LETTERS

Evidence for Efimov quantum states in an ultracold gas of caesium atoms

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Systems of three interacting particles are notorious for their complex physical behaviour. A landmark theoretical result in few-body quantum physics is Efimov's prediction[1,2] of a universal set of bound trimer states appearing for three identical bosons with a resonant two-body interaction. Counterintuitively, these states even exist in the absence of a corresponding two-body bound state. Since the formulation of Efimov's problem in the context of nuclear physics 35 years ago, it has attracted great interest in many areas of physics[3–8]. However, the observation of Efimov quantum states has remained an elusive goal[3,5]. Here we report the observation of an Efimov resonance in an ultracold gas of caesium atoms. The resonance occurs in the range of large negative two-body scattering lengths, arising from the coupling of three free atoms to an Efimov trimer. Experimentally, we observe its signature as a giant three-body recombination loss[9,10] when the strength of the two-body interaction is varied. We also detect a minimum[9,11,12] in the recombination loss for positive scattering lengths, indicating destructive interference of decay pathways. Our results confirm central theoretical predictions of Efimov physics and represent a starting point with which to explore the universal properties of resonantly interacting few-body systems[7]. While Feshbach resonances[13,14] have provided the key to control quantum-mechanical interactions on the two-body level, Efimov resonances connect ultracold matter[15] to the world of few-body quantum phenomena.

Efimov's treatment of three identical bosons[1,2] is closely linked to the concept of universality[7] in systems with a resonant two-body interaction, where the *s*-wave scattering length a fully characterizes the two-body physics. When $|a|$ greatly exceeds the characteristic range ℓ of the two-body interaction potential, details of the short-range interaction become irrelevant because of the long-range nature of the wavefunction. Universality then leads to a generic behaviour in three-body physics, reflected in the energy spectrum of weakly bound Efimov trimer states. Up to now, in spite of their great fundamental importance, these states could not be observed experimentally. An observation in the realm of nuclear physics, as originally proposed by Efimov, is hampered by the presence of the Coulomb interaction, and only two-neutron halo systems with a spinless core are likely to feature Efimov states[3]. In molecular physics, the helium trimer is predicted to have an excited state with Efimov character[4]. The existence of this state could not be confirmed[5]. A different approach to experimentally studying the physics of Efimov states is based on the unique properties of ultracold atomic quantum gases. Such systems[15] provide an unprecedented level of control, enabling the investigation of interacting quantum systems. The ultralow collision energies allow us to explore the zero-energy quantum limit. Moreover, two-body interactions can be precisely tuned on the basis of Feshbach resonances[13,14].

Efimov's scenario[1,2,7] can be illustrated by the energy spectrum of the three-body system as a function of the inverse scattering length $1/a$ (Fig. 1). Let us first consider the well-known weakly bound dimer state, which only exists for large positive a. In the resonance regime, its binding energy is given by the universal expression $E_b = -\hbar^2/(ma^2)$, where m is the atomic mass and $\hbar$ is Planck's constant divided by 2π. In Fig. 1, where the resonance limit corresponds to $1/a \rightarrow 0$, the dimer energy E_b is represented by a parabola for $a > 0$. If we now add one more atom with zero energy, a natural continuum threshold for the bound three-body system (hatched line in Fig. 1) is given by the three-atom threshold ($E = 0$) for negative a and by the dimer-atom threshold (E_b) for positive a. Energy states below the continuum threshold are necessarily three-body bound states. When $1/a$ approaches the resonance from the negative-a side, a first Efimov trimer state appears in a range where a weakly bound two-body state does not exist. When passing through the resonance the state connects to the positive-a side, where it finally intersects with the dimer-atom threshold. An infinite series of such Efimov states is found when scattering lengths are increased and binding energies are decreased in powers of universal scaling

