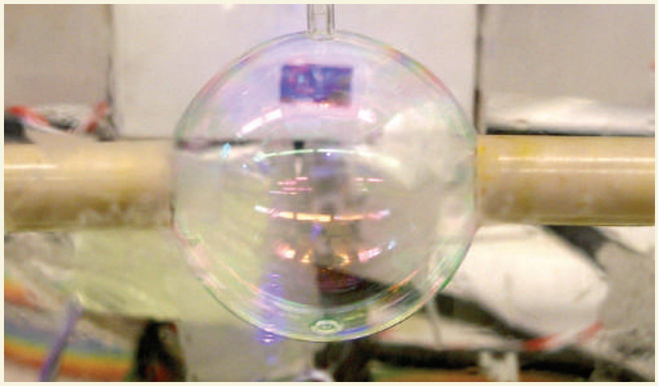
ANALYTICAL CHEMISTRY

Forever blowing bubbles


T. KANYANEE

The delightful iridescence and evanescence of soap bubbles arises from the fact that their walls are nothing but a film of water sandwiched between two layers of surfactant molecules. This unusual construction also endows soap bubbles with a uniquely large ratio of surface area to contained liquid. Tinakorn Kanyanee *et al.* (*Anal. Chem.* doi:10.1021/ac052198h; 2006) set out to exploit this feature — by 'wiring up' soap bubbles and using them as the functional heart of a fully automated detection system for trace gases.

The authors' bubble factory uses a sealed, transparent plastic box with water at the bottom to keep the environment moist and so prolong bubble life. Soap solution is first supplied to the box through the inner of two concentric tubes. As the solution spreads from this tube's slightly recessed tip, it coats the tip of the surrounding outer tube, through which a controlled blast of air is delivered, inflating the soap film and creating a bubble. Precise metering of the air pulse ensures that the bubble is inflated just enough to touch two opposing stainless-steel electrode rods that jut into the box. The bubble-box reproducibly generates long-lived bubbles of uniform size and wall-thickness, so that the conductance measured between the electrodes for a given bubble geometry depends on the bubble's chemical composition.

To use their system for trace-gas analysis, the authors added the oxidizing agent hydrogen peroxide to the soap solution and exposed the resulting bubble to air containing traces of sulphur dioxide. The sulphur dioxide readily diffused into the bubble, where it was oxidized and sulphuric acid was produced. The presence of acid increased the bubble's electrical conductance.

This effect enabled quantitative determination of part-per-billion levels of sulphur dioxide within minutes. The approach should also be applicable to a range of other soluble and reactive gases. But as Kanyanee and colleagues point out, the wider message is that soap bubbles are an attractive, yet largely unexplored, tool for concentrating trace gases to enable their detection. Whether these species are then detected through conductance measurements, or through bursting the bubble and analysing its liquid by other means, there is, in that sense, more to this story than mostly froth and bubble.

Magdalena Helmer

QUANTUM PHYSICS

A *ménage à trois* laid bare

Brett D. Esry and Chris H. Greene

Quantum bodies that can't settle down together in pairs get on fine in a cosy threesome. This startling claim about the private life of particles has just seen its first experimental confirmation.

In 1970, Vitaly Efimov, possessor of a freshly minted Russian PhD in theoretical nuclear physics, predicted a bizarre quantum-mechanical effect[1]: a system consisting of three particles, none of whose two-particle subsystems is stable, can, under certain circumstances, produce an infinite number of bound energy levels. That prediction has been a source of concern for theorists ever since. Yet time and again, attempts to disprove the 'Efimov effect' have only verified its existence, albeit — until now — purely theoretically. In this issue, more than 35 years on from the initial prediction, Kraemer *et al.* (page 315)[2] present the first convincing experimental evidence for the effect.

The question explored by Efimov was simple: if each possible pair of particles in a three-particle system is just shy of binding (so there are no bound states), what is the nature of the energy spectrum of the three particles? The answer, that the number of bound states in which the three particles can exist is infinite, is initially surprising. But it can be rationalized by noting that if two particles are already infinitesimally close to forming a bound state, just the faintest whiff of an additional attraction will be sufficient to push them over the edge to confederation. A third attracting particle accomplishes precisely that, no matter how far away from the other two it may roam, or how weak its additional attraction may be. Unsurprisingly, given this qualitative argument, three-body Efimov states have been theoretically found[3] to be extremely 'floppy', with all imaginable triangular shapes — equilateral, isosceles, scalene (Fig. 1, overleaf) — and even linear configurations being comparably probable.

