmetry axes oriented in the vertical direction (z axis with the origin at the center between the two coils). With an inner radius of only 5 mm [19] the coils generate an almost homogeneous magnetic field at the position of the atoms with a small field inhomogeneity. The minimum of the dipole trap is positioned at the symmetry axis, but shifted slightly from the origin towards the upper coil. At this position, the gravitational sag of the lithium atoms is compensated by the local magnetic field gradient. This compensation maximizes the trap depth for the lithium atoms. With this alignment, the rubidium atoms are shifted across the origin by the gravitational sag such that the local magnetic field gradient shifts the cloud further down. The resulting total separation between the two clouds amounts to 24 μm. Furthermore, the magnetic field inhomogeneity generates an additional harmonic trapping potential in the horizontal directions (x and y axes) and a harmonic antitrapping potential along the vertical direction (z axis). The latter repels the atoms from the trap center and thus limits the depth of the combined optical and magnetic trapping potential. The trap parameters can be derived from a detailed calculation of the magnetic field geometry. For a magnetic field around 665 G and a typical beam waist of $w_0 = 180\ \mu$m, the trap depths along the z axis amount to 1.6 μK for lithium and 8.4 μK for rubidium. The trapping frequencies close to the trap minimum are $\nu_x^{\mathrm{Rb}} = 46$ Hz, $\nu_y^{\mathrm{Rb}} = 109$ Hz, $\nu_z^{\mathrm{Rb}} = 95$ Hz for rubidium and $\nu_x^{\mathrm{Li}} = 154$ Hz, $\nu_y^{\mathrm{Li}} = 271$ Hz, $\nu_z^{\mathrm{Li}} = 159$ Hz for lithium. Because of the small trap depth along the z axis, there is a constant loss of atoms such that the mixture can be observed only for a limited holding time of several 10 ms before the atom numbers drop below the noise floor of shot-to-shot fluctuations. For smaller beam waists w_0, the trap is deeper, but the temperature after the adiabatic transfer from the magnetic trap is increased.

The overview in Fig. 1 shows the number of lithium atoms remaining in the trap after an interaction time of 50 ms for magnetic fields between 520 and 770 G. The spectrum is recorded with an initial temperature difference between the gases. On resonance, enhanced cross thermalization with the slightly hotter rubidium gas evaporates the lithium atoms from the dipole trap. The narrow resonances near 535 and 570 G have been fit with Gaussian functions, resulting in positions given in the Supplemental Table [21]. The very broad resonance around 661 G is observed with a highly improved signal-to-noise ratio as compared to previous observations [18]; however, it still exhibits a strong asymmetry because of the aforementioned increased losses at higher magnetic fields. A much narrower linewidth with symmetric line shape is obtained by monitoring three-body collisions in a temperature-balanced mixture. Its position is thus derived from the spectra in Fig. 2. The magnetic field was calibrated by means of a very narrow and well-known homonuclear ^{87}Rb resonance at

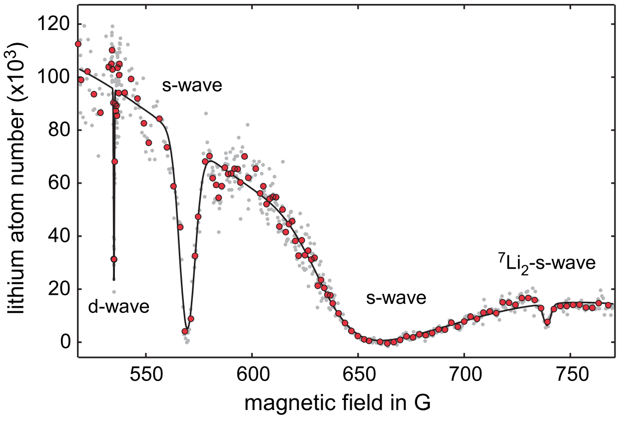

FIG. 1 (color online). Lithium losses due to cross thermalization with rubidium for different magnetic fields. The rubidium atom number of 5×10^5 remains almost constant during the interaction. After an interaction time of 50 ms, the dipole trap is turned off and the atom number is detected by time of flight imaging. Besides s- and d-wave resonances of the ^{7}Li-^{87}Rb mixture, a known s-wave $^7\mathrm{Li}_2$ resonance shows up near 737 G [20]. The red dots are the result of a threefold binning of the raw data (gray dots).

