Evidence for an Excited-State Efimov Trimer in a Three-Component Fermi Gas

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We observe enhanced three-body recombination in a three-component ^{6}Li Fermi gas attributable to an excited Efimov trimer state intersecting the three-atom scattering threshold near 895 G. From measurements of the recombination rate we determine the Efimov parameters κ_* and η_* for the universal region above 600 G which includes three overlapping Feshbach resonances. The value of κ_* also predicts the locations of loss features previously observed near 130 and 500 G [T. B. Ottenstein *et al.*, Phys. Rev. Lett. **101**, 203202 (2008); J. H. Huckans *et al.*, Phys. Rev. Lett. **102**, 165302 (2009)] suggesting they are associated with a ground-state Efimov trimer near threshold. We also report on the realization of a degenerate three-component Fermi gas with approximate SU(3) symmetry.

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A landmark result of few-body physics is Efimov's solution to the quantum mechanical three-body problem for low-energy, identical particles with a large s-wave scattering length a [1,2]. Being independent of the particular character of the two-body interaction, Efimov's predictions are universal. At resonance ($a \to \pm\infty$), an infinite series of arbitrarily shallow three-body bound states (Efimov trimers) exist with a geometric spectrum: $E_n = -(e^{2\pi/s_0})^{-n}\hbar^2\kappa_*^2/m$ (for $n = 0, 1, 2, \ldots$). Here, $s_0 \approx 1.006\,24$ is a universal constant, m is the particle's mass, and the entire spectrum is fixed by a single three-body parameter κ_* which is determined by short-range interactions [3]. For large but finite a, the spectrum of Efimov trimer states are universal functions of a and κ_*. Further, all low-energy scattering observables display a log-periodic dependence on a and the collision energy [3]. These startling predictions ignited a search for Efimov physics in a range of physical systems [4,5].

The first experimental evidence for Efimov trimers was obtained by observing both a resonant enhancement and interference minimum of three-body recombination (3BR) in an ultracold gas of bosonic Cs near a Feshbach resonance [6]. The Efimov effect in bosonic systems near an isolated Feshbach resonance is becoming well understood following the observation of atom-dimer resonances [7], Efimov resonances between bosons with different masses [8], and tests of universal log-periodic scaling [9,10].

The Efimov effect is also expected to occur for three fermions in distinguishable states ($|1\rangle$, $|2\rangle$, and $|3\rangle$) if at least two of the three pairwise scattering lengths a_{ij} (a_{12}, a_{23}, and a_{13}) are larger than the range of interaction (the van der Waals length $\ell_{\rm vdW} = \sqrt[4]{mC_6/\hbar^2}$) [3]. For a Fermi gas of ^{6}Li atoms in the three lowest spin states, investigated here, all three scattering lengths can be resonantly enhanced by three overlapping Feshbach resonances [Fig. 1(a)] [11] allowing for a study of the Efimov effect in a Fermi system deep within the universal regime $|a_{ij}| \gg \ell_{\rm vdW}$. For this ^{6}Li system, the scattering lengths are typically unequal, and any number of them can be positive. This gives rise to an Efimov spectrum with a rich structure which is only now becoming understood theoretically [12,13]. Entirely new phenomena related to the Efimov effect have been predicted in this case (e.g., interference minima in the rate of atom-dimer exchange reactions) [13].

Beyond few-body physics, superfluid phenomena in degenerate three-component Fermi gases have recently been a subject of intense theoretical interest [14–18]. For

