Nuclear-Spin-Independent Short-Range Three-Body Physics in Ultracold Atoms

Noam Gross,[1] Zav Shotan,[1] Servaas Kokkelmans,[2] and Lev Khaykovich[1]

[1]*Department of Physics, Bar-Ilan University, Ramat-Gan, 52900 Israel*
[2]*Eindhoven University of Technology, Post Office Box 513, 5600 MB Eindhoven, The Netherlands*

We investigate three-body recombination loss across a Feshbach resonance in a gas of ultracold ^{7}Li atoms prepared in the absolute ground state and perform a comparison with previously reported results of a different nuclear-spin state [N. Gross *et al.*, Phys. Rev. Lett. **103**, 163202 (2009)]. We extend the previously reported universality in three-body recombination loss across a Feshbach resonance to the absolute ground state. We show that the positions and widths of recombination minima and Efimov resonances are identical for both states which indicates that the short-range physics is nuclear-spin independent.

A remarkable prediction of three-body theory with resonantly enhanced two-body interactions is the existence of a universal set of weakly bound triatomic states known as Efimov trimers [1]. In the limit of zero collision energy only *s*-wave scattering is allowed, signifying that a single parameter, the scattering length *a* is sufficient to describe the ultracold two-body interactions. When $|a| \to \pm\infty$ the universal long-range theory (known as "Efimov scenario") predicts that three-body observables exhibit log-periodic behavior which depends only on the scattering length *a* and on a three-body parameter which serve as boundary conditions for the short-range physics [2]. After decades of failed quests for a suitable system to study the Efimov scenario [3] a number of recent experiments with ultracold atoms have demonstrated this logarithmic periodicity and verified the "holy grail" of the theory, the universal scaling factor $\exp(\pi/s_0) \approx 22.7$, where $s_0 = 1.006\,24$ [4–6]. The scaling as such, however, does not provide any knowledge about the short-range part of the three-body potential which defines the absolute location and lifetime of an Efimov state. The short-range potential is given in terms of two-body potential permutations of the two-body subsystems and a true three-body potential which is of importance only when three particles are very close together. In general, it is very difficult to solve the short-range physics exactly, and therefore this region is usually treated in terms of a three-body parameter [2,7].

Among other systems of ultracold atoms which allow the study of universal three-body physics [4,8–11], bosonic lithium provides a unique opportunity to shed some light on the short-range physics. In this Letter, we exploit the possibility to study universality in two different nuclear-spin states that both possess a broad Feshbach resonance. Experimentally the three-body observable is three-body recombination loss of atoms from a trap which is always studied in the absolute ground state where higher order inelastic processes, namely, two-body inelastic collisions, are prohibited. However, recently we showed that a gas of ^{7}Li atoms, spin polarized in the one but lowest Zeeman

sublevel ($|F = 1, m_F = 0\rangle$), experiences very weak two-body loss which allowed a study of the physics of three-body collisions [6]. Here we investigate three-body recombination on the absolute ground state ($|F = 1, m_F = 1\rangle$) across a Feshbach resonance at ~738 G. Comparison of the results of both states (further denoted as $|m_F = 0\rangle$ and $|m_F = 1\rangle$) reveals a remarkable identity between properties of the Efimov features. At these large magnetic fields the two states are basically similar in their electron spin, but different in their nuclear spin. As the position and width of an Efimov state are solely governed by the three-body parameter, our results suggest that at high magnetic fields the short-range physics is independent of nuclear-spin configuration and of the specific Feshbach resonance across which universality is studied.

Experimentally, three-body recombination loss is studied as a function of scattering length by means of magnetic field tuning near a Feshbach resonance [12]. For positive scattering lengths the log-periodic oscillations of the loss rate coefficient is caused by destructive interference conditions between two possible decay pathways for certain values of *a* [2,13]. For negative scattering lengths the loss rate coefficient exhibits a resonance enhancement each time an Efimov trimer state intersects with the continuum threshold. Recently, we found that positions of the oscillations' minimum ($a > 0$) and maximum ($a < 0$) are universally related across the Feshbach resonance on the $|m_F = 0\rangle$ state [6] in a very good agreement with theory [2,7].

