Laws of Attraction

There's exciting news in the field of Efimov physics!

In 1970, Russian theoretical physicist Vitaly Efimov predicted a strange form of matter called the Efimov state. In these strange states, three atoms can stick together in an infinite number of new quantum states, even though any two can't even form a molecule. For a long time, scientists were skeptical about Efimov's prediction. However, since the 1990s, Fellow Chris Greene's group (with J. P. Burke, JR. and Brett Esry) have expanded the theory of Efimov physics and predicted the experimental conditions under which Efimov states can be observed. In 2006, these strange states were observed experimentally for the first time.

Three-atom Efimov molecules (trimers) can form in Bose-Einstein condensates (BECs) or other ultracold gases. The Efimov trimers form because of a kind of memory “ghost” created through the attraction felt by the atoms only when they are stacked immediately on top of each other in an ultracold gas. This eerie attraction can lead to the formation of an endless sea of three bound quantum states, even when individual atoms are far apart.

Now, the Greene group has shown that dipolar Efimov trimers can also form in an ultracold system. Dipolar Efimov states are more peculiar than “ordinary” Efimov molecules. The strangest thing is that they exist at all. Theorists including senior research associate José D'Incao and Fellow Chris Greene once thought the Efimov effect would not occur with atoms and molecules in a strong electric field. However, the JILA researchers have just proved that they were mistaken.

Even though (1) the atoms in a dipolar Efimov trimer are normally very far apart and extremely weakly bound, and (2) an electric field exerts a pull on the dipolar trimers to align with the field, the Efimov effect persists in dipolar systems. In fact, in a dipole system, the stronger the electric field, the longer the Efimov molecules live! Dipolar Efimov molecules can survive long enough inside a dipolar gas that experimental physicists should be able to create and manipulate them in the laboratory.

This kind of survival is stunning when you consider that Efimov physics in an ultracold dipolar BEC is constrained by an electric field. However, the major constraint is not if the molecules can form. Rather, it is that Efimov trimers can only form inside a well-defined band of energy that looks a little like the hatband of a Mexican sombrero. Infinite numbers of similar molecules stack up inside this energy band.

Chalk one up for the laws of attraction — and the utter weirdness of the quantum world: “The quantum world we study looks crazy, but it's actually real,” says research associate Yujun Wang, who worked with D'Incao and Greene to probe the nature of the Efimov effect in an ultracold dipolar system. The researchers have predicted where in the system the Efimov states form. Once the molecules form, they are easy to see because they exhibit a clear mathematical signature. And, as soon as the first Efimov molecule appears in the system, the researchers are able to predict the energies of its sister molecules that form in limitless quantities in the same energy band. The researchers have also found a series of magic values for the electric field that led to the formation of an infinite number of Efimov states.

Not surprisingly, dipole interactions prevent the atoms in an Efimov trimer from getting too close together. And, if all the dipoles in a trimer do come close together, it is difficult to explain the physics of what happens. However, once the dipoles are far apart, the physics of their interactions becomes more universal and easier to describe mathematically. This discovery is a key insight for future ultracold molecule experiments because Efimov molecules can be destructive when they are unstable. Experimental physicists don't want unstable Efimov molecules knocking atoms out of an optical trap and destroying an ultracold system. Because Efimov molecules are more stable in an electric field, they'll also be much easier to study there.

Wang, D'Incao, and Greene hope that experimentalists will soon take up the challenge of studying Efimov states in ultracold gases in the presence of electric fields. In the meantime, though, the JILA theorists are now exploring the weird quantum states of ultracold dipolar fermions. Fermions cannot occupy the same quantum state, unlike the neighborly bosons, which happily form BECs at ultracold temperatures. So it isn't clear what will happen to dipolar fermions under conditions that would lead to the formation of Efimov molecules made of bosons. The Greene group hopes to find out soon.