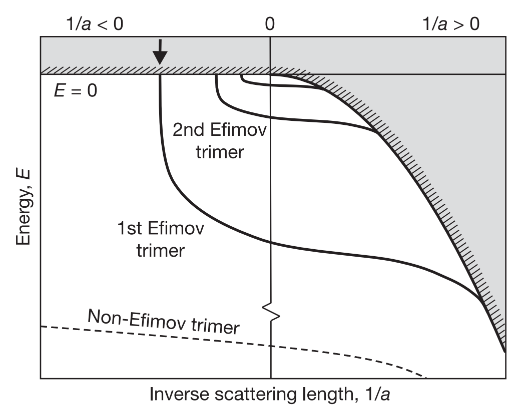

Figure 1 | Efimov's scenario. **Appearance of an infinite series of weakly bound Efimov trimer states for resonant two-body interaction. The binding energy is plotted as a function of the inverse two-body scattering length $1/a$. The shaded region indicates the scattering continuum for three atoms ($a < 0$) and for an atom and a dimer ($a > 0$). The arrow marks the intersection of the first Efimov trimer with the three-atom threshold. To illustrate the series of Efimov states, we have artificially reduced the universal scaling factor from 22.7 to 2. For comparison, the dashed line indicates a tightly bound non-Efimov trimer[30], which does not interact with the scattering continuum.**

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factors[1,2,7] $e^{\pi/s_0} \approx 22.7$ and $e^{-2\pi/s_0} \approx 1/515$ (where $s_0 = 1.00624$), respectively.

Resonant scattering phenomena arise as a natural consequence of Efimov's scenario[16]. When an Efimov state intersects with the continuum threshold at negative scattering lengths a, three free atoms in the ultracold limit resonantly couple to a trimer. This results in a triatomic Efimov resonance. At finite collision energies, the phenomenon evolves into a triatomic continuum resonance[17]. Another type of Efimov resonance[18] is found at positive values of a for collisions between a free atom and a dimer, when Efimov states intersect with the dimer–atom threshold. While the latter type of Efimov resonance corresponds to Feshbach resonances in collisions between atoms and dimers[18], triatomic Efimov resonances can be interpreted as a three-body generalization to Feshbach resonances[8].

Striking manifestations of Efimov physics have been predicted for three-body recombination processes in ultracold gases with tunable two-body interactions[7,9–12,19]. Three-body recombination leads to losses from a trapped gas with a rate proportional to the third power of the atomic number density. These losses are commonly described[20] in terms of a loss rate coefficient L_3. In the resonant case ($|a| \gg \ell$), it is convenient to express this coefficient in the form $L_3 = 3C(a)\hbar a^4/m$, separating a general a^4-scaling[20,21] from an additional dependence[9,10,12] $C(a)$. Efimov physics is reflected in a logarithmically periodic behaviour $C(22.7a) = C(a)$, corresponding to the scaling of the infinite series of weakly bound trimer states. For negative scattering lengths, the resonant coupling of three atoms to an Efimov state opens up fast decay channels into deeply bound dimer states plus a free atom.

Triatomic Efimov resonances thus show up in giant recombination loss. This striking phenomenon was first identified in numerical solutions to the adiabatic hyperspherical approximation of the three-body Schrödinger equation, assuming simple model potentials and interpreted in terms of tunnelling through a potential barrier in the three-body entrance channel[9]. A different theoretical approach[7,10], based on effective field theory, provides the analytic expression $C(a) = 4{,}590\sinh(2\eta_-)/(\sin^2[s_0\ln(|a|/a_-)] + \sinh^2\eta_-)$. The free parameter a_- for the resonance positions at a_-, 22.7 a_-,… depends on the short-range part of the effective three-body interaction and is thus not determined in the frame of the universal long-range theory. As a second free parameter, the dimensionless quantity η_- describes the unknown decay rate of Efimov states into deeply bound dimer states plus a free atom, and thus characterizes the resonance width.

Our measurements are based on the magnetically tunable interaction properties of caesium atoms[22] in the lowest internal state. By applying fields between 0 and 150 G, we varied the s-wave scattering length a in a range between $-2{,}500a_0$ to $1{,}600a_0$, where a_0 is Bohr's radius. Accurate three-body loss measurements are facilitated by the fact that inelastic two-body loss is energetically forbidden[20]. The characteristic range of the two-body potential is given by the van der Waals length[23], which for caesium is $\ell \approx 100a_0$. This leaves us with enough room to study the universal regime requiring $|a| \gg \ell$. For negative a, a maximum value of 25 is attainable for $|a|/\ell$. Efimov's estimate $\frac{1}{\pi}\ln(|a|/\ell)$ for the number of weakly bound trimer states[2] suggests the presence of one Efimov resonance in the accessible range of negative scattering lengths.