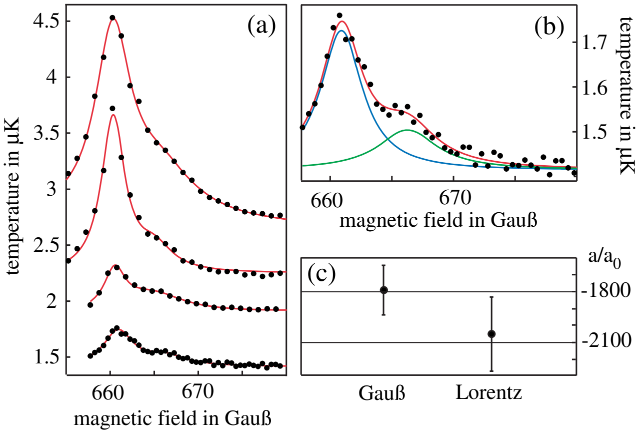

FIG. 2 (color online). (a) Temperature of the rubidium gas interacting with the lithium cloud at different magnetic fields. Before the interaction, both gases have been prepared at similar temperatures (2.7, 2.2, 1.9, 1.4 μK) and particle numbers (1.5×10^5, 1.3×10^5, 1×10^5, 0.3×10^5, top curve to bottom curve). The interaction times amount to 50, 50, 40, and 15 ms, respectively. Each point is an average from over 40 to 100 experimental runs. (b) Same data as in the lowest curve of (a). The blue and green solid lines are a Gaussian function for the pure three-body collisions and a Lorentz function for the Efimov resonance, respectively. The red solid line is the sum of both functions. (c) Scattering length of the Efimov resonance for a Gaussian and a Lorentzian function in units of the Bohr radius a_0 (see text). The error bars indicate the statistical error for the average of the four measurements shown in (a).

685.43(3) G [22]. The experimental errors are dominated by the uncertainty of this procedure.

Based on the position of the resonances, we have developed an improved model for the molecular potentials of the Li-Rb isotope system. The result is listed in the Supplemental Table [21]. The new model now reproduces all known Feshbach resonances of the Li-Rb isotope mixtures [16–18] within the statistical and systematic errors [23]. In particular, the unassigned resonance of ^{7}Li-^{87}Rb mixture near 535 G can be identified as a d-wave resonance. For the triplet and the singlet scattering length, we obtain the values $a_s = 54.75(30)a_0$ and $a_t = -66.66(10)a_0$. The long range potential is given by the parameters $C_6 = 2550.0$ a.u. and $C_8 = 2.3501 \times 10^5$ a.u. Furthermore, the new fit predicts the broad s-wave resonance near 661 G at a position shifted by about 10 G relative to the previous calculations [18]. For temperatures below 100 nK, the scattering length of this resonance can be parametrized by

$$a = a_{\mathrm{bg}}\left(1 - \frac{\Delta B_0}{B - B_0}\right), \tag{1}$$

with the back ground scattering length $a_{\mathrm{bg}} = -43.18a_0$, $B_0 = 661.44$ G, and $\Delta B_0 = -187.97$ G. The calculated strength parameter of the resonance [24] amounts to 3.54.

The high field slope of this resonance offers ideal conditions for studying Efimov physics at negative scattering length. With a mass imbalance of 12.4, the Efimov scaling factor for the ^{7}Li-^{87}Rb$_2$ trimer of 7.87 is much smaller than the corresponding value of 22.7 for homonuclear trimers [2] and is not much larger than the value of 4.88 for the ^{6}Li-^{133}Cs$_2$ system. The resonance is well isolated, and on the negative side of the resonance the absolute value of the scattering length can be tuned to low values on the order of the interspecies van der Waals radius of $44a_0$ without being perturbed by other nearby resonances.

Figure 2(a) shows temperature profiles at various preparation temperatures between 2.7 and 1.4 μK with insignificant temperature difference between the two species. The Efimov resonance appears as a shoulder at the high field slope of the temperature profile. A nearby narrow Feshbach resonance predicted for collisions between pairs in the ^{7}Li$(1,0)$-^{87}Rb$(1,1)$ channel at 666.7 G (width 0.1 G) can be excluded as an explanation for the shoulder if the spin preparation in the dipole trap is sufficiently pure. For testing the actual spin purity in the experiment, two stronger Feshbach resonances of the same channel at 642.8 G (width 0.3 G) and 762 G (width 1 G) have been checked. They turned out to be below the detection limit for the applied sample preparation.