Reference:
The IR-enhanced XUV pulses could knock an electron out of a helium atom. The researchers modified the electronic structure of helium with the IR pulses and demonstrated control over the phase and amplitude of the XUV laser pulses. This capability allows the researchers to manipulate the electronic structure of the helium atom, whether it is ionizing or preventing ionization. The researchers adjusted experimental conditions to ionize helium atoms or prevent ionization, depending on experimental conditions. The researchers modified the electronic structure of helium with the IR pulse that controls the amplitude of the XUV harmonics and the relative phase between the XUV and IR pulses. In doing so, they were able to create a quantum double-slit situation in which the researchers could control the probability of ionization by interfering two electron waves constructively or destructively. If the interference was constructive, the XUV pulses ionized helium atoms; if the interference was destructive, the XUV pulses sailed through the helium atom. The researchers said, “This is a novel way of doing experiments. New theory showed that electric fields strongly influence a helium electron. By adjusting the three colors of light (i.e., red IR photons and two higher-energy purple and blue XUV photons) influence a helium electron. By adjusting the three colors, Ranitovic and his colleagues showed that they can launch an electron wave in a helium atom along two different quantum pathways. The wave traveling the different quantum pathways has the same amplitude but opposite phases. It cancels itself out on the way out of the helium atom, thus controlling the probability that an electron will separate from its parent atom. This new technique has great promise. Ranitovic is now leading efforts to extend the novel coherent-control scheme to simple molecules such as hydrogen or H2. “Once we understand simple systems, we can apply our new technique to complex molecules and chemical reactions,” Ranitovic said.

Reference:
Conventional wisdom has asserted that to overstretch DNA, the molecule required nicks or free ends. But in a new experiment, JILA researchers found that when he tugged on this dsDNA at 65 pN, it still increased in length by 70% — even though it contained no nicks or free ends. The new experiment showed the smoking gun wasn’t conclusive in explaining whether dsDNA that lacks nicks or free ends, but still leaves the DNA free to twist around. To do this, Paik fastened the other end of the DNA via both its strands to the surface of a glass slide, a geometry that eliminated any free ends.

In a series of carefully constructed overstretching experiments, Paik found that when he tugged on this dsDNA at 65 pN, it still increased in length by 70% — even though it contained no nicks or free ends. The new experiment showed the smoking gun wasn’t conclusive in force-induced peeling. “Our data, in conjunction with prior work, suggest that there are two distinct structures produced by overstretching dsDNA,” says Perkins. “Since the two structures appear to have similar mechanical properties, they may lie at the root of this controversy.”

One structure is the peeled DNA seen by the Dutch group. The big question now is what is the other structure? It may be molten DNA. Double-stranded DNA with no nicks or free ends is not the only possible mechanism at play in DNA overstretching at 65 pN.

The mechanism for such DNA overstretching has been the subject of active debate for the last 15 years. In 2009, however, most biophysicists were certain that a pair of parallel ssDNA during overstretching. This mechanism would unwind into a straight ladderlike structure that is approximately 70% longer than the classic double-helix structure of dsDNA. "Since the two structures appear to have similar mechanical properties, they may lie at the root of this controversy." says Perkins. "This work represents the first steps in empirically determining the chemical composition of the protoplasmic disk where planets will form," Linsky says, "Being able to measure the amount of both CO and H2 is important in determining the composition and evolution of planetary atmospheres."

The COS instrument is allowing in-depth studies of young Sun-like stars like this one, which is encircled by a planet-forming disk of gas and dust.

Credit: NASA/JPL-Caltech

Linsky’s analysis of CO and H2 in the very young star systems indicates that protoplanetary disks are made of very fine material. For example, the ratio of CO to H2 in the inner part of these disks is approximately 1. This value represents a transition between the much lower value found in the interstellar medium and the higher value found in solar system comets, which formed from a similar disk 5 to 6 billion years ago.