Our experimental results (Fig. 2), obtained with optically trapped thermal samples of caesium atoms in two different set-ups (see Methods), indeed show a giant loss feature marking the expected resonance. We present our data in terms of a recombination length[9] $\rho_3 = [2m/(\sqrt{3}\hbar)L_3]^{1/4}$, which leads to the simple relation $\rho_3/a = 1.36C^{1/4}$. Note that the general a^4-scaling corresponds to a linear behaviour in $\rho_3(a)$ (straight lines in Fig. 2). A fit of the analytic theory[7,10] to our experimental data taken for negative a at temperatures $T \approx 10$ nK shows a remarkable agreement and determines the resonance position to $a_- = -850(20)a_0$ and the decay parameter to $\eta_- = 0.06(1)$. The pronounced resonance behaviour with a small value for the decay parameter ($\eta_- \ll 1$) demonstrates a sufficiently long lifetime of Efimov trimers to allow their observation as distinct quantum states.

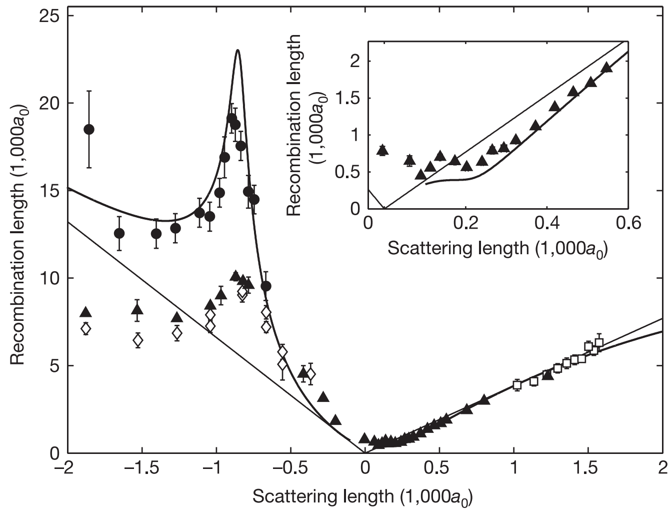

Figure 2 | Observation of the Efimov resonance in measurements of three-body recombination. The recombination length $\rho_3 \propto L_3^{1/4}$ is plotted as a function of the scattering length a. The dots and the filled triangles show the experimental data from set-up A for initial temperatures around 10 nK and 200 nK, respectively. The open diamonds are from set-up B at temperatures of 250 nK. The open squares are previous data[20] at initial temperatures between 250 and 450 nK. The solid curve represents the analytic model from effective field theory[7] with $a_- = -850a_0$, $a_+ = 1{,}060a_0$, and $\eta_- = \eta_+ = 0.06$. The straight lines result from setting the $\sin^2$ and $\cos^2$-terms in the analytic theory to 1, which gives a lower recombination limit for $a < 0$ and an upper limit for $a > 0$. The inset shows an expanded view for small positive scattering lengths with a minimum for $C(a) \propto (\rho_3/a)^4$ near $210a_0$. The displayed error bars refer to statistical uncertainties only. Uncertainties in the determination of the atomic number densities may lead to additional calibration errors for ρ_3 of up to 20%.

All the results discussed so far are valid in the zero-energy collision limit of sufficiently low temperatures. For ultralow but non-zero temperatures the recombination length is unitarity limited[19] to $5.2\hbar(mk_BT)^{-1/2}$. For $T = 10$ nK this limit corresponds to about $60{,}000a_0$ and our sample is thus cold enough to justify the zero-temperature limit. For 250 nK, however, unitarity limits the recombination length to about $12{,}000a_0$. The Efimov resonance is still visible at temperatures of 200 and 250 nK (filled triangles and open diamonds in Fig. 2). The slight shift to lower values of $|a|$ suggests the evolution of the zero-energy Efimov resonance into a triatomic continuum resonance[17]. In further experiments at higher temperatures (data not shown) we observed the resonance to disappear above ~500 nK.

