Observation of Universality in Ultracold ^{7}Li Three-Body Recombination

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(Received 25 June 2009; published 13 October 2009)

We report on experimental evidence of universality in ultracold ^{7}Li atoms' three-body recombination loss in the vicinity of a Feshbach resonance. We observe a recombination minimum and an Efimov resonance in regions of positive and negative scattering lengths, respectively, which are connected through the pole of the Feshbach resonance. Both observed features lie deeply within the range of validity of the universal theory, and we find that the relations between their properties, i.e., widths and locations, are in excellent agreement with the theoretical predictions.

DOI: 10.1103/PhysRevLett.103.163202 PACS numbers: 34.50.−s, 21.45.−v, 67.85.−d

Few-body physics is universal when interparticle interactions are insensitive to the microscopic details of the short-range interaction potentials and can be characterized by only one or few universal parameters [1]. In the limit of zero collision energy, the two-body interactions are determined by a single parameter, the s-wave scattering length a. Universality requires a to greatly exceed the two-body potential range. This can be achieved by a resonant enhancement of a, yielding the appearance of the peculiar quantum states known as quantum halos whose wave function acquires long-range properties and gives rise to loosely bound states of size $\sim a$ [2]. In the case of three interacting bosons, universality means that the three-body observables show log-periodic behavior that depends only on the scattering length a and on a three-body parameter which serve as boundary conditions for the short-range physics. Such a behavior is associated with so called Efimov physics. In a series of theoretical papers, Efimov predicted and characterized an infinite set of weakly bound triatomic states (Efimov trimers) whose binding energies (in the limit of $a \rightarrow \pm\infty$) are related in powers of a universal scaling factor $\exp(-2\pi/s_0) \approx 1/515$ where $s_0 = 1.00624$ [1,3]. Efimov trimers resisted experimental observation for nearly 35 years remaining an elusive and a long-term goal in a number of physical systems [2]. Only recently have they been experimentally discovered in a gas of ultracold cesium atoms [4,5].

Ultracold atoms provide an excellent playground to study universality. The characteristic range of the two-body interaction potential r_0, basically equivalent to the van der Waals length $r_0 \simeq (mC_6/16\hbar^2)^{1/4}$ [6], usually does not exceed $100a_0$, where a_0 is the Bohr radius. The scattering length a can be easily and precisely tuned to much higher values by means of Feshbach resonances which are present in most of the ultracold atomic species [7]. Efimov physics is not revealed by direct observation of Efimov trimers but rather through their influence on a three-body observable—the recombination loss of atoms from a trap. For positive scattering lengths, effective field theory predicts log-periodic oscillations of the loss rate coefficient with zeros as minima (for the ideal, zero energy system) which can be interpreted as destructive interference effects between two possible decay pathways [1,8]. For negative scattering lengths, the loss rate coefficient exhibits a resonance enhancement each time an Efimov trimer state intersects with the continuum threshold. Positions of the minima and the maxima are expected to be universally related [1] when regions of $a > 0$ and $a < 0$ are connected through a resonance ($a \rightarrow \pm\infty$). Despite the dramatic success in the experimental demonstration of an Efimov state in Ref. [4], difficulties arose in matching between the two regions of universality, that of positive and negative a [4,5]. These were twofold: first, the interference minimum was observed at $a \approx 210a_0$, only a factor of 2 higher than the r_0 for cesium atoms and thus not strictly in the universal regime; second, the two regions of universality were connected through a zero crossing ($a = 0$) which is a nonuniversal regime and thus questions the validity of the universal relation between them [4,9]. In a more recent experiment on Efimov physics in ultracold ^{39}K atoms, the two regions of $a > 0$ and $a < 0$ were connected through a resonance, but still significant deviations from the universal relations have been reported [10]. These deviations were attributed to the influence of details of the short-range interatomic potential. Though signatures of Efimov physics have been recently observed in other ultracold atom systems [11–13], no system has yet been able to answer the conditions in which universal relations could be verified.