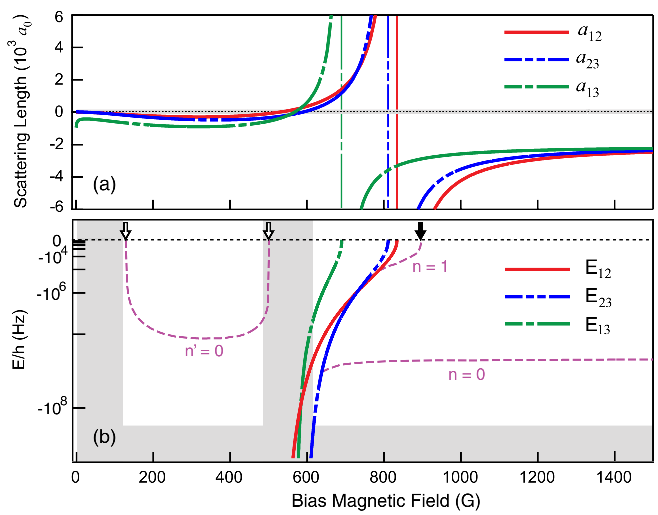

FIG. 1 (color online). (a) Three overlapping s-wave Feshbach resonances in ^{6}Li for states $|1\rangle$, $|2\rangle$, and $|3\rangle$ [11]. At high field, $a_{ij} \to -2140a_0$. (b) The binding energies (E_{12}, E_{23}, E_{13}) of the universal dimer states associated with the Feshbach resonances. The dashed lines (n and n') depict the binding energies of the Efimov trimer states (not yet accurately known). Resonant three-body recombination occurs (arrows) when an Efimov trimer intersects the three-atom scattering threshold. The gray-shaded areas identify nonuniversal regions where $E < E_{\rm vdW} = \hbar^2/m\ell_{\rm vdW}^2$ or $|a_{ij}| < 2\ell_{\rm vdW}$. (For ^{6}Li, $\ell_{\rm vdW} = 62.5a_0$.)

fermions with $a_{12} \approx a_{23} \approx a_{13} < 0$, there is a competition between trimer formation and several types of Cooper pairing [14], breached pair and unbreached pair phases [16], as well as a unique interplay between magnetization and superfluidity [17,18]. Degenerate three-component Fermi gases open a window of opportunity to determine which pairing symmetries and phases are ultimately favored by nature as parameters are tuned.

In this Letter, we report resonantly enhanced 3BR in a three-component Fermi gas with large, negative, and unequal scattering lengths that can be explained by an excited Efimov trimer state near the three-atom scattering threshold. We measure the 3BR rate for fields between 842 and 1500 G which is deeply in the universal region at high field [see Fig. 1(b)]. The data are well described by a calculation of the 3BR rate at threshold in the zero-range approximation where the only input parameters are the known scattering lengths a_{12}, a_{23}, and a_{13} [11] and the complex-valued Efimov parameter $\kappa_* \exp[i\eta_*/s_0]$ which we determine. Here, η_* has been introduced to account for the nonzero width of Efimov states due to decay to deeply bound dimer states. We find that the value of κ_* predicts that Efimov trimers also cross threshold near 130 and 500 G, strongly supporting the interpretation that loss features previously observed [19,20] are related to the Efimov effect. Finally, we produce the first degenerate three-component Fermi gas in the SU(3) symmetric regime where $a_{12} \approx a_{23} \approx a_{13}$.

The first experiments with degenerate three-component Fermi gases investigated their stability against decay via 3BR [19,20]. These experiments studied a ^{6}Li gas in the three lowest spin states ($|1\rangle$, $|2\rangle$, and $|3\rangle$) and measured the 3BR rate as the scattering lengths (a_{12}, a_{23}, and a_{13}) were tuned in a magnetic field. Enhanced 3BR was observed near fields of 130 and 500 G where $|a_{12}|, |a_{23}| \sim \ell_{\rm vdW}$ and $|a_{13}| \sim 10\ell_{\rm vdW}$. Several authors used Efimov's theoretical framework to explain the magnitude and variation of the measured 3BR rate between 100 and 500 G despite its questionable applicability near the boundaries of this field range where $|a_{12}|, |a_{23}| \sim \ell_{\rm vdW}$ [12,21–23]. In this interpretation, the resonant enhancement near 130 and 500 G is due to Efimov-like trimers crossing the three-atom threshold near or in the nonuniversal regime.

This three-component ^{6}Li mixture can be used to test universal predictions of Efimov physics with large scattering lengths since $|a_{12}|$, $|a_{23}|$, and $|a_{13}| \gg \ell_{\rm vdW}$ for fields above 660 G due to three overlapping Feshbach resonances [11] and there is negligible two-body loss [20]. While 3BR rates in the vicinity of the Feshbach resonances were measured in Ref. [20], the authors noted that the highest 3BR rates were unitarity limited and therefore could not provide tests of universal predictions [24].

Efimov's theoretical framework makes universal predictions for three-body scattering observables in the threshold regime where the collision energy is the smallest energy in the system. For identical bosons with large negative scattering lengths, the characteristic energy scale is set by the height of a barrier in the adiabatic three-body potential, $U_{\rm max} = 0.158\hbar^2/ma^2$ [24]. In the three-component ^{6}Li gas we study, where $a_{12} < a_{23} < a_{13} < 0$, we expect that for fields $B > 875$ G ($B > 960$ G), which corresponds to scattering lengths $|a_{12}| < 12\,250a_0$ ($|a_{12}| < 5000a_0$), a temperature $T \lesssim 30$ nK ($T \lesssim 180$ nK) is required in order to compare our measurements to the calculated 3BR rate at threshold.

