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An important chemical in combustion known as ethynyl radical was identified for the first time in space in the Orion Nebula, shown here. Ethynyl radical is important in the production of large carbon-rich molecules that are present in interstellar clouds. Similar large molecules are produced during combustion and play a role in the formation of soot and ash.

Credit: NASA, ESA, M. Robberto (Space Telescope Science Institute/ESA) and the Hubble Space Telescope Orion Treasury Project Team

Chemistry of the Cosmos

Searching for Clues in Quantum Fingerprints

The Nesbitt group wants to figure out how chemistry works in outer space. In particular, the group wants to understand the "cosmo" chemistry leading to the generation of soot, which is similar to products of combustion here on Earth.

"Outer space is full of molecules," Nesbitt explains. "We want to discover how these molecules are formed out there." He adds that radio telescopes have gathered evidence of molecules made of long chains of carbon atoms. Some of these molecules are quite unusual and consist of dozens of six-carbon rings. Nesbitt wants to know how interstellar clouds end up with what are essentially pieces of tar in them. One clue has been the identification of ethynyl radical (C_2H) in the Orion Nebula (shown here) and several other interstellar gas clouds.

Ethynyl radical is a reactive chemical produced when acetylene (C_2H_2) burns. Almost as soon as a beaker of acetylene is lit, centimeter-long filaments made predominantly of carbon slowly rain down on the lab bench. What is amazing is that molecules containing two carbon atoms are producing a super molecule with a million billion carbon atoms in about a millionth of a second! The Nesbitt group thinks that ethynyl radical is key to understanding this transformation.

Once produced, ethynyl radical almost instantly reacts with other carbon-containing molecules to produce increasingly complex molecules, resulting in soot and ash. Since soot is also present in space, the challenge for the Nesbitt group is to understand both cosmo chemistry and combustion as well as explain their apparent similarities.

The Nesbitt group recently tackled this problem by investigating ethynyl radical with both a high-level theoretical analysis and high-resolution spectroscopy. In the experiment, former research associate Erin Sharp-Williams, graduate student Melanie Roberts, and Fellow David Nesbitt made ethynyl radical at high temperatures, then blew it out into a vacuum, where its temperature fell almost instantly from thousands of degrees Kelvin to about 10–15 K. Then, by carefully watching what happened, they were able to discern changes in the quantum states inside the ethynyl radical molecules. In this way, the group was able to obtain a more complete quantum fingerprint of this molecule than ever before — coming one step closer to understanding combustion and chemistry in the cosmos.

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Ultracold Polar Molecules to the Rescue!

Physicists would very much like to understand the physics underlying high-temperature superconductors. Such an understanding may lead to the design of room temperature superconductors for use in highly efficient and much lower-cost transmission networks for electricity. A technological breakthrough like this would drastically reduce world energy costs. However, this breakthrough requires a detailed understanding of the physics of high-temperature superconductivity.

There is already a theoretical model, called the t-J model, that contains the ingredients needed to explain the basic physics underlying high-temperature superconductors containing copper and oxygen atoms. Unfortunately, because this model includes strong interactions of many electrons, it's far too complex to solve with traditional analytical and computational methods. Without details from the model, it's impossible to determine the relationship of experimental observations to it. Unfortunately, theorists have been stymied in their efforts to improve their understanding of high-temperature superconductivity — until now.

A powerful collaboration between researchers at JILA, CalTech, and Harvard has come up with an elegant way to tackle the problem. Research associates Salvatore Manmana and Gang Chen and Fellows Ana Maria Rey and Jun Ye worked with Alexey Gorshkov of CalTech and Eugene Demler and Mikhail Lukin of Harvard to propose and develop a novel quantum simulator. The simulator uses a quantum gas of ultracold polar molecules of potassium-rubidium (KRb) created by Fellows Deborah Jin and Jun Ye. The ultracold molecules are polar because their electrons are unevenly distributed between the K and Rb atoms, creating an electrical asymmetry that makes them susceptible to electric fields.

The KRb molecules are located in an optical lattice, which forms the simulator. Optical lattices are crystals of light formed by interacting laser beams. They make it possible to exquisitely control the quantum motions of atoms or molecules inside the simulator.

The behavior of the ultracold molecules in the new simulator will likely model that of high-temperature superconductivity in copper-containing wires because the simulator uses external electric fields to ensure that the KRb molecules obey the same t-J model that electrons obey in high-temperature superconductors. Therefore, when the experimentalists probe the behavior of the ultracold polar molecule system, they should gain insights into the fundamental physics of high-temperature superconductors.

In a study of conditions in the new simulator, the theorists demonstrated that the experimentalists should be able to adjust conditions in the simulator to enhance superfluidity, which is similar to superconductivity in solid materials. They've also come up with some suggestions for studying quantum phase transitions in the simulator system, which is being explored by the Jin/Ye collaboration.

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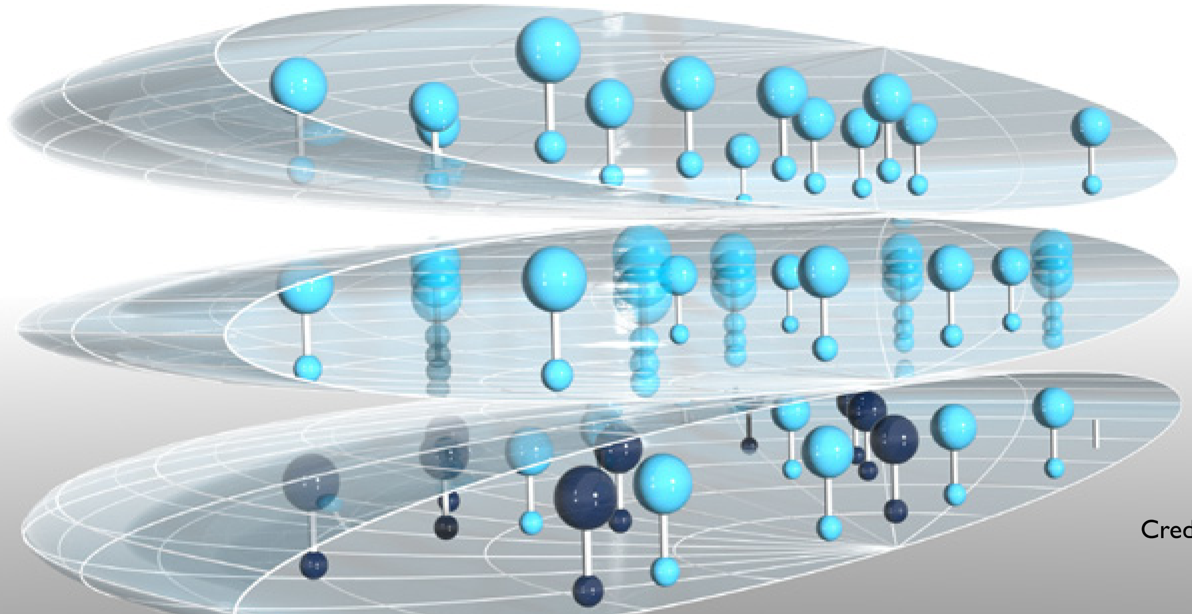


A quantum simulator made with ultracold KRb molecules will soon be shedding light on the physics underlying high-temperature superconductivity.