In this Letter, we report on evidence of universal three-body physics in ultracold ^{7}Li in the vicinity of a Feshbach resonance based on measurements of three-body recombination. We discuss the effective range of the resonance and show that it supports a wide region of universality extended to tens of Gauss around the resonance center. A recombination loss minimum and an Efimov resonance are revealed in the $a > 0$ and $a < 0$ regions, respectively, which are connected through the pole of the Feshbach resonance. The observed features lie deeply within the universal regime and verify the predictions of the universal theory regarding relations between their properties.

Compared to other atomic species currently available for laser cooling techniques, lithium has the smallest range of van der Waals potential, $r_0 \approx 31a_0$. In addition, a number of Feshbach resonances available for different Zeeman sublevels of the $|F = 1\rangle$ hyperfine state makes ^{7}Li an appropriate candidate for study of Efimov physics. In this experiment, we work with a spin polarized sample in the $|F = 1, m_F = 0\rangle$ state, which is the one but lowest Zeeman state [14]. In principle, two-body losses are possible from this state; however, they are not large, as could be the case for heavier atoms. For instance, ^{133}Cs experiences large dipolar losses caused by the second-order spin-orbit interaction [15]. We calculated the dipolar relaxation rate coefficients as a function of magnetic field via a coupled-channels calculation by using recent interaction potentials [16] and found them to be ~3 orders of magnitude smaller than the corresponding measured rate coefficients, if the experimental losses were treated as purely two-body related. Moreover, the field-dependent profile of the calculated rates is qualitatively very different from the observed rates. As a result, we exclude two-body losses and determine that the loss processes in the region of interest are related to three-body recombination.

The $|F = 1, m_F = 0\rangle$ state possesses two Feshbach resonances, a narrow and a wide one, which we experimentally detect by atom loss measurement at 845.8(7) G and 894.2(7) G, respectively. The position of the wide resonance is independently measured at 894.63(24) G by molecule association technique [17]. These positions are in agreement with theory within the uncertainty of the magnetic field calibration (± 0.5%). In Fig. 1, two collision properties are shown as a function of magnetic field: the scattering length a and the effective range R_e. These quantities are extracted from the scattering phase shift $\delta(k)$ at small relative wave numbers k by using the effective range expansion $k\cot\delta(k) = -1/a + R_e k^2/2$ [18].

The region of universality strongly depends on the width of the Feshbach resonance which is inversely proportional to the effective range close to the resonance's center

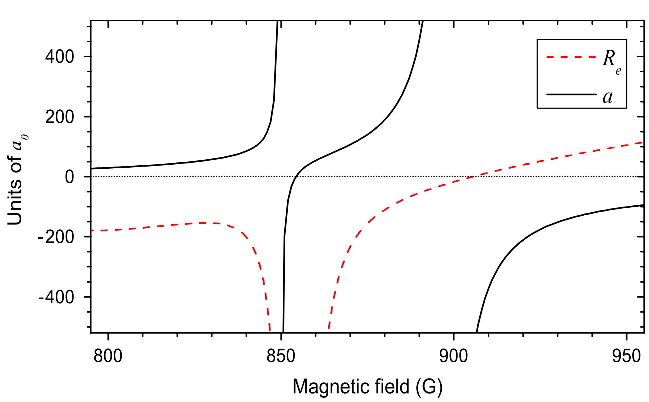

FIG. 1 (color online). The scattering length a (solid line) and the effective range R_e (dashed line) as a function of magnetic field near the two Feshbach resonances of the $|F = 1, m_F = 0\rangle$ state.

[19,20]. As a measure for the influence of the effective range, the resonance strength $s_{\rm res} = 2r_0/|R_e|$ has been introduced [7,21]. In this way, a narrow or "closed-channel dominated" resonance is characterized by $s_{\rm res} \ll 1$ and has a very narrow region of universality, for which $|a| \gg |R_e|$. In this case, R_e comes on a similar footing as and in addition to the three-body parameter to determine the short-range physics [19,22]. In contrast, a wide or "open-channel dominated" resonance is characterized by $s_{\rm res} \gg 1$. Here, the universal region spans over a broad range of magnetic field strengths for which $a \gg r_0$ and the scattering problem can be described in terms of an effective single-channel model [7].