The Efimov effect is distantly related to Llewellyn Hilleth Thomas's 1935 proof[4] that, in its ground state, a system of three particles that interact only within a vanishingly small range collapses to an infinitely small size, and its binding energy becomes infinitely large. Efimov discussed the link particularly clearly in a 1971 article[5] that derived an effective potential-energy curve for such a system as a function of a three-particle 'hyperradius', R, which is proportional to the root-mean-square distance of the three particles from their centre of mass. The three-body potential-energy function turns out to be proportional to R^{-2}, and it has a universal, negative coefficient of proportionality. The properties of such a potential are well known, because a similar form governs the motion of a charged particle in the field of a permanent dipole (where two charges of equal and opposite sign are separated by a small distance).

The allowed energy levels of a quantum system can be determined by solving the radial, time-independent Schrödinger equation (which yields the energy levels, E_n, of a quantum system). When the equation is solved for a system with an R^{-2} potential, the allowed energy levels that result follow on iteratively from each other according to the rule $E_{n+1} = E_n \exp(-2\pi/s_0)$, where s_0 is a constant related to the strength of the so-called effective dipole moment with a value slightly greater than one. Thus, as n increases, the binding energies of successive levels decrease exponentially. This scaling also carries over to other observable parameters, such as the size of the state. Thomas's collapsed states are the infinitely tightly bound states that occur as n approaches $-\infty$, whereas the Efimov states are those states that are only just bound, arising as n approaches $+\infty$. In real physical systems, the fact that the range of interparticle interactions can never be zero prevents a Thomas collapse, so this effect will, one presumes, never be observed. There is, however, no similar obstacle to observing the Efimov effect.

The strength of the interparticle interaction is described in terms of a parameter known as the scattering length, a. In a system consisting of two atoms, if a is large and positive, a weakly bound state of the diatomic molecule exists. If a is negative, the atoms experience an attraction but are not quite bound together. Kraemer and colleagues' experimental work[2] relied on manipulating the atom–atom scattering length of caesium atoms by the now almost routine technique of tuning a magnetic field to a value very close to a 'Feshbach resonance' — a short-lived, low-energy, two-body molecular state[6]. Controlling the scattering length is crucial, as the formation of Efimov states is only expected for scattering lengths much greater in magnitude than the range of two-body interactions.

Kraemer and colleagues did not actually measure bound states at all, so the simplest 'smoking gun' evidence for Efimov states — a pattern of energy levels that fits the characteristic exponential formula — has yet to be observed. The authors studied instead the low-energy interactions of three ultracold caesium atoms, measuring the three-body recombination process Cs + Cs + Cs → Cs_2 + Cs, which had already been tackled theoretically[7–10]. Crucially, in 1999, Efimov states were predicted[8] to show up as an infinite series of resonances in the rate of recombination at negative values of the scattering length, a link confirmed independently[10] two years later.

Kraemer *et al.*[2] saw only one such resonance (Fig. 2), at a scattering length of $-850a_0$, where $a_0 = 0.53$Å is the Bohr radius, a standard unit of distance in atomic physics. The fact that they did not see more (according to the theory, the next resonance should appear at a scattering length 22.7 times more negative, near a scattering length of $-19{,}000a_0$) leaves them open to the charge that the effect could be some unrelated, non-Efimov three-body resonance effect, or even just a two-body effect.