Credit: Brad Baxley, JILA

(Above) Ice on the Kongakut River, Arctic National Wildlife Refuge
Photo Credit: Wayne Phillips

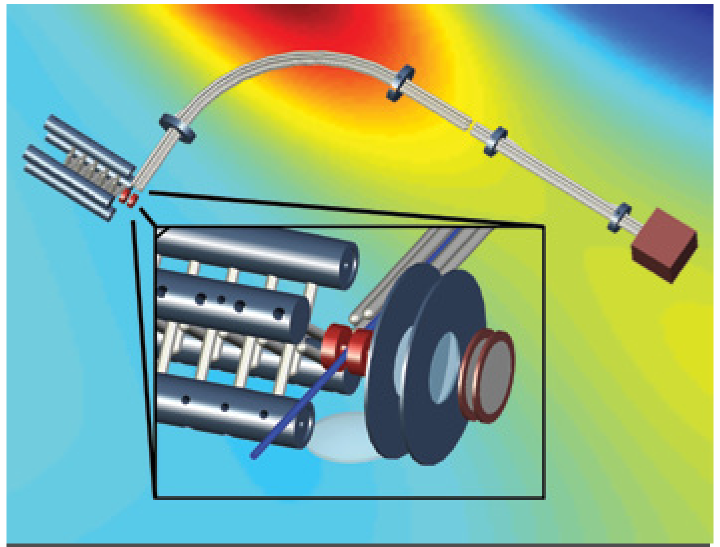
The Cold Case

The Ye group has built a cool new system for studying cold collisions between molecules. The system is far colder than a typical chemistry experiment that takes place at room temperature or hotter (300–500 K). But, it's also much warmer than experiments that investigate ultracold-molecule collisions conducted at hundreds of billionths of a degree above absolute zero (0 K). The new system is known as "the cold molecule experiment" and operates at temperatures of approximately 5 K (-450 °F).

Now most people would still consider this temperature unbelievably cold. But for physicists, collisions between polar molecules at temperatures near 5 K are not just unbelievably cold. They're also really interesting. That's because cold collisions occur in the crossover region between the classical world familiar to most people and the mysterious quantum world.

In this crossover region, the interactions of two molecules are simple enough to be modeled quantum mechanically, even though these interactions are far more complex than those between ultracold molecules at much lower temperatures. The new quantum mechanical description of cold collisions was provided by the Ye group's theorist colleagues from Harvard and the University of Maryland. This work helped the experimentalists investigate the crossover region, where everything moves slowly enough to reveal new details about molecule collisions. The group's investigations were made possible by the experimental setup shown in the figure.

This setup was designed by former graduate student Brian Sawyer, graduate students Ben Stuhl and Mark Yeo, research associates Matt Hummon and Yong Xia, Fellow Jun Ye, and colleagues from Harvard and the University of Maryland. The researchers used the apparatus shown in the inset to slow and trap a beam of hydroxyl molecules (OH) at a temperature of 70 mK. Then, they propelled a beam of ammonia made with heavy hydrogen atoms (ND_3) mixed with helium (at 5 K) through the bent tube above the trap. A set of electrically charged rods guided only the ND_3 around a bend and onto the trap holding the OH molecules.



The Ye group has combined three experimental techniques to create a new cold molecule experiment for studying molecule collisions at a temperature of approximately 5 K.

Credit: Brian Sawyer, JILA

Once the ND_3 was flowing over the trapped OH, the experimentalists studied cold collisions between them. Because both OH and ND_3 are dipolar molecules, they have an uneven internal distribution of electric charge resulting in one end being more positively charged, and the other end being more negatively charged. Cold dipoles exhibit interactions that are small compared to similar molecules at room temperature, infrequent, and, until now, hard to measure. However, with the new setup, the Ye group was able to observe these characteristically subtle effects and manipulate them by adjusting external electric fields. The researchers observed that external electric fields increased the number of collisions between the dipolar molecules that result in OH molecules disappearing from the trap.

Their theorist colleagues were able to explain that two different kinds of collisions were responsible for this loss. A few OH molecules were knocked out of the trap by "elastic" collisions. Such collisions occur when two dipoles fly past one another, and give each other a little kick. If the kick is hard enough, an OH molecule will fly right out of the trap. However, at temperatures of around 5 K, most elastic collisions aren't hard enough to do this.

A second kind of collision, known as an inelastic collision, is actually responsible for most of the disappearance of OH molecules from the trap. This purely quantum mechanical interaction changes the quantum state of an OH molecule. Once this state change happens, the molecule simply falls out of the trap, since the trap only works on molecules in specific quantum states.

Clearly, there's much more exciting physics to learn about the behavior of molecules inside the cold molecule experiment. That's a good thing, too, because the cold molecule experiment is ideally suited for studying many of the molecules found on Earth and in space.

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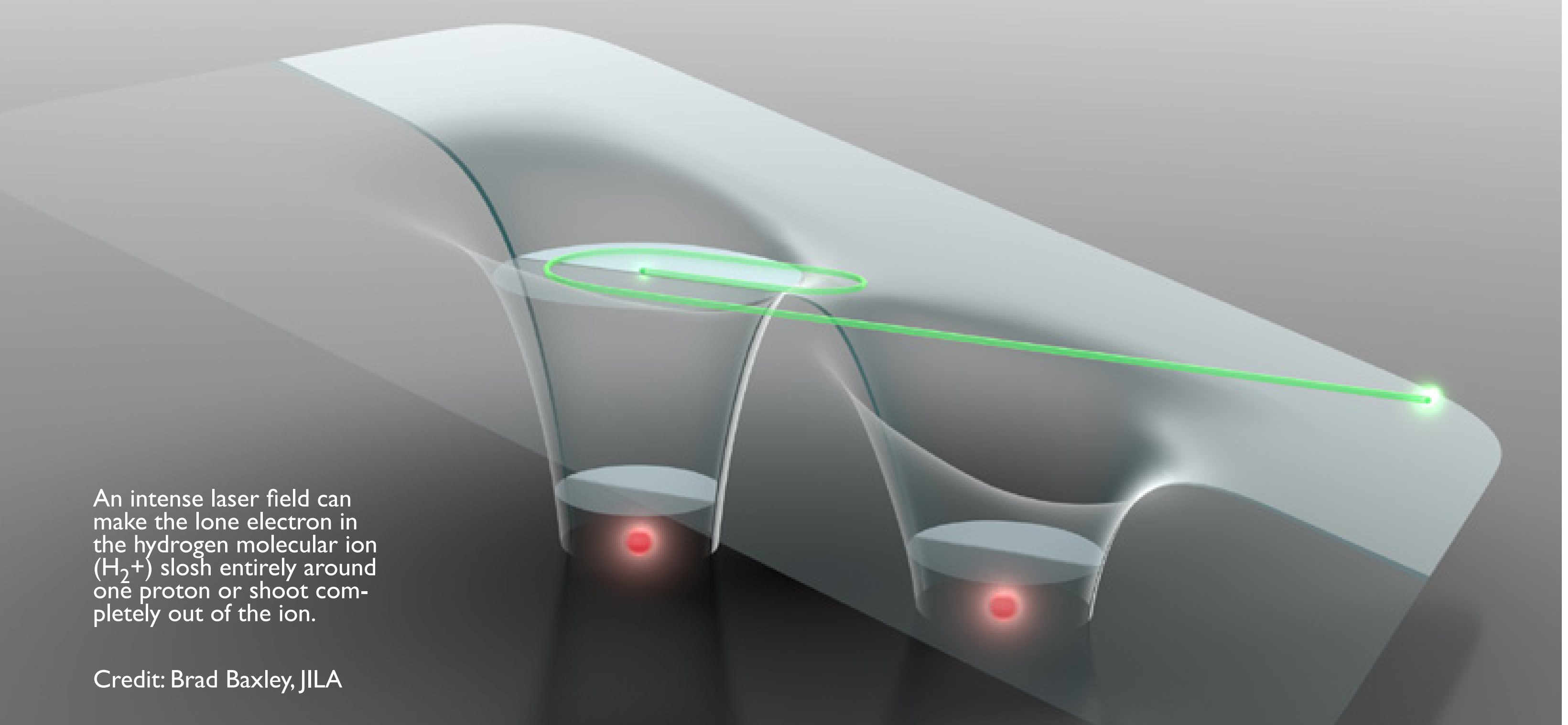


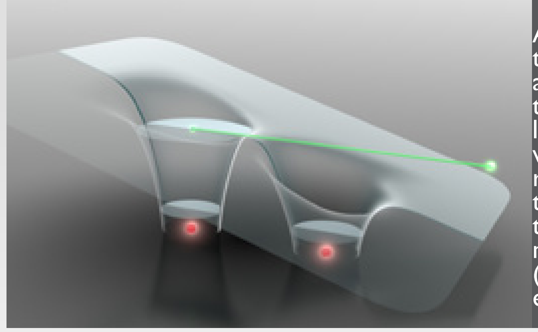
An intense laser field can make the lone electron in the hydrogen molecular ion (H_2^+) slosh entirely around one proton or shoot completely out of the ion.