The effective range is very large in the vicinity of the narrow resonance which signifies its "close-channel dominated" character while around the wide resonance, the effective range is small and crosses zero near the pole of the resonance (Fig. 1). This is a clear demonstration of an "open-channel dominated" resonance which expects to provide a wide region of universality extended to tens of Gauss around the resonance where $s_{\rm res}(B) \gtrsim 1$.

In the experiment, we perform measurements of three-body recombination loss as a function of magnetic field near the wide Feshbach resonance. Each loss rate coefficient is calculated from a fit of a lifetime measurement to the solution of the atom loss rate equation: $\dot{N} = -K_3\langle n^2\rangle N - \Gamma N$, where K_3 and Γ are the three- and single-body loss rates, respectively. Γ is determined independently by measuring a very long decay tail of a low density sample. This simplified model does not include effects such as saturation of K_3 to a maximal value $K_{\rm max}$ due to finite temperature (unitarity limit) [23], recombination heating and "anti-evaporation" [24]. The first and the second effects can be neglected for K_3 values which are much smaller than $K_{\rm max}$. In our case, the highest measured K_3 values are at least an order of magnitude smaller than $K_{\rm max}$, and therefore this assumption is reasonable. As for the latter, we treat the evolution of our data to no more than ~30% decrease in atom number for which "anti-evaporation" is estimated to induce a systematic error of ~23% towards higher values of K_3. This effect is evaluated not to limit the accuracy of the reported results.

Our experimental setup is described in details elsewhere [14]. In brief, we load atoms directly from a magneto-optical trap into a single-beam far-detuned optical dipole trap and perform a preliminary forced evaporation at the wing of the narrow resonance at 824 G. During a second evaporation step, we add a second beam which intersects with the first, and the atoms are loaded into a tightly confined crossed-beam dipole trap. A final evaporation step is performed at a slightly higher magnetic field of 832 G. Evaporation at this step can proceed all the way to the Bose-Einstein condensation (BEC) threshold but it is interrupted before a degeneracy is reached. A transition to the magnetic field of interest in which a lifetime measurement will be taken is performed in two main steps. The first is a rapid change in magnetic field over the position of the

Feshbach resonance to avoid strong inelastic losses. The second is an adiabatic approach to the target magnetic field. After different waiting times, the remaining atoms' number is determined by *in situ* absorption imaging.

For measurements in the positive scattering lengths, we cut the evaporation at $T \approx 2\ \mu$K and $\sim 10^5$ atoms with peak density of $\sim 5 \times 10^{12}\ \mathrm{cm}^{-3}$. We then shift rapidly to a magnetic field of 858 G in less than 1 ms while crossing the narrow resonance and wait for 500 ms to let the system relax. Then, we ramp the magnetic field in 25 ms to 880 G, roughly in the center of the region of interest, and wait there for another 100 ms before the last move to the final magnetic field (in 5 ms) where the measurements of lifetime and temperature are performed. For the negative scattering lengths, we cut the evaporation at $T \approx 1\ \mu$K, just on the verge of a BEC. A fast jump is then made to a magnetic field of 930 G, far beyond the position of the wide resonance. After a relaxation time, we slowly move to 915 G and wait there again before a last ramp to the final magnetic field is performed.

For the treatment of three-body recombination loss in the domain of universality, we adopt the language of Refs. [4,5]. The convenient form to represent the theoretically predicted loss rate coefficient is $K_3 = 3C_\pm(a)\hbar a^4/m$ where m is the atomic mass and where $\pm$ hints at the positive $(+)$ or negative $(-)$ region of the scattering length. In that form, an a^4 dependence [25] is separated from the additional log-periodic behavior $C_\pm(a) = C_\pm(22.7a)$ which reflects the Efimov physics of infinite series of weakly bound trimers. An effective field theory provides analytic expressions for $C_\pm(a)$ that we use in the form presented in Refs. [4,5] to fit our experimental results. For $a > 0$, $C_+(a)$ includes oscillations on log scale between the maximum recombination loss of $C_+(a) \sim 70$ and the minimum which in an ideal system can be vanishingly small [1]. For $a < 0$, $C_-(a)$ displays resonance behavior each time an Efimov trimer state hits the continuum threshold. The free parameters of the theory are $a_\pm$ which are connected to the unknown short-range part of the effective three-body potential and $\eta_\pm$ which describe the unknown decay rate of Efimov states. Moreover, a_- defines the resonance position in the decay rate and $\eta_\pm$ are assumed to be equal.