In a third COS study, Linsky, France, and colleagues from UCSB analyzed UV emissions from solar-type stars, some younger than the Sun and some older. Their goal was to learn more about the far-UV emissions from the young Sun and how such emissions affect the young Earth’s atmosphere. Chemists and researchers focused on the COS instrument’s first-ever measurements of the far-UV continuum emission produced by magnetically heated gas in the outer layers of the stellar atmosphere. Before COS, this faint continuum emission could not be detected between the strong bright emission lines. The researchers found that the continuum emission from young, rapidly rotating stars was more intense than that from older, more slowly rotating stars like the Sun. However, the continuum emission from the young stars was similar to what is seen in regions of the Sun with strong magnetic fields.

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Paik and Perkins are now working to better understand what actually happens during overstretching. They want to see how temperature, acidity, and salt concentrations affect overstretching and thereby determine if overstretching DNA with an M-DNA structure is the only possible mechanism at play in DNA overstretching at 65 pN. Their goal is a deeper understanding of the science of DNA overstretching. This understanding will be invaluable for the development of new DNA as a standard for forces between 0.1 and 100 pN (see JILA Light & Matter, Winter 2008).

References:
D. Hern Paik and Thomas T. Perkins, Journal of the American Chemical Society 133, 2319–2321 (2011) [Cover article].
QUANTUM
CT SCANS

They see only their own shadows or the shadows of one another, which the fire throws on the opposite wall of the cave — Plato

The Lehnert group and collaborators from the National Institute of Standards and Technology (NIST) recently made what was essentially a CT scan of the quantum state of a microwave field. The researchers made 25 measurements at different angles of this quantum state as it was zigzagging. During the measurements, they were able to circumvent quantum uncertainties (in a process known as squeezing) to make virtually noiseless measurements of amplitude changes in their tiny microwave signals. Multiple precision measurements of the same quantum state yielded a full quantum picture of the microwave field.

“The what we did was a quantum version of the CT scan for light at microwave frequencies,” says Lehnert. “Since we can represent information as a state of a microwave field, this is a likely topic in the field of quantum information processing.” Lehnert adds that information as a state of a microwave field, this is a lively topic in the field of quantum information processing. “Since we can represent quantum precision is a full tomographic image of a single state of a microwave field.

With results like these, the collaboration is ready to explore what happens when they use four JPA to create two microwave squeezed states at the same time and then combine the squeezed states in a beam splitter. The researchers are already beginning to imagine the creation of millions of bits of entanglement every second. At this rate, the new quantum CT scan could soon seem like child’s play.

Reference:

The key ingredient in creating quantum entanglement as well as in measuring the quantum state of a microwave field is a Josephson parametric amplifier, or JPA. The best-ever design of such a device was created in 2008 by the JLA/NIST collaboration. This JPA not only functioned as a virtually noiseless amplifier (See JLA Light & Matter, Fall 2008) but also had ability to squeeze most of the quantum fluctuations (wiggles) out of one of the two directions of a coordinate system.

In their recent experiment, the researchers used one JPA as a preamplifier to improve the quantum efficiency of their measurement from 2 to 36% and the other to squeeze the microwave field. In the squeezed direction, the measured field change was as low as 46% of the amount of quantum fluctuation that normally occurs in a vacuum. In other words, this JPA works better in one direction than even Mother Nature does. The result of all this quantum precision is a full tomographic image of a single state of a microwave field.

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JILA MONSTR and the CHAMBER OF SECRETS

The semiconductor gallium arsenide (GaAs) is used to make tiny structures in electronic devices such as integrated circuits, light-emitting diodes, laser diodes, and solar cells that directly convert light into electrical energy. Because of GaAs’s importance to modern electronics, the Cundiff group seeks to understand the fundamental physics of its light-matter interactions on atomic and subatomic levels. Such an understanding requires the ability to “look” inside tiny boxes of GaAs (called quantum dots) with a series of laser pulses as the researchers probe the pattern of frequencies produced by the interaction of laser light with particles in the boxes. How does one create a two-dimensional “CT scan” inside these quantum “chambers of secrets” is a major challenge.

