Exotic, gigantic molecules fit inside each other like Russian nesting dolls

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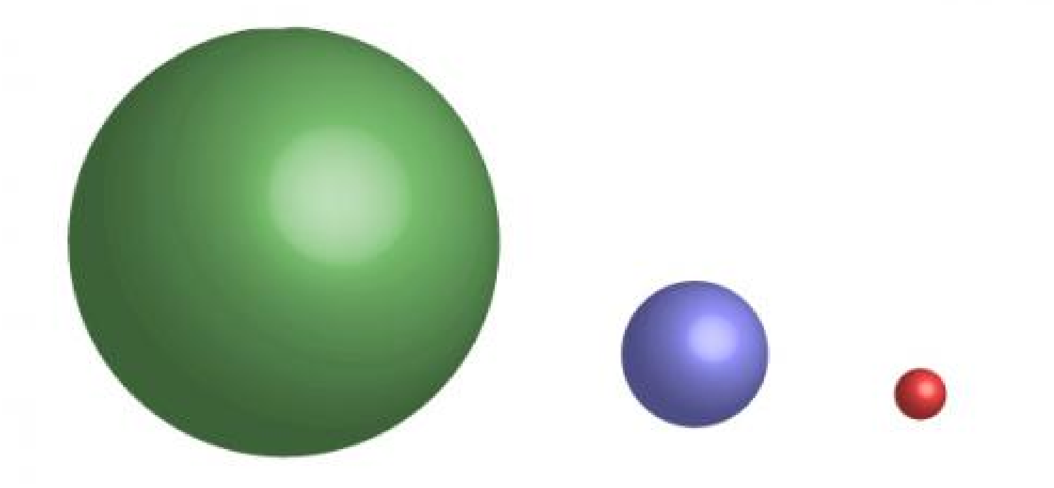

Sizes of triatomic molecules that follow the geometrical scaling predicted by Vitaly Efimov in 1970. University of Chicago physicists have reported evidence of this geometric scaling in three-atom, lithium-ceisum Efimov molecules at a temperature 200 nanokelvin, a fraction of a degree above absolute zero (minus 459.6 degrees Fahreneheit). Credit: Cheng Chin group, University of Chicago

University of Chicago scientists have experimentally observed for the first time a phenomenon in ultracold, three-atom molecules predicted by Russian theoretical physicist Vitaly Efimov in 1970.

In this quantum phenomenon, called geometric scaling, the triatomic molecules fit inside one another like an infinitely large set of Russian nesting dolls.

"This is a new rule in chemistry that molecular sizes can follow a geometric series, like 1, 2, 4, 8…," said Cheng Chin, professor in physics. "In our case, we find three molecular states in this sequence where one molecular state is about 5 times larger than the previous one."

Chin and four members of his research group published their findings Dec. 9, 2014, in *Physical Review Letters*.

"Quantum theory makes the existence of these gigantic molecules inevitable, provided proper—and quite challenging—conditions are created," said Efimov, now at the University of Washington.

The UChicago team observed three molecules in the series, consisting of one lithium atom and two cesium atoms in a vacuum chamber at the ultracold temperature of approximately 200 nanokelvin, a tiny fraction of a degree above absolute zero (minus 459.6 degrees Fahrenheit).

Infinitely large molecules

Given an infinitely large universe, the number of increasingly larger molecules in this cesium-lithium system also would extend to infinity. This remarkable idea stems from the exotic nature of quantum mechanics, which confirms to different laws of physics than those that govern the universe on a macroscopic scale.

"These are certainly exotic molecules," said Shih-Kuang Tung, the postdoctoral scholar, now at Northwestern University, who led the project. Only under strict conditions could Tung and his colleagues see the geometric scaling in their Efimov molecules. It appears that neither two-atom nor four-atom molecules can achieve the Efimov state. "There's a special case for three atoms," Chin said.

Efimov's reaction to the research was twofold. "First, I am amazed by the predictive power of the quantum theory," he said. "Second, I am amazed by the skill of the experimentalists who managed to create those challenging conditions."

The finding is important because it shows that Efimov molecules, like other complex phenomena in nature, follow a simple mathematical rule. One other example in nature that displays geometric scaling is snowflakes, rooted in the microscopic physics of their hexagonal crystal structure.

A team at the University of Innsbruck in Austria, which included Chin, experimentally observed the first Efimov molecular state in 2006 in molecules consisting of three cesium atoms. In this Efimov state, three cesium atoms become entangled at temperatures slightly above absolute zero. They form a Borromean ring of three interlocking circles. Any two of them, however, will not interlock.

Scaling factor

"The difficulty is that based on what we understand of Efimov's theory, the scaling factor is predicted to be 22.7 for the cesium system, which is a very large number," explained Chin, who also is a member of UChicago's James Franck and Enrico Fermi institutes. Scaling at such a large value demands an extremely low temperature, challenging to reach experimentally.

But the scaling factor of the lithium-cesium triatomic molecule was predicted to be more manageable of 4.8. Indeed, after setting up their experiment, "We were able to see three of them at a more accessible temperature of 200 nano-Kelvin," Chin said. "Their sizes are measured to be 17, 86 and 415 nano-meters, respectively. They closely follow a geometric progression with the predicted scaling factor."

But even the lithium-cesium system presented a difficulty: the significantly differing masses of the two elements, which was critical for observing multiple Efimov states. Lithium is one of the lightest elements on the periodic table, while cesium is quite heavy. "One is really massive compared to the other," Tung said.

He compared working both elements into an ultracold experiment to dangling a monkey and an elephant from springs. They would hang at different levels, but still needed to interact.

In the experiment, the UChicago physicists lowered the temperatures of the lithium and cesium atoms separately, then brought them together to form the triatomic, Efimov molecules.

"It's a very complicated experiment," Tung said, one requiring an ultracold experimental tool called Feshbach resonance. Carried out in a magnetic field, Feshbach resonance allowed researchers to bind and control the interactions between the cesium and lithium atoms.

Cold atoms are subject to manipulation via Feshbach resonance, which allows the observation of geometric scaling. "Feshbach resonance is a really important tool for us," Tung said. He and his associates learned how to wield the tool effectively in the past three years.

"We needed to tune the Feshbach resonances very carefully in order to generate these Efimov molecules," Tung said.

The efforts culminated in experimental success. Efimov said the results made him feel like the parent of a successful child. "The parent is proud of the child's achievement, and he is also proud that in a sense he is part of the child's success."

More information: "Geometric Scaling of Efimov States in a

6Li-133Cs Mixture," by Shih-Kuang Tung, Karina Jiménez-García, Jacob Johansen, Colin V. Parker, and Cheng Chin, *Physical Review Letters*, DOI: dx.doi.org/10.1103/PhysRevLett.113.240402

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