Credit: Brad Baxley, JILA

QUANTUM BODY SWAPPING

"THERE'S SOMETHING HAPPENIN' HERE, WHAT IT IS AIN'T EXACTLY CLEAR"—BUFFALO SPRINGFILED

Theorists Norio Takemoto (now at the Weizmann Institute of Science) and Fellow Andreas Becker figured that something was amiss when they first analyzed the details of what occurs when an ultrafast laser dislodges an electron from a "simple" molecular ion, H_2^+. Since H_2^+ has already lost one of its electrons, its two protons only have one electron left to play with. How hard would it be to "see" what happened to this electron in a strong laser field? After all, a widely accepted theory said that a strong laser field would make it easier for the lone electron to escape when the ion was stretched apart (as opposed to contracted). Thus, the strength of the laser field was supposed to correspond to a high probability of the loss of the remaining electron in a process known as ionization.



Artist's conception of widely accepted theory that a strong laser field will allow the remaining electron to escape the hydrogen molecular ion (H_2^+) more easily.

Takemoto and Becker were just going to fill in a few details in this story. But, to their surprise, their analysis revealed multiple bursts of ionization during one half of the oscillation of the laser electric field, including one burst earlier than expected and another later than expected. The later of the extra bursts occurred when the lone electron temporarily (and somewhat randomly) surrounded one of the protons. This strange behavior appeared to be induced by the laser pulse itself.

When Becker and Takemoto were getting ready to send off an article to *Physical Review Letters* on the strange ionization behavior in H_2^+, Becker's friend Reinhard Dörner of Germany's J.W. Goethe-Universität contacted Becker, reporting that his experimental lab was studying the ionization of H_2^+, and "H_2^+ is doing something crazy."

"Yes, I know," Becker responded. He explained what their theoretical study had shown and agreed to enhance the new theory to take account of the particular experimental conditions in Dörner's lab. The goal was to further explain the strange quantum swapping of the lone electron between the ion's two protons. Because this quantum body swapping had been observed in both theory and experiment, the researchers were fairly sure it was real. It took Takemoto and Becker a year to complete their enhanced theoretical analysis that closely mirrored the German experiment, which had used a more complicated laser polarization than had been modeled earlier.

Becker, Dörner, Takemoto, and their colleagues reported their results in the September 30, 2011, issue of *Physical Review Letters*. They concluded that since the electron has wave-like properties, the laser field makes it behave like sloshing water. "There's always some probability that the whole wave breaks up and one part will first slosh around one proton while the other part shoots out of the ion," Becker explained. He added that the two protons sometimes also act like a double slit, with part of the electron wave swapping between the protons and then interfering with itself! This interference can cause a variety of strange behavior, depending on whether it is constructive (the wave segments add together) or destructive (the wave segments subtract and disappear).

Unraveling this strange behavior was so much fun that Becker's group is now working on designing a theoretical molecule with three or four protons to see what happens to a single electron inside this molecule when exposed to a strong laser field.

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A FLAIR FOR LASING

Triatomic hydrogen ion (H_3^+) has many talents. In interstellar clouds, it can be blown apart by low-energy free electrons, which interact with the ion core (H_3^+), briefly forming unstable H_3 molecules. The interaction of the electron with the ion core almost immediately causes the molecule to fall apart into three hydrogen atoms (3H) or a hydrogen molecule (H_2) and an H atom. This reaction is known as dissociative recombination (See JILA Light & Matter, Spring 2006).

Back on Earth, H_3^+ will collide with free electrons and helium or neon in the laboratory to eventually form the same products. However, the laboratory reaction occurs in a series of steps inside an ionized gas (plasma). The Earthbound pathway to dissociation includes excited H_3 molecules lasing at infrared (IR) wavelengths to lose enough energy for the molecule to fall apart. Despite differing mechanisms, H_3^+ dissociation on Earth and in outer space does have one thing in common: The Greene theory group at JILA has explained them both.

Recently, graduate student Jia Wang and Fellow Chris Greene worked with experimentalists at the University of California, Berkeley, (1) to explain what is lasing inside the plasma and why, and (2) to elucidate a complex dissociation pathway involving interactions of H_3^+ ions, free electrons, H_3 molecules, and helium atoms (He) inside a supersonically expanding plasma. In 2007, the experimentalists found the lasing spectrum in the lab and determined it could only be due to H_3 molecules. Greene, who was on sabbatical at Berkeley at the time, and Wang calculated more than 20 different lasing line frequencies for the H_3 molecule. Their theoretical frequencies corresponded reasonably well to the ones measured experimentally.

Since then, Greene and Wang have worked with the experimentalists at Berkeley to come up with an explanation of the behavior of the H_3 molecules in the lab experiment: The researchers found that H_3 molecules are created in collisions of H_3^+ ions with free electrons in the plasma. But, unlike H_3 molecules formed in space, these molecules don't immediately fall apart. When an H_3 molecule is formed inside a plasma in the laboratory, the captured electron can collide with a helium atom and gain angular momentum, which makes it harder for the electron to interact with the ion core.

Consequently, highly excited H_3 molecules inside the plasma will cascade through states of decreasing energy by spontaneously losing energy. The H_3 molecules eventually reach a quasi-stable state in which collisions with He no longer lower their energy, and they accumulate inside the plasma. Eventually, these H_3 molecules will lase at infrared frequencies. The lasing process transfers the H_3 molecules to a state in which their electrons are traveling slowly enough to interact with their ion cores. As soon as this interaction occurs, the molecule falls apart into either three H atoms or an H atom and an H_2 molecule.

The elucidation of the mechanism underlying the H_3 molecules' flair for lasing was a coup for both the JILA theorists and the Berkeley experimentalists. Their article on this key accomplishment was selected as a 2010 "Editor's Choice" by the *Journal of Chemical Physics*.