Fortunately, peering into quantum dots is the perfect job for the JILA MONSTR. The MONSTR is a precision optics instrument containing three cascaded and folded interferometers that split incoming laser pulses into four identical pulses. The sequence and spacing of three of the pulses can be controlled to probe the GaAs quantum dots. The process is akin to striking a bell with a hammer three times. The first strike makes the bell vibrate. The second creates an interference pattern in the original vibration, enhancing some frequencies and damping out others. The third interacts with the remaining frequencies and the resulting interference pattern contains information about the dynamics of the bell.

Similarly, the signals produced by interactions with a series of laser pulses reveal information about the dynamics of the strange world inside the GaAs quantum dots. When particles there interact with one or more pulses of laser light, they radiate light of different colors (frequencies). Researchers use a spectrometer and computer to convert these signals into multidimensional frequency spectra that make it easier for them to look for evidence of particle interactions.

Recently a team led by graduate student Galen Moody used the MONSTR to not only learn more about GaAs quantum dots, but also the interactions of particles inside the dots with the GaAs quantum well that surrounds them. The experimenters used quantum dots similar to the ones used in the Oreos® cookies! The cookies correspond to the sample holder, the filling corresponds to a two-dimensional quantum well, and the cream “islands” in the filling correspond to the zero-dimensional GaAs quantum dots inside both quantum dots and the quantum well. The laws of quantum mechanics determine behavior of particles inside.

Gaining a better understanding of how those laws affect the behavior of particles in the quantum dots was one goal of Moody’s experiment. Moody was assisted by former research associates Mark Siemens, Alan Bristow, Xingtan Dai, and Denis Karaiskija; researchers from the Naval Research Laboratory, and Fellow Steven Cundiff.

A series of three laser pulses from the JILA MONSTR interacts with tiny boxes (called quantum dots) of gallium arsenide semiconductor material. The combined signal that emerges from the boxes contains information about the quantum interactions of the particles inside the boxes.

Credit: Brad Baxley, JILA

The researchers studied excitons both inside the quantum dots and in the surrounding quantum well. An exciton is an atomic-like particle consisting of a free electron bound to the positively charged hole that an electron leaves behind when it exists in a semiconductor. The observed excitons were not as strongly held within the quantum dots as had been predicted. They existed in both bright and dark states and could switch back and forth.

If excitons formed inside a quantum dot, they tended to stay there rather than move into the quantum well. There appeared to be stronger interactions between excitons in quantum dots and the quantum well at lower temperatures. However, at higher temperatures, interactions between the excitons and the vibrations of GaAs crystal structure caused the excitons to actually move between the quantum dots and the quantum well.

The researchers studied the behavior of excitons in superpositions of their ground and excited energy states. Such superpositions appear only in the quantum world. They occur when one or more quantized particles (which exist as waves) completely overlap. Over time, the researchers observed that exciton superpositions in the GaAs quantum dots gradually decay back to their ground states. The decay rate was influenced by interactions between the excitons and vibrations in the GaAs crystal structure.

One interesting observation was that sometimes two excitons inside the same quantum dot would hook up to form molecule-like biexcitons. The formation of biexcitons was more likely to occur in smaller quantum dots because the strength of exciton-exciton interactions increases with decreasing quantum-dot size.

The information about GaAs quantum dots garnered by Moody and his colleagues caught the attention of the Physical Review B editors, who picked their journal about this topic as an “Editor’s Suggestion” in the March 23, 2011, issue.

References:
Gwen Dickinson for being awarded a JILA PRA Exemplary Contribution Award for her significant contribution to the JILA beautification project.

Chris Greene for being named a College Professor of Distinction by the University of Colorado at Boulder’s College of Arts & Sciences.

Jim McKown for being awarded a JILA PRA Exemplary Contribution Award for providing critical leadership in bringing the new JILIAC computer cluster to JILA.

Cindy Regal for being awarded an Office of Naval Research Young Investigator Grant of $170,000 a year for three years. Her proposal was entitled “Cavity Optomechanics for Wavelength Conversion of Optical Quantum States.”

Jun Ye for being elected as one of 72 new members of the National Academy of Sciences. Ye was recognized for his distinguished and ongoing achievements in original research.