For positive scattering lengths, we found three-body losses to be typically much weaker than for negative values. Our measurements are consistent with a maximum recombination loss of $C(a) \approx 70$, or equivalently $\rho_3 \approx 3.9a$, as predicted by different theories[9,11,12] (straight line for $a > 0$ in Fig. 2). For a below $600a_0$ the measured recombination length significantly drops below this upper limit (inset in Fig. 2). The analytic expression from effective field theory[7,12] for $a > 0$ reads $C(a) = 67.1e^{-2\eta_+}(\cos^2[s_0\ln(a/a_+)] + \sinh^2\eta_+) + 16.8(1 - e^{-4\eta_+})$ with the two free parameters a_+ and η_+. The first term describes recombination into the weakly bound dimer state with an oscillatory behaviour that is due to an interference effect between two different pathways[9,11]. The second term results from decay into deeply bound states. We use this expression to fit our data points with $a > 5\ell \approx 500a_0$. This somewhat arbitrary condition is introduced as a reasonable choice to satisfy $a \gg \ell$ for the validity of the universal theory. The fit is quite insensitive to the value of the decay parameter and yields $\eta_+ < 0.2$. This result is consistent with the theoretical assumption[10] of the same value for the decay

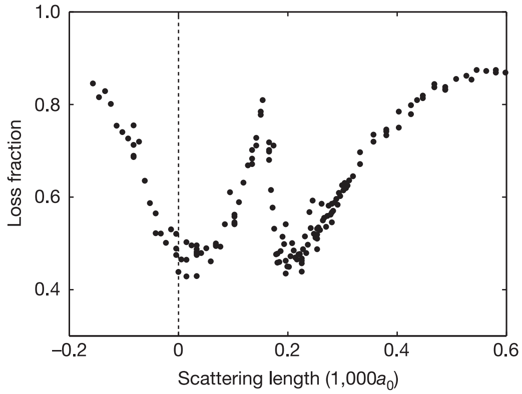

Figure 3 | Atom loss for small scattering lengths. Besides a minimum near zero scattering length, we identify a minimum of recombination loss at $\sim 210a_0$, which can be attributed to a predicted destructive interference effect[9,11,12].

parameter for positive and negative a, which in our case is $\eta_+ = \eta_- = 0.06$. For maximum $C(a)$, we obtain $a_+ = 1{,}060(70)a_0$. According to theory[7], the trimer state hits the dimer–atom threshold at $a = 1.1a_+ \approx 1{,}170a_0$. The logarithmic periodicity of the Efimov scenario suggests that adjacent loss minima occur at $\sqrt{22.7} \times 1{,}060a_0 \approx 5{,}000a_0$ and at $1{,}060a_0/\sqrt{22.7} \approx 220a_0$. While the former value is out of our accessible range, the latter value ($a \approx 2\ell$) is too small to strictly justify universal behaviour in the resonance limit ($a \gg \ell$). Nevertheless, our experimental results (inset to Fig. 2) indicate a minimum at $a \approx 210a_0$ and the analytic expression for $C(a)$ is found to describe our data quite well down to this minimum.

The occurrence of the interference minimum in three-body loss is demonstrated more clearly in another set of experiments (Fig. 3), where we simply measured the loss of atoms after a fixed storage time in the optical trap. This minimum is located at $a = 210(10)a_0$ in addition to a second minimum close to zero scattering length. We point out that the existence of the minimum at $210a_0$ is very advantageous for efficient evaporative cooling of caesium as it combines a large scattering cross-section with very low loss. Inadvertently, we have already benefited from this loss minimum for the optimized production of a Bose–Einstein condensate of caesium[24].

The comparison of our experimental results to available three–body theory shows remarkable agreement, although the collision physics of caesium is in general a very complicated multi-channel scattering problem. We believe that the particular nature of the broad, "open-channel dominated" Feshbach resonance[25] that underlies the tunability of our system plays a crucial role. For such a resonance, the two-body scattering problem can be described in terms of an effective single-channel model. It is very interesting to investigate to what degree this great simplification of the two-body physics extends to the three-body problem. Here we particularly wonder how the regions of positive and negative scattering lengths are connected in our experiment, where a is changed through a zero crossing—that is, through a non-universal region, and not across the universal resonance region.