To reach such low collision energies, we adiabatically release a two-component mixture of ^{6}Li atoms prepared in a crossed optical dipole trap (see Ref. [20]) into a larger volume optical trap with smaller oscillation frequencies. We use two different trapping geometries for the large volume trap to study atoms at $T \simeq 30$ nK and $T \simeq 180$ nK, respectively. For trap I (II), the combination of optical forces (from a 1064 nm dipole trap) and the small curvature of the bias magnetic field produce a trap with frequencies $\nu_x = 15(2)$ Hz, $\nu_y = 0.242\sqrt{B}$Hz $\pm$ 1%, and $\nu_z = 12(1)$ Hz ($\nu_x = 33\sqrt{1 + 1.4 \times 10^{-3}(B - 842\text{ G})}$ Hz $\pm$ 3%, $\nu_y = 21\sqrt{1 + 3.6 \times 10^{-3}(B - 842\text{ G})}$ Hz $\pm$ 3%, and $\nu_z = 94(2)$ Hz) [25]. The dependence of the frequencies on the bias field B (in gauss) for trap I (II) arises from the nonzero field curvature of a large (small) set of electromagnets used to produce B.

Starting from an incoherent 50-50 mixture of atoms in states $|1\rangle$ and $|2\rangle$, we create a three-component mixture with equal population in states $|1\rangle$, $|2\rangle$, and $|3\rangle$ by simultaneously applying radio-frequency magnetic fields driving $|1\rangle$-$|2\rangle$ and $|2\rangle$-$|3\rangle$ transitions at the field B. Each of the fields yields a resonant Rabi frequency $\Omega/2\pi \sim 10$ kHz, is broadened to a width of 10 kHz, and is applied for a variable time (chosen to be at least twice the observed decoherence time) between 10 and 100 ms depending on the bias field.

We have confirmed (for the fields studied here) that the decay of each possible two-component mixture is consistent with one-body loss due to background gas collisions which give a $1/e$ lifetime $1/\Gamma = 2.8$ s. In the three-component mixture, 3BR involving one atom from each spin state can also occur. In this case, the number of atoms in each of the equally populated spin states $N(t)$ evolves according to $\dot{N}/N = -\Gamma - L_3\langle n^2\rangle$ where L_3 is the 3BR rate constant and $\langle n^2\rangle$ is the average value of the squared density per spin state. For a thermal distribution at temperature T in a harmonic trap, $N(t)$ evolves according to

$$\frac{1}{N}\frac{dN}{dt} = -\Gamma - \frac{L_3}{\sqrt{27}}\left(\frac{2\pi m\bar{\nu}^2}{k_B T}\right)^3 N^2, \qquad (1)$$

where $\bar{\nu} = (\nu_x\nu_y\nu_z)^{1/3}$. Empirically, the temperature of the gas remains approximately constant. This is consistent with the fact that the energetic atom and molecule produced in a 3BR event have a mean free path much larger than the sample size and exit the cloud without depositing energy. Our measurements are consistent with a model that includes a small rise in temperature due to "antievapora-

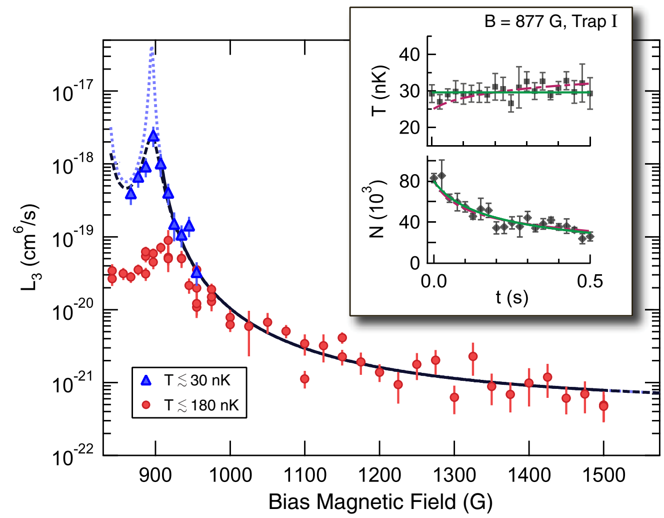

FIG. 2 (color online). The measured three-body recombination rate constant L_3. Resonant three-body recombination near 900 G is caused by an excited Efimov trimer crossing the three-atom scattering threshold (see text). The inset shows typical data for $N(t)$ and $T(t)$ which are fit to extract L_3. In the inset the solid (dashed) line shows the fit to a model which does not include (includes) antievaporation.

tion'' [20] (see inset of Fig. 2). However, lower values of χ^2 are obtained if the temperature is simply assumed to remain constant.