Our experimental setup is described in detail elsewhere [6,14]. In brief, we perform evaporative cooling at a bias magnetic field of ~830 G near a Feshbach resonance when the gas of ^{7}Li atoms is spontaneously spin purified to the $|m_F = 0\rangle$ state [14]. The atoms are cooled down to the threshold of degeneracy and transferred into the absolute ground state $|m_F = 1\rangle$ by means of rapid adiabatic passage using a radio frequency (rf) sweep scanning 1 MHz in 20 ms at a lower bias magnetic field (35 G). The transfer efficiency is better than 90%. Finally, the bias field is
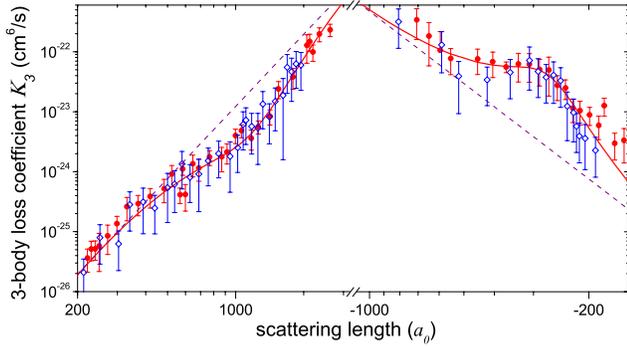
FIG. 1 (color online). Experimentally measured three-body loss coefficient K_3 as a function of scattering length (in units of Bohr radius a_0) for the $|m_F = 1\rangle$ state (red solid circles). The solid lines represent fits to the analytical expressions of universal theory. The dashed lines represent the a^4 upper (lower) limit of K_3 for $a > 0$ ($a < 0$). The error bars consist of two contributions: the uncertainty in temperature measurement which affects the estimated atom density and the fitting error of the atom-number decay measurement. K_3 values of the $|m_F = 0\rangle$ state, reported by us in Ref. [6], are represented by blue open diamonds.

ramped to the vicinity of the absolute ground state's Feshbach resonance [738.3(3) G] where we measure atom-number decay and temperature as a function of magnetic field from which we extract the three-body loss coefficient K_3. Details of the experimental procedure and the data analysis are similar to those elaborated in Ref. [6]. A typical temperature of the atoms for positive (negative) scattering lengths is 1.8 μK (1.3 μK) which matches the conditions of previously reported measurements on the $|m_F = 0\rangle$ state [6].

Experimental results of the three-body loss coefficient are summarized in Fig. 1 where K_3 is plotted as a function of the scattering length a for the $|m_F = 1\rangle$ state (red solid circles). Also plotted are the results of K_3 measurements for the wide resonance of the $|m_F = 0\rangle$ state (blue open diamonds) from Ref. [6]. The qualitative resemblance between the two measurements is striking. Further investigation is achieved by treating the three-body recombination loss as done in Ref. [6]. In short, 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. An effective field theory provides analytic expressions for the log-periodic behavior of $C_\pm(a) = C_\pm(22.7a)$ that we use in the form presented in Ref. [8] to fit our experimental data. The free parameters are $a_\pm$ ($\eta_\pm$) which are connected to the real (imaginary) part of the three-body parameter [2,15]. Moreover, a_- defines the position of the decay rate (Efimov) resonance and the decay parameters η_+ and η_-, which describe the width of the Efimov state, are assumed to be equal. Results of this fitting procedure are summarized in Table I along with former results of the $|m_F = 0\rangle$ state [6].

TABLE I. Fitting parameters to universal theory obtained from the measured K_3 values of the $|m_F = 1\rangle$ and the previously reported $|m_F = 0\rangle$ states [6].

State	η_+	η_-	a_+/a_0	a_-/a_0	$a_+/|a_-|$
$|m_F = 0\rangle$	0.232(55)	0.236(42)	243(35)	−264(11)	0.92(14)
$|m_F = 1\rangle$	0.188(39)	0.251(60)	247(12)	−268(12)	0.92(6)

The solid line in Fig. 1 represents the fit to the measurements performed in the $|m_F = 1\rangle$ state. The theoretical assumption that the real part of the three-body parameter across a Feshbach resonance is the same for negative and positive scattering lengths regions requires a_+ and a_- to obey a universal ratio $a_+/|a_-| = 0.96(3)$ [2]. Indeed, the fit yields a remarkably close value of 0.92(6) which confirms the above assumption. Moreover, the fact that η_+ and η_- are equal within the experimental errors suggests that also the imaginary part of the three-body parameter is identical. We thus confirm the universality in three-body recombination across a Feshbach resonance which we observed earlier in the $|m_F = 0\rangle$ state [6]. Note that the recent work by the Rice group on the $|m_F = 1\rangle$ state [5] has reported different values for the fitting parameters. We shall address this apparent discrepancy later on.

