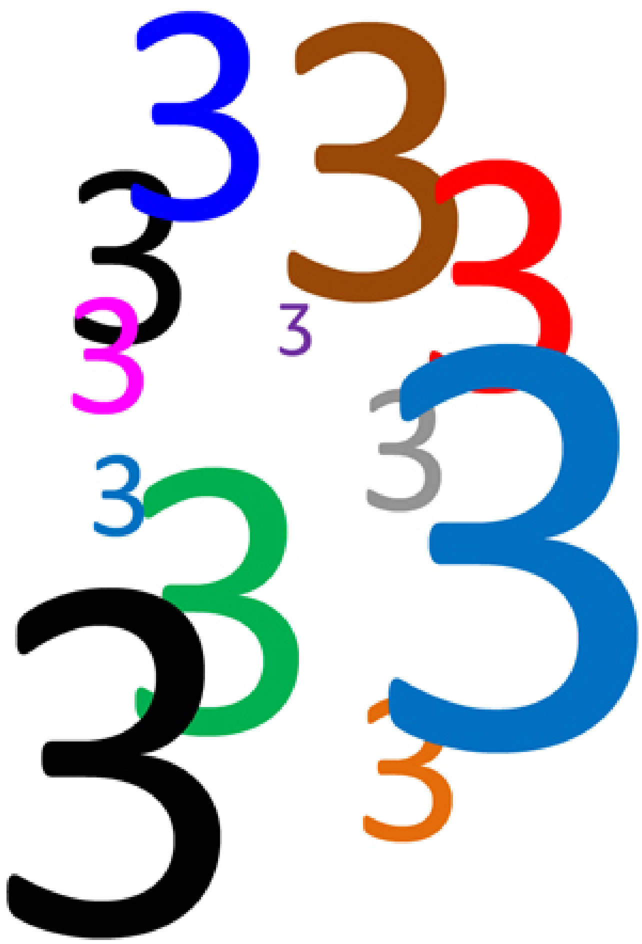
Physicists settle debate over how exotic quantum particles form

June 23 2017, by Carla Reiter



Here "3" symbolizes an Efimov molecule comprised of three atoms. While all "3"s look about the same, research from the Chin group observed a tiny "3" that is clearly different. Credit: Cheng Chin

New research by physicists at the University of Chicago settles a longstanding disagreement over the formation of exotic quantum particles known as Efimov molecules.

The findings, published last month in *Nature Physics*, address differences between how theorists say Efimov molecules should form and the way researchers say they did form in experiments. The study found that the simple picture scientists formulated based on almost 10 years of experimentation had it wrong—a result that has implications for understanding how the first complex molecules formed in the early universe and how complex materials came into being.

Efimov molecules are quantum objects formed by three particles that bind together when two particles are unable to do so. The same three particles can make molecules in an infinite range of sizes, depending on the strength of the interactions between them.

Experiments had shown the size of an Efimov molecule was roughly proportional to the size of the atoms that comprise it—a property physicists call universality.

"This hypothesis has been checked and rechecked multiple times in the past 10 years, and almost all the experiments suggested that this is indeed the case," said Cheng Chin, a professor of physics at UChicago, who leads the lab where the new findings were made. "But some theorists say the real world is more complicated than this simple formula. There should be some other factors that will break this universality."

The new findings come down somewhere between the previous experimental findings and predictions of theorists. They contradict both and do away with the idea of universality.

"I have to say that I am surprised," Chin said. "This was an experiment where I did not anticipate the result before we got the data."

The data came from extremely sensitive experiments done with cesium and lithium atoms using techniques devised by Jacob Johansen, previously a graduate student in Chin's lab who is now a postdoctoral fellow at Northwestern University. Krutik Patel, a graduate student at UChicago, and Brian DeSalvo, a postdoctoral researcher at UChicago, also contributed to the work.

"We wanted to be able to say once and for all that if we didn't see any dependence on these other properties, then there's really something seriously wrong with the theory," Johansen said. "If we did see dependence, then we're seeing the breakdown of this universality. It always feels good, as a scientist, to resolve these sorts of questions."

Developing new techniques

Efimov molecules are held together by quantum forces rather than by the chemical bonds that bind together familiar molecules such as H2O. The atoms are so weakly connected that the molecules can't exist under normal conditions. Heat in a room providing enough energy to shatter their bonds.

The Efimov molecule experiments were done at extremely low temperatures—50 billionths of a degree above absolute zero—and under the influence of a strong magnetic field, which is used to control the interaction of the atoms. When the field strength is in a particular, narrow range, the interaction between atoms intensifies and molecules form. By analyzing the precise conditions in which formation occurs, scientists can infer the size of the molecules.

But controlling the magnetic field precisely enough to make the measurements Johansen sought is extremely difficult. Even heat generated by the electric current used to create the field was enough to change that field, making it hard to reproduce in experiments. The field could fluctuate at a level of only one part in a million—a thousand times weaker than the Earth's magnetic field—and Johansen had to stabilize it and monitor how it changed over time.

The key was a technique he developed to probe the field using microwave electronics and the atoms themselves.

"I consider what Jacob did a tour de force," Chin said. "He can control the field with such high accuracy and perform very precise measurements on the size of these Efimov molecules and for the first time the data really confirm that there is a significant deviation of the universality."

The new findings have important implications for understanding the development of complexity in materials. Normal materials have diverse properties, which could not have arisen if their behavior at the quantum level was identical. The three-body Efimov system puts scientists right at the point at which universal behavior disappears.

"Any quantum system made with three or more particles is a very, very difficult problem," Chin said. "Only recently do we really have the capability to test the theory and understand the nature of such molecules. We are making progress toward understanding these small quantum clusters. This will be a building block for understanding more complex material."

More information: Jacob Johansen et al. Testing universality of Efimov physics across broad and narrow Feshbach resonances, *Nature Physics* (2017). DOI: 10.1038/nphys4130

Provided by University of Chicago