To determine L_3, we measure for each field B the number and temperature of the trapped atoms as a function of time by *in situ* absorption imaging. An example data set for a particular field B is shown in the inset of Fig. 2. The number evolution at each field is fit with an analytic solution to Eq. (1) using L_3, the initial number (N_0), and temperature (T) as free parameters. For fields between 834 and 1500 G, L_3 is shown in Fig. 2 for data sets taken with traps I and II. The triangles (circles) correspond to trap I (II) and give L_3 for atoms at a temperature $\lesssim 30$ nK ($\lesssim 180$ nK) and an initial peak density per spin state $n_0 \simeq 5 \times 10^9$ atoms/cm^3 ($n_0 \simeq 5 \times 10^{10}$ atoms/cm^3). The error bars give the statistical error from the fit and the uncertainty in the trap frequencies added in quadrature. A systematic uncertainty of $\pm 60\%$, which arises from our uncertainty in the absolute atom number ($\pm 30\%$), is not included in these error bars. As we vary the field, the scattering lengths are tuned by broad Feshbach resonances at 690, 811, and 834 G and the observed value of L_3 changes by several orders of magnitude. In addition to a smooth variation of L_3, resonant 3BR is observed near 900 G in both data sets.

To compare our data to zero-temperature calculations of the 3BR rate, we require that the temperature be in the threshold regime and that the data are unaffected by the unitarity limit [24]. As argued above, the threshold regime should be obtained for the 30 nK (180 nK) gas for fields above 875 G (960 G). At a low but nonzero temperature T, the 3BR rate constant for three distinguishable fermions with equal mass is unitarity limited to a maximum value $L_{3\,\max} = \alpha/(k_B T)^2$ where $\alpha = \sqrt{108}\pi^2\hbar^5/m^3$ [24,26]. For a thermal gas with $T = 30$ nK ($T = 180$ nK), $L_{3\,\max} = 8 \times 10^{-18}$ cm^6/s ($L_{3\,\max} = 2 \times 10^{-19}$ cm^6/s). The measured values of L_3 are $\lesssim (1/10) L_{3\,\max}$ for the 30 nK (180 nK) data for fields above 907 G (975 G). These subsets of the data should be in excellent agreement with zero-temperature calculations of the 3BR rate.

Recently, Braaten and co-workers calculated L_3 in the zero-range approximation for three fermions in distinguishable spin states at threshold [12]. By numerically solving a generalization of the Skorniakov-Ter-Martirosian (STM) equation, they calculate the 3BR rate constant for the case $a_{12}, a_{23}, a_{13} < 0$. The only inputs to this calculation are a_{12}, a_{23}, and a_{13} (known for ^{6}Li [11]) and the three-body parameters, κ_* and η_*, which, respectively, fix the spectrum and linewidth of the Efimov trimer states. For equal scattering lengths, the STM equation reduces to that for identical bosons and, in this case, an analytic expression for L_3 is known [12]

$$L_3 = \frac{16\pi^2 C \sinh(2\eta_*)}{\sin^2[D|a|\kappa_*] + \sinh^2\eta_*} \frac{\hbar a^4}{m} \quad (\text{for } a_{ij} = a < 0). \tag{2}$$

Here the constants $C = 29.62(1)$ and $D = 0.6642(2)$ have been determined from numerical calculations [12]. Equation (2) exhibits resonant enhancement at values $a = a_n^- = -(e^{\pi/s_0})^n (D\kappa_*)^{-1}$ for integer n which occur when Efimov trimer states cross the three-atom threshold. For $a_{12} \neq a_{23} \neq a_{13}$, as in our experiment, the STM equations must be solved numerically [27] to accurately determine L_3.