In our case, there is no obvious connection between the Efimov state that leads to the observed resonance for $a < 0$ and the states responsible for the behaviour for $a > 0$. In our analysis of the experimental data, we have thus independently fitted the data sets for negative and positive a. Nevertheless, the resulting values for the two independent fit parameters a_- and a_+ do suggest a connection: for the ratio $a_+/|a_-|$ our experiment yields 1.25(9), whereas universal theory[7] predicts 0.96(3). These numbers are quite close in view of the Efimov factor of 22.7. If it is not an accidental coincidence, we speculate that the apparent relation between a_+ and a_- may be a further consequence of universality in a system where the resonant two-body interaction can be modelled in terms of a single scattering channel. In general, the multi-channel nature of three-body collisions near Feshbach resonances[26,27] leads to further interesting questions, such as whether there may be resonance effects beyond the Efimov scenario. Advances in three-body theory are necessary to answer these questions and to provide a complete interpretation of our present observations.

In the past few years, applications of Feshbach resonances in ultracold gases and the resulting ability to create dimer states have set the stage for many new developments in matter-wave quantum physics. The observation of an Efimov resonance now confirms the existence of weakly bound trimer states and opens up new ways[6,8] of experimentally exploring the intriguing physics of few-body quantum systems.

METHODS

Magnetic tuning of the two-body interaction. For Cs atoms in their energetically lowest state (quantum numbers $F = 3$ for the total spin and $m_F = 3$ for its projection) the s-wave scattering length a varies strongly with the magnetic field[22]. Between 0 and 150 G the dependence can in general be well approximated by the fitting formula:

$$a(B)/a_0 = (1{,}722 + 1.52B/\mathrm{G})\left(1 - \frac{28.72}{B/\mathrm{G} + 11.74}\right)$$

except for a few narrow Feshbach resonances[22]. The smooth variation of the scattering length in the low-field region results from a broad Feshbach resonance centred at about -12 G (equivalent to $+12$ G in the state $F = 3$, $m_F = -3$). In all our measurements we excluded the magnetic field regions where the narrow Feshbach resonances influence the scattering behaviour through coupling to other molecular potentials. The Efimov resonance is centred at 7.5 G.

Trap set-ups and preparation of the Cs gases. All measurements were performed with trapped thermal samples of caesium atoms at temperatures T ranging from 10 to 250 nK. We used two different experimental set-ups, which have been described elsewhere[24,28].

In set-up A we first produced an essentially pure Bose–Einstein condensate with up to 250,000 atoms in a far-detuned crossed optical dipole trap generated by two 1,060-nm Yb-doped fibre laser beams[24]. We then ramped the magnetic field to 16.2 G, where the scattering length is negative with a value of $-50a_0$, thus inducing a collapse of the condensate[29]. After an equilibration time of 1 s we were left with a thermal sample at typically $T = 10$ nK containing up to 20,000 atoms at peak densities ranging from $n_0 = 3 \times 10^{11}\,\mathrm{cm}^{-3}$ to $3 \times 10^{12}\,\mathrm{cm}^{-3}$. Alternatively, we interrupted the evaporation process before condensation to produce thermal samples at $T \approx 200$ nK in a crossed dipole trap generated by one of the 1,060-nm beams and a 10.6-μm CO_2 laser beam. After recompression of the trap this produced typical densities of $n_0 = 5 \times 10^{13}\,\mathrm{cm}^{-3}$. The measurements in the region of the loss minima as displayed in Fig. 3 were taken after a storage time of 200 ms at initial densities of $n_0 = 6 \times 10^{13}\,\mathrm{cm}^{-3}$.

In set-up B we used an optical surface trap[28] in which we prepared a thermal sample of 10,000 atoms at $T \approx 250$ nK via forced evaporation at a density of $n_0 = 1.0 \times 10^{12}\,\mathrm{cm}^{-3}$. The dipole trap was formed by a repulsive evanescent laser wave on top of a horizontal glass prism in combination with a single horizontally confining 1,060-nm laser beam propagating along the vertical direction.

Determination of three-body loss rate coefficients. We measured three-body loss rates in set-up A by recording the time evolution of the atom number N and the temperature T. A detailed description of this procedure has been given in ref. 20. In brief, the process of three-body recombination not only leads to a loss of atoms, but also induces 'anti-evaporation' and recombination heating. The first effect is present at any value of the scattering length a. The second effect occurs for positive values of a when the recombination products remain trapped. Atom loss and temperature rise are modelled by a set of two coupled nonlinear differential equations. We used numerical solutions to this set of equations to fit our experimental data. From these fits, together with measurements of the trapping parameters, we obtained the rate coefficient L_3. In set-up B we recorded the loss at decay times sufficiently short to make sure that heating is negligible.

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