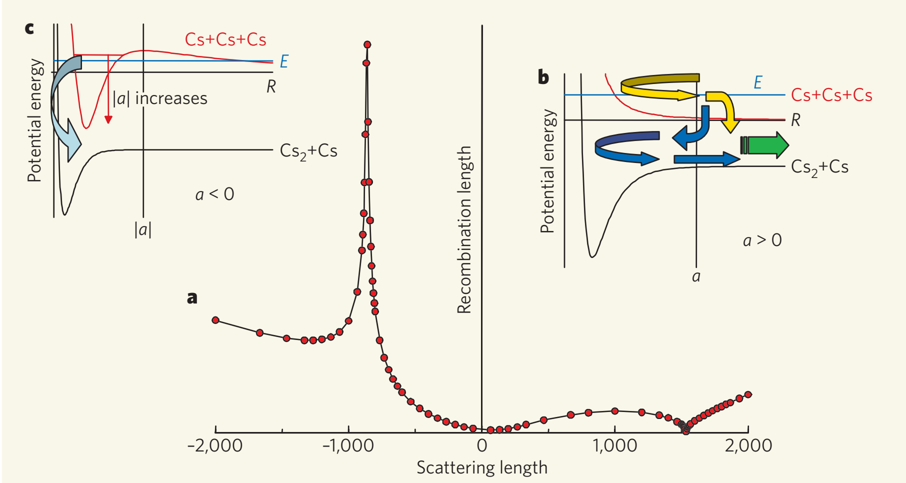


Figure 2 | Features predicted[7–11] and observed[2] in ultracold three-body recombination. a, The theoretical rate (in terms of a 'recombination length'[8]) of the three-body recombination process Cs + Cs + Cs → Cs_2 + Cs, obtained from numerical solutions of the three-body Schrödinger equation[8,11] and plotted as a function of the two-body scattering length a (in units of the Bohr radius a_0). The first interference minimum[7–11] at $a > 0$ and the first resonance maximum[8–10] at $a < 0$ — features predicted by theory — were observed by Kraemer *et al.*[2] in their studies of caesium recombination. Insets **b**,**c**, the three-body potentials responsible for these features: the potential before recombination of three incident atoms at energy E (blue line) is shown in red; that after recombination, in black. **b**, For positive a, the transition between the two potentials takes place at a 'hyperradius' $R \sim a$ by one of two paths. First, the system 'jumps' into the lower recombined channel when still decreasing in size to $R \sim a$. The atom then rebounds off the dimer (R increases) but the system remains in the recombined state (blue pathway). Second, the three atoms initially rebound elastically and only recombine in their outward traversal of $R \sim a$ (yellow path). Minima and maxima in the recombination rate arise from quantum-mechanical interference between these two paths in the outgoing channel (green arrow). **c**, For $a < 0$, the transition occurs at R much smaller than $|a|$, and the system must tunnel quantum mechanically into the small-R potential well in order to recombine. When there are resonances (an allowed quasi-bound energy state, indicated by the horizontal red line) behind this barrier, the tunnelling probability is effectively enhanced, giving a maximum in the recombination rate. The resonance positions change with the scattering length (shown by the arrow), tuning the system in and out of resonance and yielding a series of peaks in the recombination length.

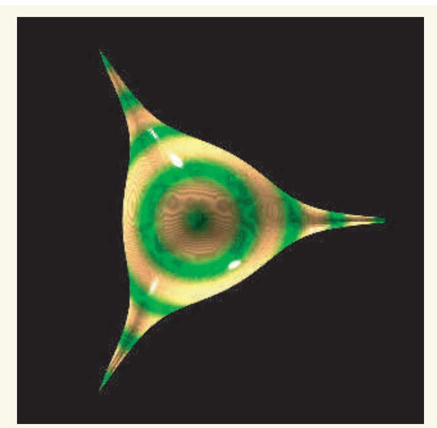


Figure 1 | Floppy triangles. The Efimov-state probability density as a function of two 'hyperangles' that control the shape of the three-particle triangle. In this representation, the radius in any direction from the centre of the object measures the probability density of a particular triangular shape; the spikes indicate a somewhat higher probability for the system to exist in configurations where two of the three atoms are close to each other, whereas the near-spherical part of this object shows that all other triangle shapes occur with very comparable probabilities.

That interpretation is rendered unlikely, however, by the appearance of an interference minimum (Fig. 2) in the experimental spectrum at a positive scattering length, $a^{min} = 210a_0$. Theoretical studies[7–10] agree that, when Efimov physics occurs, a series of such minima in the three-body recombination should appear for large positive values of a. However, one study[10] places the first minimum correctly to within 25% of the experimentally observed location[2], even though its formula would not be expected to be valid at such low values of a. On the other hand, numerical solutions of the three-body Schrödinger equation[8,11] place this minimum at a different location, near $a^{min} = 1{,}500a_0$ (Fig. 2). Resolution of this disagreement will require further work.

Although the evidence is not yet conclusive, the appearance of both predicted phenomena — a resonance maximum[8,10,11] and an interference minimum[7–11] — implies strongly that Efimov physics has been observed. Developments in the theory are pointing the way to further experiments that would provide even more definitive confirmation[11].

The Efimov effect, so long eluding observation, is beginning to yield up its secrets. As our theoretical understanding of Efimov states has deepened, so has our vision of their wider implications, such as those for the recombination physics studied by Kraemer *et al.*[2]. We look forward to seeing how the spark provided by this impressive new experiment ignites a new round of exploration into the rich quantum-mechanical world of exotic few-body systems. ■

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