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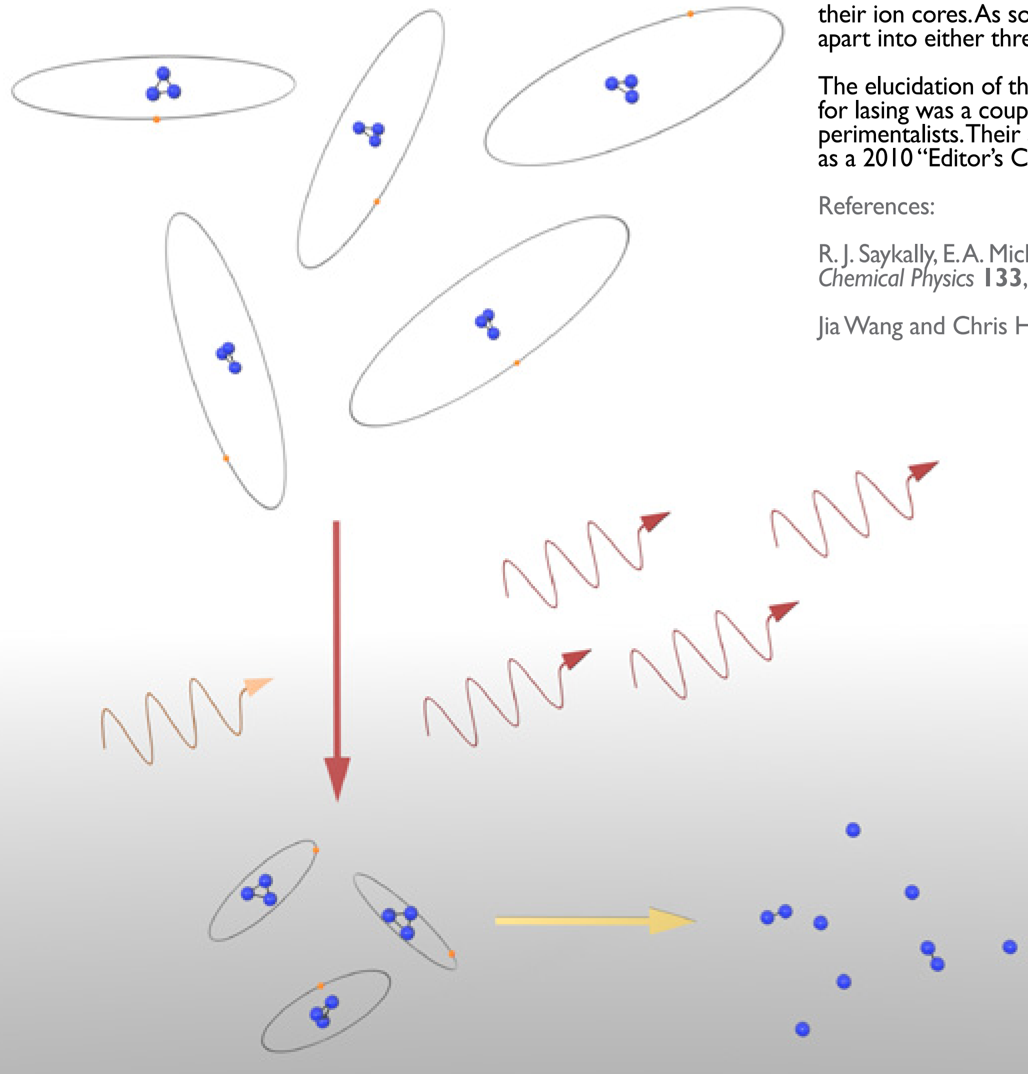
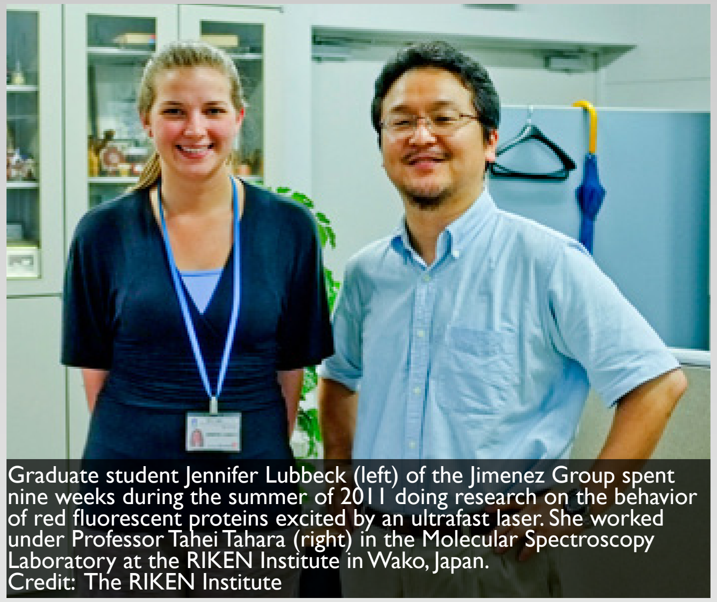


In laboratory experiments, excited H_3 molecules pile up until they lose energy by lasing at infrared wavelengths, creating H_3 molecules with lower energy. The electrons in these molecules are then able to interact with the H_3^+ ion core, which causes the molecule to fall apart.

Credit: Brad Baxley, JILA

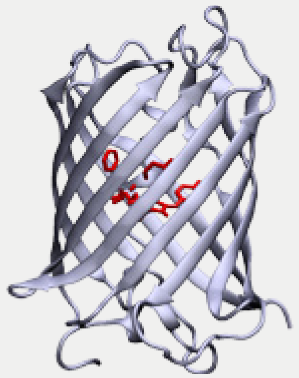
Cross-Cultural Spectroscopy



Graduate student Jennifer Lubbeck (left) of the Jimenez Group spent nine weeks during the summer of 2011 doing research on the behavior of red fluorescent proteins excited by an ultrafast laser. She worked under Professor Tahei Tahara (right) in the Molecular Spectroscopy Laboratory at the RIKEN Institute in Wako, Japan. Credit: The RIKEN Institute

Graduate student Jennifer Lubbeck (Jimenez Group) spent the summer of 2011 doing research in the Molecular Spectroscopy Laboratory at the RIKEN Institute in Wako, Japan (near Tokyo). Her host's group included 16 postdocs and four graduate students. The group was under the direction of Chief Scientist Tahei Tahara. However, Lubbeck actually worked directly with just five other young scientists under the supervision of Professor Kunihiko Ishi (Ishi-san).

"I was able to learn ultrafast techniques there that aren't in use here at JILA," Lubbeck says. "The experience helped me become a more well-rounded biophysics researcher."



Credit: Jimenez Group, JILA

Lubbeck's project was the study of the response of red fluorescent proteins to ultrafast laser light. Red fluorescent proteins are derived from sea anemones and coral. They have a barrel-shaped symmetric structure that surrounds and protects a color-producing entity (chromophore) that fluoresces red. Because developing a more stable red fluorescent protein is her thesis project, Lubbeck was able to overnight samples from the Jimenez lab to RIKEN for use in her summer project.

"At RIKEN, I primarily used spectroscopy to see which areas of the protein moved the most when the chromophore was excited by the laser," Lubbeck said. "I was especially interested in finding out if some red fluorescent proteins were more flexible than others, because increased flexibility of the part of the protein holding the chromophore could indicate a structural weakness." In the process of learning to make careful measurements of time-dependent protein spectra, Lubbeck was also able to introduce some biophysics techniques to her lab mates.

"It was a good exchange," Lubbeck reflects now on her 10-week summer program, which began with a week of orientation at the Sodenkai Institute in Hayama, Kanagawa prefecture. Her orientation included classes in Japanese language, musical instruments, and tea ceremony. At the end of orientation, she stayed with a local family, who introduced her to Karaoke and took her to see the sights of Kamakura.

Odori Park in Sapporo, Japan. Lubbeck's colleagues at RIKEN took her to a weeklong scientific conference in Sapporo, on the island of Hokkaido. The conference provided Lubbeck with a good survey of Japanese physical chemistry. Credit: Jennifer Lubbeck, JILA

After orientation, Lubbeck spent most of the next nine weeks working on her spectroscopy project at RIKEN. Her RIKEN colleagues did take her to a weeklong scientific conference (conducted in English) on the island of Hokkaido.

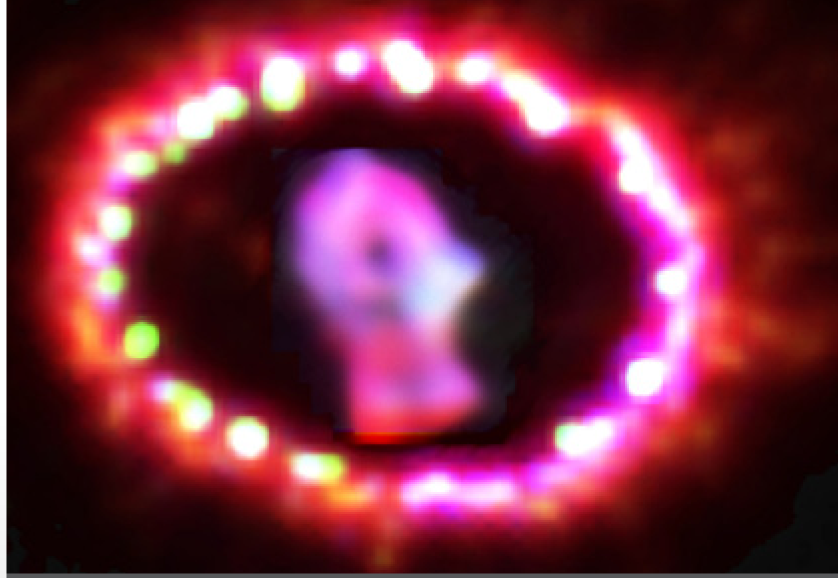
Back at RIKEN, Lubbeck was able to collect good data on her red fluorescent proteins by working really hard, typically from 10 a.m. to 11 p.m. She describes her regular work schedule as like "JILA on steroids." On days off and weekends, she took the opportunity to do some intense traveling in Japan.