Comparing the fitting parameters on different nuclear-spin states (see Table I) reveals striking similarities in corresponding numbers that agree with each other exceptionally well. We hence conclude that the three-body parameter in these states is the same within the experimental errors. We note that both Feshbach resonances are comparable yet slightly different in width (see Table II, last two rows) which has no effect on the positions of Efimov features. Moreover, in the $|m_F = 0\rangle$ state there is a narrow resonance in close proximity to the wide one (see Table II, first row) but it does not affect the positions of the Efimov features either.

The reported results crucially depend on precise knowledge of the Feshbach resonance position and the scattering length in its vicinity. We use here the same coupled-channels (CC) calculation as in Ref. [6] to predict the scattering length dependence on magnetic field, which is then fitted with a conveniently factorized expression [16]:

$$\frac{a}{a_\text{bg}} = \prod_{i=1}^{N}\left(1 - \frac{\Delta_i}{(B - B_{0,i})}\right). \quad (1)$$

Here a_bg is the background scattering length, Δ_i is the i's

TABLE II. Feshbach resonance parameters for both states obtained from a fitting of the CC calculation with Eq. (1).

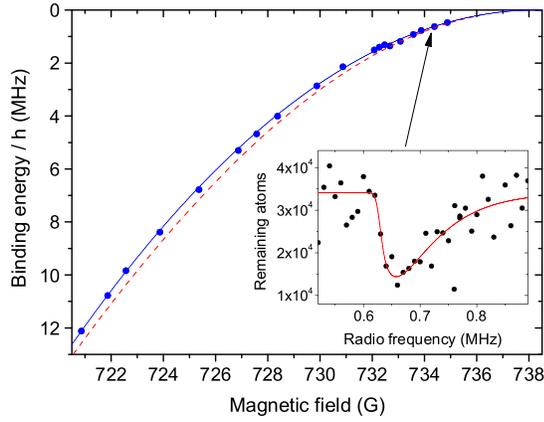| State	Type	B_0 (G)	Δ (G)	a_bg/a_0
$|m_F = 0\rangle$	narrow	849.7	4.616	−18.94
$|m_F = 0\rangle$	wide	898.4	−235.1	−18.94
$|m_F = 1\rangle$	wide	742.2	−169.0	−20.64

FIG. 2 (color online).   rf spectroscopy of the molecular binding energy near the Feshbach resonance in the $|m_F = 1\rangle$ state. The solid line represents fitting to Eq. (2). CC calculation prediction (dashed line) is plotted as well. Inset—an example of a loss resonance at $B = 734.4$ G fitted numerically to a convolution of Maxwell-Boltzmann and a Gaussian distributions (solid line).

resonance width and $B_{0,i}$ is the i's resonance position. Table II summarizes these parameters for all Feshbach resonances in both nuclear-spin states.

To verify the $|m_F = 1\rangle$ Feshbach resonance parameters we use a powerful experimental technique that measures the binding energy of the Feshbach molecules with high precision. The method uses a weak rf field to resonantly associate weakly bound Feshbach dimers which are then rapidly lost through collisional relaxation into deeply bound states [17]. The remaining atom number is measured by absorption imaging as a function of rf frequency at a given magnetic field. In the experiment the rf modulation time is varied between 0.5 and 3 sec and the modulation amplitude ranges from 150 to 750 mG. rf-induced losses at a given magnetic field are then numerically fitted to a convolution of a Maxwell-Boltzmann and a Gaussian distributions (see inset in Fig. 2). The former accounts for broadening of the spectroscopic feature due to finite kinetic energy of atoms at a typical temperature of $\sim$1.5 μK. The latter reflects broadening due to magnetic field instability and shot-to-shot atom-number fluctuations. From the fit we extract the molecular binding energy (E_b) corresponding to zero temperature. The rf spectroscopy of E_b is shown in Fig. 2.