Parallel to the temperature increase, the atom numbers decrease. However, we observe strong shot-to-shot fluctuations in the numbers of the individual species while fluctuations of the total atom number stay within a few percent. This effect is probably caused by light-induced collisions during the preparation of the combined magneto-optical traps [25]. Because of the differential shot-to-shot fluctuations, we cannot reliably extract the recombination rate coefficients $K_3^{\text{Li-Rb-Rb}}$ and $K_3^{\text{Li-Li-Rb}}$ for the two types of interspecies three-body collisions by interpreting the shape of the decay curves [8,15]. The experiment is thus only sensitive to a weighted sum of both coefficients. Efimov enhancement is expected only for Li-Rb-Rb collisions since the effective three-body potential for Li-Li-Rb trimers is much smaller than for Li-Rb-Rb trimers [2].

To extract the position of the Efimov feature, we fit the data with the sum of two heuristic line shape functions, one for the Feshbach resonance and one for the Efimov feature. The Efimov resonance is described by a Lorentzian function with position, width, and height as fit parameters. For the Feshbach resonance, we use a Lorentzian and alternatively a Gaussian again with position, width, and height as fit parameters. Each function is combined with an offset and a constant slope as additional fit parameters. Figure 2(b) shows the experimental data at the lowest preparation temperature together with the Gaussian function. After fitting the four curves of Fig. 2(a) and taking the average of the resulting fit parameters, the two line-shape functions return the same value for $B_F = 660.5(3)$ G.

For the position of the Efimov resonance, we obtain $B_E = 665.4(3)$ and $665.9(3)$ G, respectively. The total error for B_F and B_E amounts to 0.5 G and is dominated by the uncertainty of the magnetic-field calibration of 0.4 G. Systematic shifts of the magnetic field because of heating of the coils remain below 0.1 G. The value determined in this way for B_F deviates from the molecular potential calculations [Eq. (1)] by 0.94 G, which is explained by the uncertainty of the magnetic field calibration and the finite temperature corrections to Eq. (1). The effect of using different functions also for fitting the Efimov resonance is small and can be neglected. To make the connection between the magnetic field B_E and the scattering length a, we use Eq. (1). By setting $B = B_E$, we obtain the values for the scattering length shown in Fig. 2(c). The error bars indicate the statistical error after averaging the fit results for the four profiles shown in Fig. 2(a). The final result is the weighted average $-1870(121)a_0$. The systematic error due to the uncertainty of the magnetic field calibration amounts to $166a_0$ for the Gaussian fit function and $311a_0$ for the Lorentzian fit function.

We compare our experimental findings for the scattering length of the first Efimov resonance with the theoretical model of Ref. [14]. It predicts universality for the three-body parameter for heteronuclear mixtures by means of the universal properties of the van der Waals potential between the two heavy atoms. For the ^{6}Li-^{87}Rb mixture, the first Efimov resonance is expected at $a = -1600a_0$. For the ^{7}Li-^{87}Rb mixture, unpublished calculations indicate a slightly different value of about $a = -1800a_0$ [26], which agrees well with our observations. Thermal corrections are expected to be small since the thermal wave length still exceeds the scattering length at the Efimov resonance by about a factor of 4. For heteronuclear systems with large mass difference, experimental data also exist for the ^{6}Li-^{133}Cs mixture [5]. Here, the observed position of the first Efimov resonance of $-320a_0$ seems to contradict the theoretical prediction of $-1400a_0$ [14]. However, the calculations assume a large and positive value of $a_{\mathrm{CsCs}} = 2000a_0$ for the heavy-atom–heavy-atom scattering length as typical for Cs. For the actual experiment, it later emerged that, at the magnetic field of the Li-Cs-Feshbach resonance, the value for a_{CsCs} has a similar magnitude but a negative sign. With this taken into account, the calculations now predict a first Efimov-like resonant feature in the three-body recombination rate in good agreement with the experimentally observed position [26].

In summary, we have investigated collisional heating of the ^{7}Li-^{87}Rb mixture with the goal of exploring Efimov physics in heteronuclear mixtures with large mass imbalance. An Efimov resonance at negative scattering length has been observed near $-1870a_0$, which supports theoretical predictions of a universal three-body parameter in cold atomic mixtures. With an improved model for the molecular potentials, all known Feshbach resonances for the different isotope mixtures of Li-Rb systems are now explained. In particular a new d-wave resonance has been identified. Based on the known scaling factor, a second Efimov resonance is expected at about $-15\,000a_0$, corresponding to a magnetic field of 662.0 G. This seems to be within experimental reach if the temperature can be reduced to a few 100 nK. The observation of a third resonance at $-115\,000a_0$ appears to be very difficult, and even at very low temperatures, thermal effects will play an important role, which is a topic in itself [27]. Experimentally more accessible is the question of universality of the three-body parameter. This requires a systematic search for Efimov resonances in different mixtures [13]. Here, the various Li-Rb mixtures offer a number of unexplored Feshbach resonances.

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