Before leaving "early" at 6:00 p.m. one day to climb Mt. Fuji, for instance, she worked a "short" 10-hour day. After a two-hour bus ride, she got to the Mt. Fuji trailhead around 8:30 p.m. She hiked all night, arriving at the summit in time for the sunrise and amazing views. Then she hiked back down the mountain, caught the bus back to Wako, arriving at her apartment at noon. After sleeping until the next morning, she went back to work for a regular 15^{+} hour day.

"The experience was well worth it," she says now. "I had the opportunity to see a hierarchical lab structure and learn how Japanese scientists run a laboratory. For instance, my boss Ishi-san decided everyday which one of us would get laser time. The labs at JILA have a much flatter structure."

Back at JILA, Lubbeck is hard at work analyzing data from the summer research program. Her expenses for the program were paid by a grant from the U. S. National Science Foundation, with a contribution from the Japan Society for the Promotion of Science.

EVERYTHING IS ILLUMINATED



2011 Hubble Space Telescope image of Supernova 1987A showing a central debris cloud. Surrounding the cloud is an illuminated ring of gas shed by the original star 20,000 years before it exploded.

Credit: NASA, ESA, and P. Challis (Harvard-Smithsonian Center for Astrophysics)

Supernova 1987A is illuminating its own past. The brightest supernova to light up Earth's night skies since the Renaissance, it appeared in the southern sky on February 23, 1987 when a blue supergiant star exploded in the Large Magellanic Cloud, a galaxy located 160,000 light years from Earth. For nearly 25 years, Fellow Dick McCray and his colleagues have studied the unfolding story of this remarkable event in the visible, ultraviolet, and x-ray wavelengths. Today, the scientists not only understand the star's spectacular demise, but also are now learning about the blue supergiant's chemistry prior to going supernova.

For instance, there are four pieces of circumstantial evidence that the blue supergiant was undergoing a core merger of two stars when it blew up. First, the cylindrical symmetry of the explosion (illuminated in the center of a recent Hubble Space Telescope picture, shown here) suggests the presence of two stellar cores. Second, there are two outer rings beyond the one that is brightly illuminated in the picture. These rings strongly resemble the planetary nebulae surrounding binary star systems. Third, because a second star isn't anywhere to be found, it must have merged with the blue supergiant. Finally, blue supergiant stars typically don't go supernova. Ordinarily, huge red supergiant stars, which are as big as our solar system, are the stars that explode. However, the merger of two stellar cores would be capable of causing a relatively small blue supergiant star to explode.

The two-star merger theory also explains a key step in the evolution of the star that exploded. About 20,000 years before the supernova, a red supergiant star (formed when the two stars initially began to merge) shed a dense outer layer and became a smaller blue supergiant star. About ten years after the supernova, a ring composed of the ejected outer layer of the star began to light up. Hot spots developed when the supernova shockwave began to enter dense fingers of gas that protrude inward from the edge of the dense ring. These fingers had been formed prior to the supernova by the interaction of the ring with a high-speed stellar wind emanating from the blue supergiant star. This wind also sculpted out the cavity between the star and the ring, which is now completely encircled by hot spots.

Evidence supporting these theories about the evolution and explosion of the blue supergiant star has been available for some time. However, recent ultraviolet and x-ray images are adding new information about the blue supergiant star that exploded.

For instance, the newly refurbished Space Telescope Imaging Spectrograph (STIS) aboard the Hubble Space Telescope began sending ultraviolet (UV) spectra of the debris cloud and the circumstellar ring in 2010 after a hiatus of more than six years. In comparing two spectral emission lines produced by the main stellar ingredient hydrogen, the researchers discovered that one of them, called Lyman-alpha, is produced primarily in the ring's hot spots and scattered toward the observer by collisions with hydrogen atoms in the debris. The other, called H-alpha, comes from hydrogen atoms in the debris entering shocked gas near the rings.

A more sensitive instrument, the Cosmic Origins Spectrograph (COS), installed in 2009 on the Hubble Space Telescope was able to detect UV lines emitted by trace elements in the debris as the debris impacted the circumstellar ring. With COS, the scientists identified clear signals from carbon, nitrogen, and helium ions emitted by the debris.

When the scientists compared the ratio of nitrogen to hydrogen in the ring and in the supernova explosion debris, they found ten times more nitrogen and ten times less carbon in the debris cloud than in the ring. They had already determined that the ring itself had ten times more nitrogen than the interstellar space around it. The explanation for this finding lies in the chemistry of the supernova progenitors.

The nuclear furnace inside the original red supergiant star had already been converting carbon and oxygen to nitrogen when it shed the outer layer. This process accounts for the tenfold enrichment of nitrogen in the circumstellar ring. However, during the 20,000 years before the supernova, the nuclear furnace in the smaller blue supergiant continued to forge new nitrogen from carbon and oxygen. By the time the star exploded, its nitrogen content had increased tenfold and its carbon content had dropped tenfold.

Evidence of stellar chemistry has also been detected by NASA's Chandra X-Ray Observatory. After 25 years, the stellar explosion appears to have overtaken the ring, creating a reverse shock wave that is illuminating the supernova debris with x-rays. (Shock heating is also making the debris glow in visible light.) The x-rays are expected to reveal even more information about the star(s) whose merger led to Supernova 1987A.

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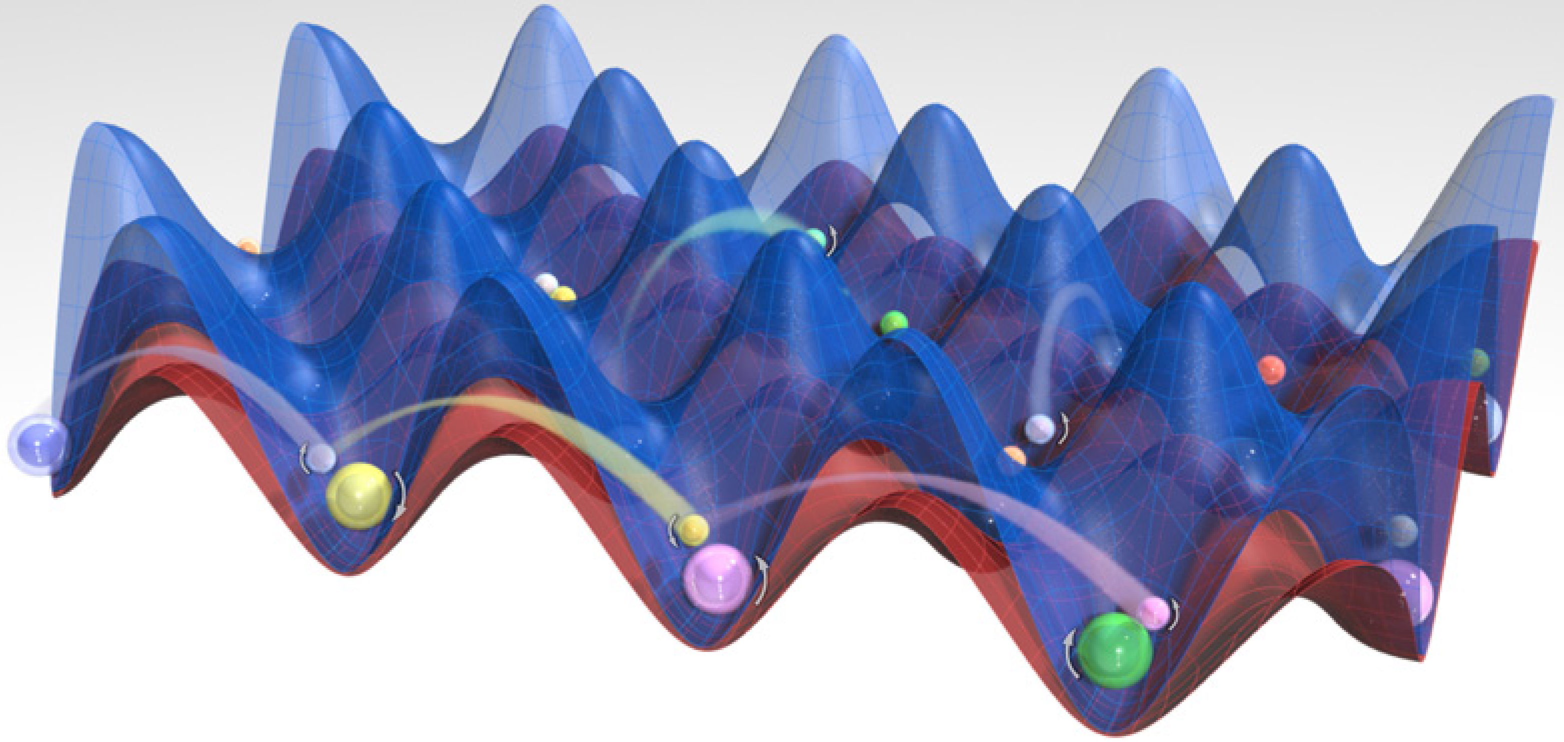

