Hints of universal behavior seen in exotic three-atom states

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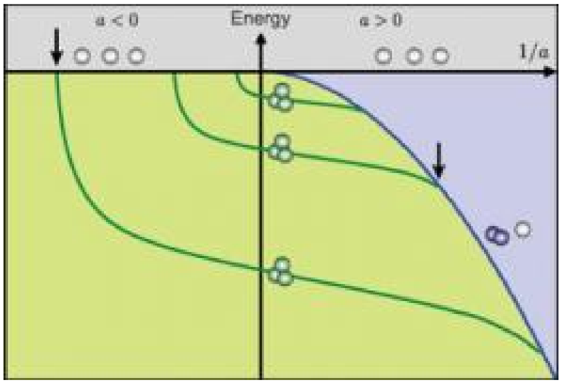

This graph shows the existence of Efimov triplet states as a function of the scattering length, a, and the binding energy. Outside the green area the three atoms exist singly or as a pair plus a lone atom. Inside the green area a series of three-atom states can exist. Credit: Picture courtesy of the University of Innsbruck

A novel type of inter-particle binding predicted in 1970 and observed for the first time in 2006, is forming the basis for an intriguing kind of ultracold quantum chemistry. Chilled to nano-kelvin temperatures, cesium atoms -- three at a time -- come together to form a bound state hundreds or even thousands of times larger than individual atoms. Unlike the case of ordinary atoms, wherein electrons are bound to a nucleus in a spectrum of energy levels on the order of an electron volt (that is, it would typically take an eV of energy to free the electron), the cesium triplets feature energy levels that are measured in trillionths of an electron volt (peV). Stranger still, a new experiment observing four such cesium states reports that the states' sizes are roughly the same. This has taken theorists by complete surprise.

In the seventeenth century Isaac Newton derived the classical force laws used to calculate the force between two objects. Calculating the behavior of three-body groupings such as the Moon/Earth/Sun system was much harder; indeed Newton never succeeded. Nowadays such problems can be studied with powerful computers, but only numerical simulations are possible, and not exact, analytical solutions.

In 1970, however, Russian physicist Vitaly Efimov predicted that under some special conditions, three bodies, such as atoms at ultralow temperatures, could be made to enter into stable states whose behavior could be calculated with remarkable ease. Then in 2006 exactly such states were actually observed by scientists at the University of Innsbruck. Now, these researchers have extended their work and demonstrated that the "three-body parameter," used to describe how the three participating bodies interact, varies in a consistent way regardless of the atomic species used.

Paul Julienne, a scientist at the Joint Quantum Institute (JQI), operated by the University of Maryland and the National Institute of Standards and Technology (NIST), contributed theoretical help to the Innsbruck scientists conducting the experiment, a team led by Rudolf Grimm. "None of the experts in three-body physics had expected this kind of universal behavior to show up in these 3-atom systems," Julienne said. "This behavior came as a big surprise." And the universality, in turn, might suggest the existence of some new kind of ultracold chemistry at work.

Efimov's 1970 work met with much skepticism, especially since his prediction specified that three particles could form stable partnerships even though none of the two-particle matchups were stable. That is, 3 particles could accomplish what 2 particles could not. This novel arrangement has been compared to the "Borromean Rings," a set of three rings used on heraldic symbol for the Borromeo family during the Italian Renaissance. The three rings hold together unless any one of the rings is removed.

Efimov's prediction applies not just to atoms but to any 3 particles. For example, helium-6, a semi-stable nucleus consisting of 2 protons and 4 neutrons, can be made by from a helium-4 nucleus and 2 extra neutrons. The 2 neutrons cannot form a stable composite; neither can He-4 plus 1 extra neutron. But the three-body He4-n-n system is stable, at least for a while.

Such Borromean nuclei have been known for some time, but atoms have turned out to be more useful in pursuing the novel interactions called for in Efimov's theory. That's because atoms can be chilled to nano-kelvin temperatures in traps and made to interact with great precision. As atoms cool down, they get larger---at least in a quantum sense: as waves, their equivalent wavelength can be many times larger than their nominal particle size (a hydrogen atom is about 0.1 nm across). Furthermore, by applying an external magnetic field, subtle interactions among neutral atoms can be achieved.

Such interactions, called Feshbach resonances, were used to bring cesium atoms together, three at a time, in Efimov states. These atoms were part of a vapor held at temperatures of tens of nano-K. In 2006 the Innsbruck team reported seeing one such troika of atoms. Now, in the 16 September 2011 issue of Physical Review Letters, the Innsbruck-JQI-Durham researchers are reporting the observation of three more state of 3 atoms bound together.

These trimers are quantum objects; they have no classical counterpart.

The weak binding of the super-cold Cs atoms is described in terms of a parameter, a, called the scattering length. If a is positive and large (much larger than the nominal range of the force between the atoms), weak binding of atoms can happen. If a is negative, a slight attraction of two atoms can occur but not binding. If, however, a is large, negative, and three atoms are present, then the Efimov state can appear. Indeed an infinite number of such states can occur. The Efimov state has an energy spectrum, as if it were a chemical element all by itself, with each binding energy level scaling with the value of a. This kind of universal behavior was expected.

The effective size of these Efimov-triplets is referred to as the three-body parameter. In the case of the four cesium states seen so far, the value is just about the same, about 50 nm, or about 500 times the size of a hydrogen atom. This, combined with the three-body-parameter values observed in experiments for lithium and possibly for other elements being studied right now, suggests that while adjusting for the size of the respective atoms all the species are behaving in the same way. This kind of universality was totally unexpected.

"It is really amazing how the new research field developed since we found the first traces of Efimov states, "said Grimm. "Now things have become reality, things we did not even dream about five years ago."

More information: "Universality of the Three-Body Parameter for Efimov States in Ultracold Cesium," by M. Berninger, A. Zenesini,1 B. Huang, W. Harm, H.-C. Na¨gerl, F. Ferlaino, R. Grimm, P. S. Julienne, and J. M. Hutson, 16 September 2001 *Physical Review Letters.*

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