Since $|a_{12}|, |a_{23}|, |a_{13}| \gg \ell_{\mathrm{vdW}}$ and $a_{12}, a_{23}, a_{13} < 0$ for fields above 834 G, the data shown in Fig. 2 should be well described by the zero-range calculation of L_3 in Ref. [12] and will allow the first determination of the three-body parameters for this three-component ^{6}Li gas in the high-field regime. The best fit (solid line) to subsets of the 30 nK data ($B \geq 907$ G) and the 180 nK data ($B \geq 975$ G) (as described above) is shown in Fig. 2. The only free parameters in this fit are κ_* and η_*. From the fit we obtain $\kappa_* = 6.9(2) \times 10^{-3} a_0^{-1}$ and $\eta_* = 0.016^{+0.006}_{-0.010}$ where the uncertainties—combined statistical and systematic—indicate 1 standard deviation. The zero-temperature 3BR rate for these three-body parameters calculated for fields between 840 and 1550 G is shown as the dotted line in Fig. 2. In this model, the resonant peak in the 3BR rate occurs at 895 G where an Efimov trimer crosses the three-atom scattering threshold. The measured 3BR rate for the 30 nK data also peaks near 895 G, though at a significantly smaller magnitude due to the unitarity limit. The dashed line shows a ''unitarized'' recombination rate [28] given by $(1/L_3 + 1/L_{3\mathrm{sat}})^{-1}$ to account for the observed saturation of the 3BR rate in the thermal gas to a value $L_{3\mathrm{sat}} \approx L_{3\,\max}/3$.

We can identify the Efimov trimer that crosses threshold at 895 G with the first excited state of the Efimov spectrum.

The binding energy of this Efimov trimer, in the limit of infinite scattering lengths, is $E_1 = e^{-2\pi/s_0}\hbar^2\kappa_*^2/m = h \times 55(3)$ kHz. In this limit, the ground-state Efimov trimer has a binding energy a factor of $e^{2\pi/s_0} \approx 515$ larger, $E_0 = h \times 28(2)$ MHz. This is the lowest state with a binding energy smaller than the van der Waals energy scale $E_{\rm vdW} = \hbar^2/m\ell_{\rm vdW}^2$. If it were the case that $a_{12} = a_{23} = a_{13} = a < 0$, the first excited trimer would cross threshold at $a = a_1^- = -5.0(1) \times 10^3 a_0$ and the adjacent trimer states would cross threshold at values of a either larger or smaller by a factor of $e^{\pi/s_0} \approx 22.7$. In reality, an Efimov trimer of the ^{6}Li system crosses threshold at 895 G where $a_{12} = -8584a_0$, $a_{23} = -5702a_0$, and $a_{13} = -2893a_0$. We identify this trimer as the first excited Efimov trimer since a_1^- falls within this range of a_{ij} values. In the high-field region ($B > 608$ G), the ground-state Efimov trimer asymptotes to a binding energy $E_0(a_{ij} = -2140a_0) = h \times 24(2)$ MHz with a width $\gamma = h \times 1.5^{+0.6}_{-1}$ MHz (corresponding to a 100^{+180}_{-24} ns lifetime) as calculated from expressions given in Ref. [3].

One aspect of Efimov physics that can now be tested with ultracold atom experiments is the extent to which the universal results can be applied when scattering lengths are tuned across poles or across nodes. For the ^{6}Li gas studied here, there are two universal regions ($122 < B < 485$ G and $B > 608$ G) where the zero-range approximation should be applicable, separated by a nonuniversal region where the scattering lengths become smaller than $2\ell_{\rm vdW}$. We find that the value $\kappa_* = 6.9(2) \times 10^{-3}a_0^{-1}$, determined above for the high-field region, is close to the value $\kappa_* = 6.56 \times 10^{-3}a_0^{-1}$ previously determined from the position of the narrow loss feature in the low-field region near 130 G [12]. Indeed, the 3BR rate calculated in the zero-range approximation using $\kappa_* = 6.9(2) \times 10^{-3}a_0^{-1}$ predicts Efimov resonances at 125(3) and 499(2) G in reasonable agreement with observations [19,20]. These resonances occur when the ground-state Efimov trimer crosses threshold. The value of η_* is nearly an order of magnitude larger in the low-field region [12] than in the high-field regime. The significant change in η_* is likely due to the dramatic difference in the binding energy of the deep dimer states for the two regions [23].

Finally, we note that despite the large 3BR rate that occurs in this system, we can produce quantum degenerate three-component Fermi gases in the high-field regime where the three scattering lengths are large, negative, and approximately equal. Starting from a degenerate two-component mixture of ^{6}Li atoms at $B = 1500$ G in trap II, we prepare a three-component mixture as described above. After equilibration, the three-component mixture has $N = 6(2) \times 10^4$ atoms per spin state, a temperature $T = 50(10)$ nK, a Fermi temperature $T_F = 180(20)$ nK, and a degeneracy temperature $T/T_F = 0.28(6)$. The difference in mean field energies is more than 1 order of magnitude smaller than any other energy scale in the system making it useful for future investigations of three-component Fermi gases with SU(3) symmetry [14–18].

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Note added.—Recently we became aware that enhanced 3BR in a ^{6}Li gas near 900 G was also observed by S. Jochim and co-workers [23].

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