The Rey group recently combined two powerful tools for exploring ultracold gases: the optical lattice, shown here, and Feshbach resonances. The group has developed a model that sheds light on the fundamental physics of the new resonant lattices.

Credit: Brad Baxley, JILA

The Secret of the Resonant Lattice

Theoretical physicists recently combined two powerful tools for exploring ultracold atomic gases: optical lattices and Feshbach resonances. Optical lattices are crystals of light formed by interacting laser beams. Feshbach resonances in an ultracold atom gas occur at a particular magnetic field strength and cause ultracold atoms to form very large, loosely associated molecules. However, because lattice atoms interact strongly at a Feshbach resonance, the physics of Feshbach resonances in an optical lattice is quite complicated. Fortunately, a recent analysis of the behavior of two single atoms in a resonant lattice has led to a powerful new mathematical model capable of shedding light on the fundamental physics of the quantum behavior of these systems.

The creators of the new model included senior research associate Javier von Stecher, Fellow Ana Maria Rey, and their colleagues Victor Gurarie and Leo Radzihovsky from the University of Colorado. Von Stecher and his colleagues found that atoms in an optical lattice couldn't move at any speed they want to. Rather, the atoms were confined to hundreds of discrete energy bands. However, at ultracold temperatures, the atoms moved so slowly, they could only move in the lowest energy band. This restriction made it easier for the researchers to understand their behavior as they interacted with one another.

However, things changed at a Feshbach resonance, which made the atoms interact more strongly. Now the two atoms could collide and form a molecule. And, each of the atoms in the new molecule could end up in hundreds of different energy bands. Interestingly, von Stecher and his colleagues discovered that it was not necessary to describe the molecule as made up of two atoms in different energy bands. Rather, they looked at the molecule as if it were a new particle that could only move in its own energy bands. These molecular bands were different from those of the atoms.

There were as many molecular energy bands as atomic bands. But, there was a key difference: A molecular band would move in response to changes in the magnetic field. The atomic bands would not.

Tuning the magnetic field turned out to be the control knob for making things really interesting in a resonant lattice. As a molecule band moved in response to changes in the magnetic field, it inevitably ran into (touched) an atom band. When this happened, a new kind of lattice Feshbach resonance appeared. This resonance created a new, intriguing coupling mechanism for the two atoms that could take place as a molecule band interacted with an atom band.

During this interaction, the molecule band became distorted. Several things could then happen. If the molecule was not moving, it wouldn't even "see" or interact with the atoms it was passing by. However, if the molecule was moving (even just a little bit), it would "see" the atoms around it. This kind of molecule could break apart into atoms, remain as a molecule, or give rise to another new molecule. In fact, the real quantum state of the molecule under the influence of the Feshbach resonance was not any of these possibilities; rather it was a superposition of all of them at the same time.

The new Feshbach resonance is not only fascinating, but also has given von Stecher and his colleagues the key to creating a new and simpler model that will be capable of describing a more complicated system with many particles. Because the new model makes a complex system easier to understand, it will help researchers better understand the physics of very complex systems such as liquids and solids.

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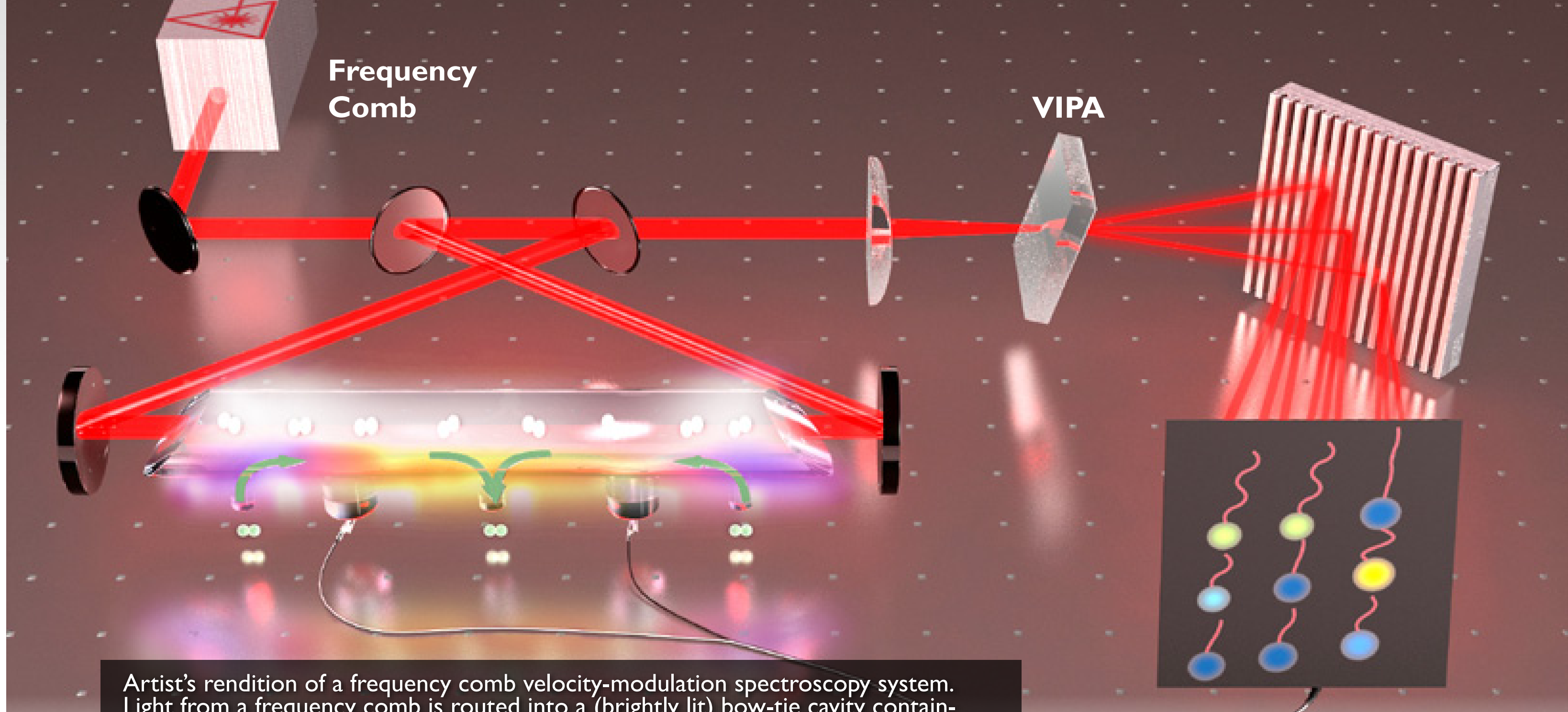


Artist's rendition of a frequency comb velocity-modulation spectroscopy system. Light from a frequency comb is routed into a (brightly lit) bow-tie cavity containing the ions under investigation plus an alternating-current discharge tube. The AC discharge modulates the signals from the ions, making it possible for the Cornell and Ye collaboration to determine the source and frequency of the signals.