Our experimental results are shown in Fig. 2. For positive scattering lengths, we observe a pronounced minimum in the three-body recombination rate at a scattering length of $a \approx 1160a_0$ which is much larger than r_0 and in that sense occurs deep within the universal region [26]. The upper limit for universality, due to finite temperature, is estimated to be at $a \approx 2800a_0$ ($K_{\max} \approx 6 \times 10^{-21}\ \mathrm{cm}^6/\mathrm{s}$) [23]. Adjacent minima are expected at $1160a_0/22.7 \approx 50a_0$, which is too close to the nonuniversal region, and at $1160a_0 \times 22.7 \approx 26000a_0$, well above the finite temperature limit. Our measurements are fitted remarkably well with the analytical expression of $C_+(a)$ for a large range of scattering lengths as shown by a solid line in Fig. 2. For lower scattering lengths, K_3 saturates at $\sim 130a_0$ (870 G). Interestingly, it occurs when $s_{\mathrm{res}}(B) \approx 0.4$, and it roughly corresponds to the position where the effective range $R_e(B)$ starts to diverge due to the presence of the scattering length's zero crossing (see Fig. 1), and its absolute value is about the same as that of the scattering length [$R_e(B = 870\ \mathrm{G}) \approx -170a_0$]. From the fit, we obtain $a_+ = 243(35)a_0$, $\eta_+ = 0.232(55)$. The upper limit for the three-body recombination rate (dashed line in Fig. 2) is represented by $C_+(a) \approx 54.7$, which is smaller than the commonly known value of $C_+(a) \approx 70$ due to the relatively large value of η_+.

Measurements of three-body recombination rates for negative scattering lengths reveal a region of significant

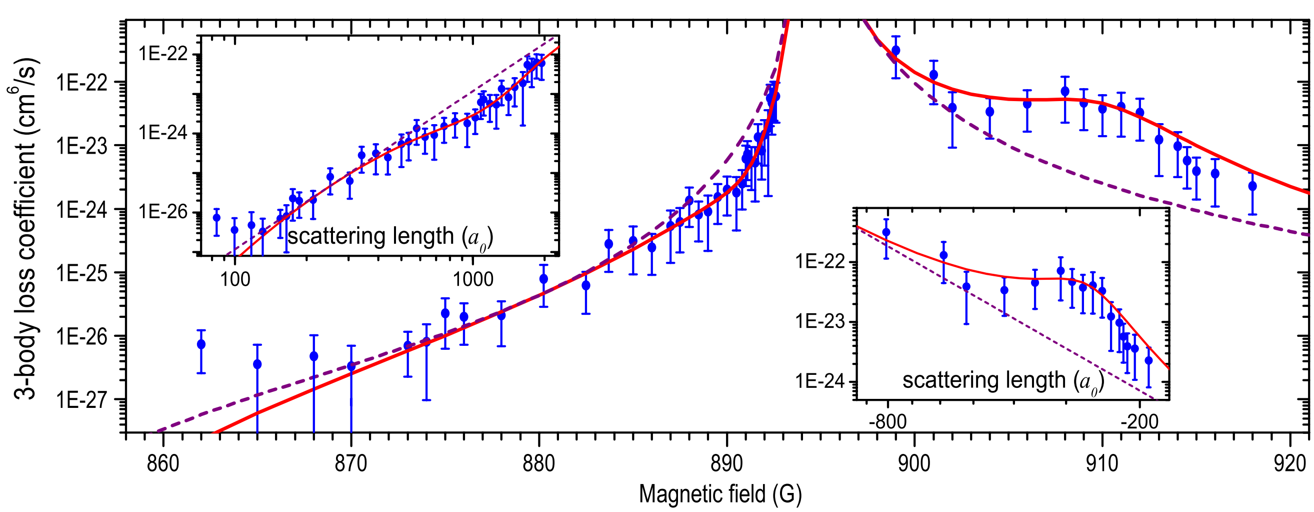

FIG. 2 (color online). Three-body loss coefficient K_3 is shown as a function of magnetic field and scattering length (insets). The solid lines represent fittings to the analytical expressions of universal theory. The dashed lines represent the upper (lower) limit of K_3 for $a > 0$ ($a < 0$). The error bars consist of two contributions: the uncertainty in temperature measurement ($\sim 20\%$) which affects the estimated atom density and the fitting error of the lifetime measurement.