The scattering length a in the vicinity of the Feshbach resonance can be extracted from our measurement by a numerical fit to the CC calculation. This analysis will be

the subject of a future publication. Instead we plot in Fig. 2 (dashed line) the binding energies of molecules according to the prediction of the CC calculation with no fitting parameters apart from a shift of -3.9 G to the experimentally determined position of the resonance (discussed next). A notably good agreement between the measurements and theory indicates that very small corrections are needed to tune the theory to the experimental data. Here we use a simple analytical model to estimate these corrections and to pinpoint the resonance's position.

Very close to a Feshbach resonance the molecular binding energy has the following form [12]:

$$E_b = \frac{\hbar^2}{m(a - \bar{a} + R^*)^2}, \qquad (2)$$

where m is the atomic mass and $\bar{a}$ and R^* accounts for a finite range and a resonance strength corrections to the universal $1/a^2$ law, respectively. $\bar{a}$ is the mean scattering length which is an alternative van der Waals length scale [18], and $R^* = \hbar^2/(ma_{bg}\Delta(\delta\mu))$ [19], where $\delta\mu$ is the differential magnetic moment [12]. Equation (2) is applied in the limit of $a \gg \bar{a}$ and $a \gg 4R^*$. When Eq. (1) is substituted into Eq. (2) the latter provides us with a fitting expression that can be used to extract Δ, a_{bg} and B_0 from our experimental data. However, a few comments should be made.

We restrict the fit to values of $E_b/h < 4$ MHz, where $a > 300a_0$, which corresponds to $\sim$5% of the Feshbach resonance width, to meet the requirement $a \gg \bar{a} = 29.88a_0$ (the fitting curve presented as a blue line in Fig. 2 is plotted to the entire range of E_b). Thus, according to Eq. (1), as $(B - B_0) \ll |\Delta|$ the fitting procedure is only sensitive to the product $\Gamma = a_{bg}\Delta$. Large uncertainties are anticipated in the parameters a_{bg} and Δ if they are fitted simultaneously. We therefore arbitrary choose to fix the values of either a_{bg} or Δ to the CC calculation prediction (see Table II, last row). The values in the second row of Table III are obtained from this fitting procedure. To check the self-consistency of the use of Eq. (2) we calculate $R^* = 51.8a_0$ using the fitting data and find it to satisfy the second requirement of $a \gg 4R^*$ though less strictly. We note that Eq. (2) was verified against the CC calculation for $E_b/h < 4$ MHz and they were found to agree with each other to better than 3%.

Table III shows, along with the fitting data (second row), predictions of CC calculation (first row, same as the last row in Table II) and experimental results of the Rice group

TABLE III.   The $|m_F = 1\rangle$ Feshbach resonance parameters as derived from different sources.

Source	B_0 (G)	Δ (G)	a_{bg}/a_0	Γ (G)
CC calculation	742.2	-169.0	-20.64	3488
rf spectroscopy	738.3(3)	–	–	3600(150)
in-situ BEC size measurement [20]	736.97(7) [5]	$-192.3(3)$	$-24.5^{+3.0}_{-0.2}$	4711^{+46}_{-584}

[5,20] where a was derived from BEC *in-situ* size measurements (third row).

The parameters of the Feshbach resonance, as determined here, appear to be in poor agreement with the one reported by the Rice group. The position of the resonance B_0 is shifted to a higher value of the magnetic field beyond the experimental error [21]. As for Γ, while the current measurement only slightly modifies the CC calculation result, it differs significantly from that reported in Ref. [5]. We note that rf spectroscopy is very robust being independent of experimental parameters such as trap strength, absolute number of atoms or atomic cloud size, whereas the BEC size measurement is highly sensitive to uncertainties in these measurements [20]. The results summarized in Table I are obtained based on the CC calculation and the experimentally determined value of B_0.