Credit: Brad Baxley, JILA

PROBING THE TELL-TALE IONS

JILA's quest to determine whether the electron has an electric dipole moment (eEDM) began in 2006 with a suggestion by Fellow Eric Cornell that the molecular ion hafnium fluoride (HfF^+) might be well suited for an eEDM experiment. An electric dipole moment is a measure of the separation of positive and negative charges in a system. If an electron does have an electric dipole moment, it's a pretty darn small one. So small, in fact, that if the electron were the size of the Earth, its eEDM would only alter the planet's roundness by less than the width of a human hair. But, even a very small eEDM would have large implications for our understanding of fundamental physics. Consequently, the John Bohn group did a theoretical study of HfF^+ and found Cornell's intuition was right on the money. (See JILA Light & Matter, Fall 2006). The Cornell group soon began preparing to meet the challenge of detecting it in the laboratory.

Five years later, the Cornell and Ye groups are collaborating on an experiment to detect an eEDM — if it exists. The groups are investigating HfF^+ because the two atoms in this molecular ion are capable of creating a huge internal electric field in response to a much smaller field applied to it in the laboratory. A small electric field applied in the laboratory to an ensemble of trapped HfF^+ ions would precisely align all the internal electric fields of the ions, making it possible for researchers to test for an eEDM in an unpaired electron located near the Hf atom.

But, before the scientists can attempt to identify an eEDM signal, they must understand the electronic structure of HfF^+. That's the only way they can identify which tree in a whole forest of normal transitions in the ion is most suitable for observing the coveted eEDM signal.

Unfortunately, researchers have only recently become interested in HfF^+, and there is as yet little experimental data on its electronic structure. Even theoretical models have large uncertainties. This situation is about to change, however, thanks to graduate students Laura Sinclair and Kevin Cossel, undergraduate Tyler Coffey, and Fellows Jun Ye and Eric Cornell.

Sinclair and her colleagues recently invented an ultrahigh-sensitivity, high-resolution technique called frequency comb velocity-modulation spectroscopy that will make it possible to rapidly identify and characterize the electronic structure of HfF^+. In a nutshell, the new technique shakes up a mixture of HfF^+ ions and HfF molecules. Shaking modulates just the signals coming from the ions. The researchers then hone in on the modulated signals by looking for either increases or decreases in frequency. It's like pinpointing the location of an ambulance running with a siren by analyzing whether the sound you hear is getting louder and higher pitched (as it comes closer to you) or softer and lower pitched (as it moves away from you).

This powerful and efficient new technique allows the researchers to rapidly look for many signals at once. In only 30 minutes, the researchers can precisely identify many transition frequencies over a wide range by finding the relatively small frequency shifts set off by the shaking. Without the technique, it would take the researchers at least two weeks to painstakingly gather the same information. It's as if there were many ambulances scattered around a city and you wanted to find them all, you would have two choices: (1) you could go to every street corner and listen for the sirens, or (2) you could place microphones on the street corners and listen to all of them at once.

Sinclair, Cossel and their colleagues have invented a technique that essentially allows them to quickly see which "microphones" are picking up a signal and then scan those locations for multiple different transition frequencies. Their goal is to identify the electronic transition expected to be most conducive to revealing an eEDM during their upcoming experiment.

To finish laying the necessary groundwork for the experiment, Cossel is now leading the team working on characterizing HfF^+. But, just to be sure he and his colleagues have the best possible chance for success, they are also using frequency comb velocity-modulation spectroscopy to probe the electronic transitions of radioactive thorium fluoride (ThF^+), which may be an even better candidate for an eEDM experiment. ThF^+ lasts longer before decaying than HfF^+. It is also predicted to be approximately three times more sensitive to the presence of an eEDM than HfF^+. Now that the researchers have such a powerful tool for probing the electronic structure of a molecular ion, they'll soon be able to determine whether ThF^+ or HfF^+ stands the best chance of producing a measurable signal from an eEDM.

Reference:

Laura C. Sinclair, Kevin C. Cossel, Tyler Coffey, Jun Ye, and Eric A. Cornell, *Physical Review Letters* **107**, 093002 (2011).

This image, from a NASA-led research effort, is an example of the terrestrial planet formation modeled by Fellow Phil Armitage and his colleagues. Rocky planets are forming between the star and a giant gas planet (lower left). Their ultimate fate will be determined by the behavior of the system's outer gas planets, which formed earlier and farther away from the star. Insets show two types of terrestrial planets, a water world like Earth and a carbon-rich planet, with a smoggy, methane-rich atmosphere.

Credit: NASA/FUSE/Lynette Cook

SCULPTING A STAR SYSTEM: THE INNER PLANETS

The Solar System has a remarkable number of planets. It includes four rocky planets (Mercury, Venus, Earth, and Mars), four giant gaseous planets, and countless smaller worlds. Early on, there may even have been a fifth rocky planet that collided with the Earth, forming the Moon. We owe the survival of so many terrestrial planets (and our own evolution as a species) to the relatively stable orbits of Jupiter, Saturn, Uranus, and Neptune during the 100 million years it took to form the inner planets of the Solar System.

Most extrasolar planetary systems may not have been so fortunate. They show signs of being survivors of violent instabilities that knocked at least one giant planet completely out of the system. The worst instabilities would have resulted in the destruction of all the system's rocky planets. Some "milder" instabilities left a single rocky planet intact, but badly shaken up. The survival of two or more rocky planets like those in our Solar System requires a stable set of giant gas and ice planets. And, theoretical calculations suggest that such stability may be relatively uncommon.

Only 15–25% of planetary systems around Sun-like stars end up with three or four terrestrial planets, according to a recent simulation by Fellow Phil Armitage and his colleagues at the Université de Bordeaux, Princeton University, Cambridge University, Weber State University, NASA Goddard Space Flight Center, and Boston University. These planetary systems had calm environments conducive to the formation and preservation of terrestrial planets. Most also still have large disks of dust and other debris in orbits beyond those of the system's giant planets. These large debris disks mirror the favorable conditions for inner planet formation so well that Armitage and his colleagues say that bright cold dust emission around Sun-like stars could well serve as signposts of terrestrial planet formation.

A notable exception is our own Solar System. The Solar System's outer region has a relatively meager collection of dust, rocks and planetismals (rocky bodies a few kilometers or more in diameter) known as the Kuiper belt. The Kuiper belt's relatively small size tells us something important about the Solar System's unique history, Armitage says. About 700 million years after the birth of the Solar System, Uranus and Neptune moved far enough away from Jupiter and Saturn to interact with the then much-larger Kuiper belt. This interaction brought Uranus and Neptune into their present orbits. It also destabilized countless planetismals, hurtling many into outer space and others straight into the heart of the Solar System. This bombardment was responsible for some of the craters still visible today on the Moon. It must have inflicted even more damage on the Earth and Mars, and on the moons of the giant planets.

Despite the scars we see today, the bombardment came much too late to significantly affect the evolution of our Solar System's inner planets. Fortunately for us, they remained stable. However, there is evidence that the bombardment increased the amount of wobble in the orbits of both Earth and Venus. On Earth, lulls in the rain of impacting comets and asteroids may even have allowed any primitive life forms to survive.

Reference:

S. N. Raymond, P. J. Armitage, A. Moro-Martin, M. Booth, M. C. Wyatt, J. C. Armstrong, A. M. Mandell, F. Selsis, and A. A. West, *Astronomy & Astrophysics* **530**, A62 (2011).

PROFILE: DOUGLAS GOUGH

Douglas Gough

Credit: Institute of Theoretical Astronomy, Cambridge

Fellow Adjoint Douglas Gough and Fellow Juri Toomre have known one another since they were both graduate students in the Department of Applied Mathematics and Theoretical Physics (DAMTP) at the University of Cambridge (UK) in the mid-1960s. At that time, Toomre was studying fluid dynamics and Gough was exploring astrophysics.