enhancement of K_3 as an expected manifestation of an Efimov resonance (Fig. 2). We fit our data with the analytic expression of $C_-(a)$ (solid line) to obtain the position of the Efimov resonance at $a_- = -264(11)a_0$ and its width $\eta_- = 0.236(42)$. The resonance is observed well within the universal regime with $|a_-| \approx 8.5r_0$ and far enough from the upper limit (due to the finite temperature) which is estimated at $a \approx -1500a_0$ ($K_{\max} \approx 4 \times 10^{-21}$ cm^6/s) [23]. This limit prevents the observation of the next Efimov resonance at $a \approx -6000a_0$. The two independent fit parameters a_+ and a_- are predicted to obey the universal ratio $a_+/|a_-| = 0.96(3)$, and the experiment yields a remarkably close value of 0.92(14). This seems like an observation of the long hunted universal behavior of a three-body observable in a physical system with resonantly enhanced two-body interactions. In addition, the large width of the resonance, indicating short lifetimes of the Efimov trimer, is in excellent agreement with the theoretical assumption of $\eta_+ = \eta_-$.

For positive scattering lengths the Efimov trimer is expected to intersect with the atom-dimer threshold at $a_* \approx 1.1a_+$ [1]. Theory predicts that a_* and a_- of the same trimer state are related as $a_- \approx -22a_*$ [1]. This means that if the observed resonance at a_- indicates the lowest state, the one expected at a_* indicates the first excited state as the lowest one becomes nonuniversal.

The determination of the Feshbach resonances positions is important for the discussed fitting procedure because it defines the value of the scattering length at a given magnetic field. These positions were located by atom loss and molecule association measurements with an accuracy of <1 G. Independently, we allow the position of the wide resonance to be determined by the fitting procedure. For that purpose, we first fit the coupled-channels calculation of scattering length as a function of magnetic field (shown in Fig. 1) with a formula that includes two nearby resonances: $a = a_{\rm bg}[1 - \Delta_1/(B - B_1) - \Delta_2/(B - B_2)]$ where $a_{\rm bg}$ is a common background scattering length and Δ_1, B_1 and Δ_2, B_2 are widths and positions of the narrow and the wide resonances, respectively. We then introduce the result into the expressions of $C_\pm(a)$ while substituting B with $B - \delta B$ (δB being a fitting parameter). For $a > 0$ ($a < 0$), the fitting yields the position of the wide resonance at 894.65(11) G [893.85(37) G]. These two independent fits are in good agreement with each other as well as with the atom loss and the molecule association measurements.

It is interesting to note that the observed position of the Efimov resonance reveals the same numerical factor $|a_-|/r_0 \approx 8.5$ as in the experiments on ^{133}Cs [4] which may or may not be an accidental coincidence. It is also interesting that while our results agree with the universal theory, the results on ^{39}K show significant deviations from it [10]. This might hint at an additional parameter to describe the three-body physics of ^{39}K atoms, such as the effective range $R_e(B)$ that becomes more important for narrow Feshbach resonances.

The absolute ground state of ^{7}Li also possesses a wide Feshbach resonance across which Efimov features are expected. If so, it would provide a possibility to test universality in different channels of the same atomic system. Recently, evidence for universal four-body states related to Efimov trimers were reported [10,27]. Signatures of these states are subject for future research.

We gratefully acknowledge discussions with R. Grimm and F. Ferlaino. This work was supported, in a part, by the Israel Science Foundation and by the Netherlands Organization for Scientific Research (NWO). N. G. is supported by the Israel Academy of Sciences and Humanities.

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