The Efimov scenario was recently investigated in the $|m_F = 1\rangle$ state of ^{7}Li atoms by the Rice group in an impressive work reporting in total 11 different features on both sides of the Feshbach resonance connected to three- and four-body universal states [5]. However, a_+ and a_- parameters are in apparent discrepancy with those reported here. To address this discrepancy we compare the observed features on a magnetic field scale instead of a scattering length scale using an inverted version of Eq. (1) and the corresponding Feshbach resonances' parameters indicated in Table III. For $a > 0$, the Rice and our group's loss minima are obtained at 735.23(4) and 735.39(14) G, respectively, (we consider the second minimum in the Rice results). There is a perfect agreement between the two positions even within the fit errors only (see Table I and Ref. [5]). For $a < 0$, the Efimov resonances are located at 754.2(6) and 752.4(7) G, respectively, which also reasonably (within $\sim 2\times$ the error range) agree with each other. We therefore conclude that the only discrepancy between our groups is in the conversion of magnetic field into scattering length, caused by the use of different Feshbach resonance parameters. Stressing again the reliability and precision of the method used here for resonance characterization, we believe that a quantitative reinterpretation of the Rice group's results will most probably resolve this discrepancy.

The nuclear-spin independent short-range physics which we report here are partially due to the special conditions which apply already for two-body physics at large magnetic fields. Here we are in the Paschen-Back regime, where the electron and nuclear spins precess independently around the magnetic field. Then the hyperfine coupling can be neglected resulting in an uncoupled and (for $|m_F = 0\rangle$ and $|m_F = 1\rangle$) very similar two-body potential. This means that nonresonant parameters, such as the back-

ground scattering length, should be very similar for the two different states (see Table II). However, since the derived three-body parameters are also very similar (see Table I), it suggests that the true three-body forces [7] are either also nuclear-spin independent, or they have a relatively unimportant contribution. We note that based on similar arguments Ref. [22] predicts a negligible change in the three-body parameter for isolated Feshbach resonances in Cs atoms.

[1] V. Efimov, Phys. Lett. B **33**, 563 (1970).
[2] E. Braaten and H.-W. Hammer, Phys. Rep. **428**, 259 (2006).
[3] A. S. Jensen et al., Rev. Mod. Phys. **76**, 215 (2004).
[4] M. Zaccanti et al., Nature Phys. **5**, 586 (2009).
[5] S. E. Pollack, D. Dries, and R. G. Hulet, Science **326**, 1683 (2009).
[6] N. Gross et al., Phys. Rev. Lett. **103**, 163202 (2009).
[7] J. P. D'Incao et al., J. Phys. B **42**, 044016 (2009).
[8] T. Kraemer et al., Nature (London) **440**, 315 (2006); S. Knoop et al., Nature Phys. **5**, 227 (2009).
[9] T. B. Ottenstein et al., Phys. Rev. Lett. **101**, 203202 (2008); A. N. Wenz et al., Phys. Rev. A **80**, 040702(R) (2009).
[10] J. H. Huckans et al., Phys. Rev. Lett. **102**, 165302 (2009); J. R. Williams et al., ibid. **103**, 130404 (2009).
[11] G. Barontini et al., Phys. Rev. Lett. **103**, 043201 (2009).
[12] C. Chin et al., Rev. Mod. Phys. **82**, 1225 (2010).
[13] B. D. Esry, C. H. Greene, and J. P. Burke, Phys. Rev. Lett. **83**, 1751 (1999); E. Nielsen and J. H. Macek, ibid. **83**, 1566 (1999).
[14] N. Gross and L. Khaykovich, Phys. Rev. A **77**, 023604 (2008).
[15] B. Marcelis et al., Phys. Rev. A **77**, 032707 (2008).
[16] A. D. Lange et al., Phys. Rev. A **79**, 013622 (2009).
[17] S. T. Thompson, E. Hodby, and C. E. Wieman, Phys. Rev. Lett. **95**, 190404 (2005).
[18] G. F. Gribakin and V. V. Flambaum, Phys. Rev. A **48**, 546 (1993).
[19] D. S. Petrov, Phys. Rev. Lett. **93**, 143201 (2004).
[20] S. E. Pollack et al., Phys. Rev. Lett. **102**, 090402 (2009).
[21] We verified the position of the resonance by measuring the microwave transition between $|F = 1, m_F = 0\rangle$ and $|F = 2, m_F = 1\rangle$ states at $B = 740$ G.
[22] N. Gemelke et al., Proceedings of the XXI International Conference on Atomic Physics (World Scientific, Singapore, 2009), p. 240.