Gough's first post doc (1966–1967) was at JILA with Fellows John Cox and Carl Hansen. With them, he developed a theory to explain the interaction of stellar convection with pulsation. At his next post doc (1967–1969) at the Goddard Institute for Space Studies in New York, Gough ran into Toomre again. This time, both worked in the same group on exploring how the theory of convection in fluids might apply to understanding the structure and dynamics of stars.

Two years later, Gough joined the Institute of Theoretical Astronomy in Cambridge as a member of the graduate staff. He spent a long and productive career at the institute and served as its director from 1999–2004 and as a professor in DAMTP. During his entire career, he has stayed in close contact with his close friend and collaborator Toomre.

Juri Toomre

Credit: Kristin Conrad, JILA

In 1972–1973, Gough came to JILA to work with Toomre, who had joined CU's Department of Astro-Geophysics and become a member of JILA in 1971. The two researchers collaborated on a simulation of how ocean (i.e., salt water) convection involves both heat and salt transport. Gough soon began exploring whether what they'd learned could be applied to studying convection in stars, which are composed mainly of hydrogen and helium. He hypothesized that the frequency of the Sun's oscillations could provide clues to its internal structure and motions.

In developing techniques to determine whether they were correct, Gough and Toomre consulted seismologists, who were already using sound waves to figure out the internal structure and motions of the Earth. By 1975, Gough realized that it was likely scientists would be able to deduce the internal structure of the Sun by studying its oscillations. Thus the brand new field of helioseismology was born in the same year Toomre became a JILA Fellow.

Gough continued to collaborate with Toomre during regular visits to JILA. The publication of a theory paper in the late 1970s led to an additional collaboration with Jack Harvey at Boulder's High Altitude Observatory. By 1984, the helioseismology field was exploding as observations of the Sun confirmed the basic tenets of the new theory. By then, Gough was focusing on the internal structure and basic physics of the Sun. For his part, Toomre was exploring the motions inside the Sun and a fundamental theory of convection. These were exciting times for the two researchers. In 1986, JILA formally recognized the long-term relationship between Gough and Toomre by making Gough an Adjoint Fellow of JILA.

"By the mid-1980s, I started thinking about applying helioseismology to other stars," Gough recalls. "And, I've dabbled in asteroseismology ever since." However, Gough says that things work slightly differently in different types of stars. The challenge is interpreting the oscillations of different stars correctly so that they reflect the correct internal structures.

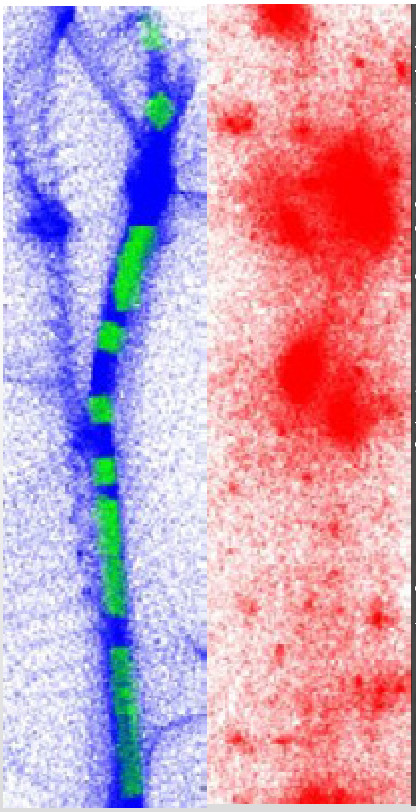
Gough continues his theoretical studies of asteroseismology even though he retired from the University of Cambridge in 2008. And, he is still coming to JILA every summer to collaborate with Toomre and his colleagues, whose recent simulations include other Sun-like stars at different points in their evolution. While Gough was here this past summer, he stopped by the JILA Light & Matter office to reflect on his long-term association with Toomre and JILA.

He told a delightful story of becoming a Mousquetaire d'Armagnac at a surprise induction ceremony at Chateau de Mons in France in 2001. (The Musketeers had reformed as a group early in the 20th Century after having been disbanded during the French Revolution.) Gough had intended to be at JILA at the time of the induction ceremony, but Toomre had told Gough not to come then because he (Toomre) might be at a conference (even though there wasn't one scheduled).

"I didn't know anything about the ceremony until I was handed a boarding pass, and my wife directed me to the chateau after we landed," he recalls. "When I saw Juri sitting there, I suddenly knew why he'd been so unfriendly about my travel plans."

Luckily, they got that all straightened out because Gough plans to be back at JILA for the 50th Anniversary celebration in mid-July 2012. "I wouldn't miss it!" he says.

HITCHHIKER'S GUIDE INTO THE GALAXY



(left) Superhighways consisting of filaments (blue) and with regions of uniform temperatures (green) route enough gas into nascent galaxies to make it possible for the galaxies to form stars. The blue filament shown here is about 720,000 light years long and runs through just a few major galaxies.

(right) Patterns of dark matter close to the same galaxies show no relationship to the transport of gas.

Credit: A. Gayler Harford, JILA

Long, long ago galaxies now far away formed around ravenous black holes scattered throughout the Universe. Some 12.5 billion years later, JILA scientist Gayler Harford and Fellow Andrew Hamilton have identified the superhighways that funneled gas into some of the nascent galaxies. These thruways not only routed gas to feed the monster black holes, but also supplied raw materials for the billions and billions of stars that have illuminated those galaxies ever since.

The cosmic gas-transporting superhighways were filaments of ordinary matter that extended outwards from primordial galaxies and often linked entire strings of galaxies, according to simulations performed by Nick Gnedin of Fermilab and analyzed by Harford. Under favorable conditions in the simulation, the filaments formed long cylinders of gas at uniform temperatures, typically 10,000 to 20,000 K. The simulations suggest that the properties of the gas entrained in the filaments are far more important in determining filament structure than any nearby dark matter.

Haloes of dark matter surround most galaxies. Scientists have long thought dark matter's role to be so critical to galaxy formation that the structure and behavior of nearby gas clouds could be ignored in models of galaxy formation. However, Harford's results suggest that the gas hitchhiking along the filaments into the core of galaxies may be more important than dark matter in determining whether an emerging galaxy can pull in enough gas to form stars.

Many of the galaxies analyzed by Harford do not have intergalactic filaments attached to them. Such galaxies may be unable to accumulate enough gas to form stars. Harford says that there may be a new class of galaxies in the Universe that have not been detected because they are not luminous.

There may even be some of these dark galaxies near our own Milky Way. The standard model of cosmology predicts many more satellite galaxy haloes around the Milky Way than the galaxies we see. According to Harford, the galaxies may well be there. We just can't see them.

Reference:

Gayler Harford and Andrew J. S. Hamilton, *Monthly Notices of the Royal Astronomical Society* **416**, 2678–2687 (2011).

Kudos to...

Debbie Jin and **Jun Ye** for being awarded a Department of Commerce Gold Medal for their seminal work on ultracold molecules and cold chemistry. The Gold Medal, which is the highest award presented by the Department of Commerce and NIST, will be presented to Jin and Ye at a Department of Commerce ceremony in December in Washington, D. C.

W. Carl Lineberger for being confirmed as a member of the National Science Board. As a board member, he will help establish the policies of the National Science Foundation and serve on an advisory board for the President and Congress on issues involving science and engineering. He was nominated for this position by President Barack Obama.

Cindy Regal for winning a David and Lucille Packard Fellowship for Science and Engineering. Regal will receive $875,000 over five years to support her pioneering work in experimental atomic physics.

JILA alum **Markus Greiner** (now at Harvard University) for being named a 2011 Fellow by the John D. and Catherine T. MacArthur Foundation. Greiner joins former JILA colleagues Deborah Jin and Margaret Murnane as winners of the prestigious MacArthur "genius grants."

Sarah Edwards for winning a JILA award for exemplary performance by a PRA. Edwards was cited for organizing several of the most complicated foreign trips taken by NIST scientists at JILA.

Loree Kaleth for winning a JILA award for exemplary performance by a PRA. Kaleth was cited for accomplishing demanding and time-consuming extra duties.

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