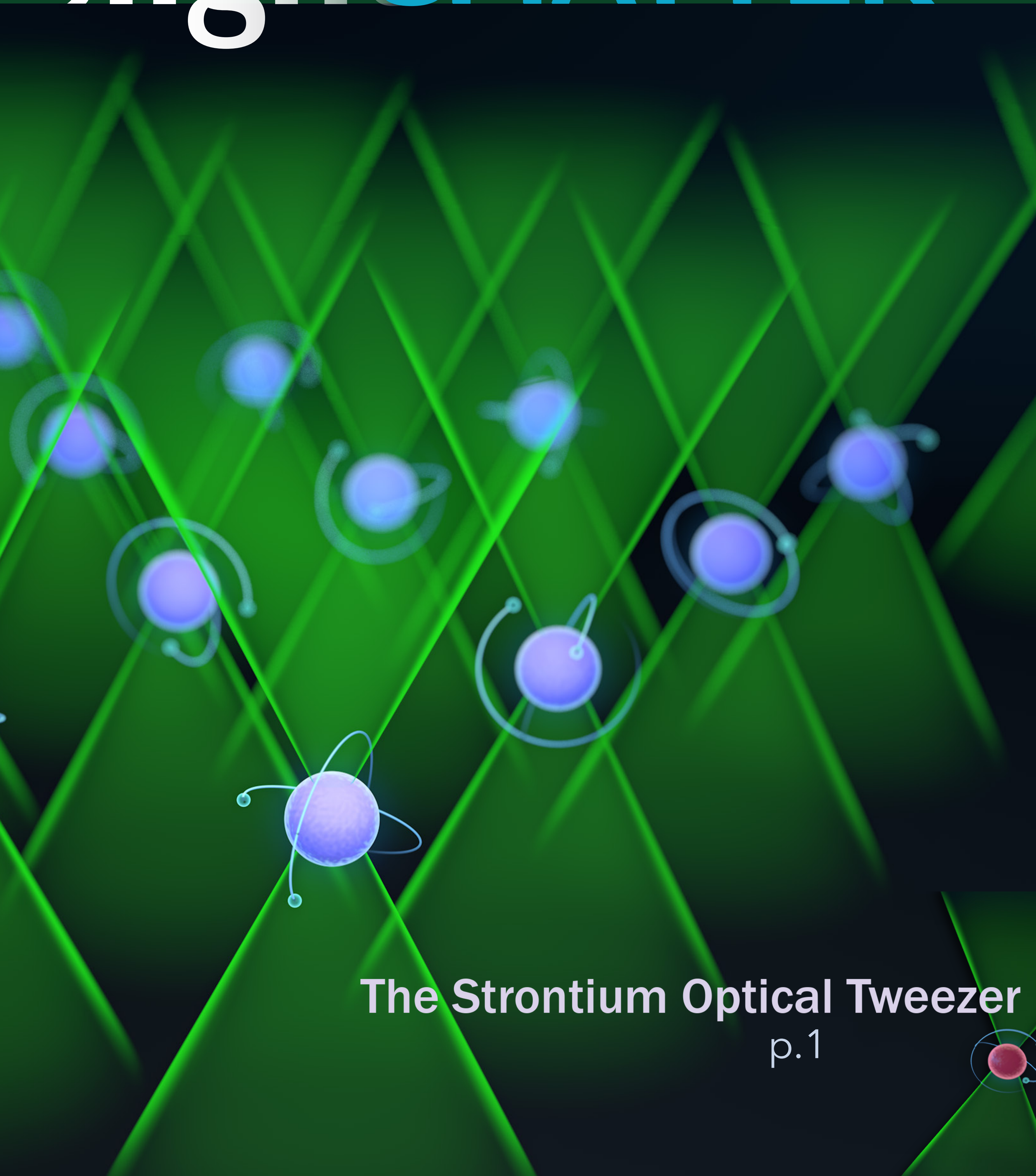
JILA light & MATTER
Winter/Spring 2019 | jila.colorado.edu



The Strontium Optical Tweezer
p.1

On February 20th, from 9am–2pm in the Reception Lobby, all JILAns had the chance to review the pet photos submitted by Fellows and Staff and then attempt to match the pet with the Fellow/Staff person they thought it belonged to. Congratulations to the WINNERS of the contest: Amy Allison (JILA Staff), Rebecca Hirsch (JILA Graduate Student), and Leah Dodson (JILA Postdoc).

JILA Light & Matter is published quarterly by the Science Communications Office at JILA, a joint institute of the University of Colorado Boulder and the National Institute of Standards and Technology.

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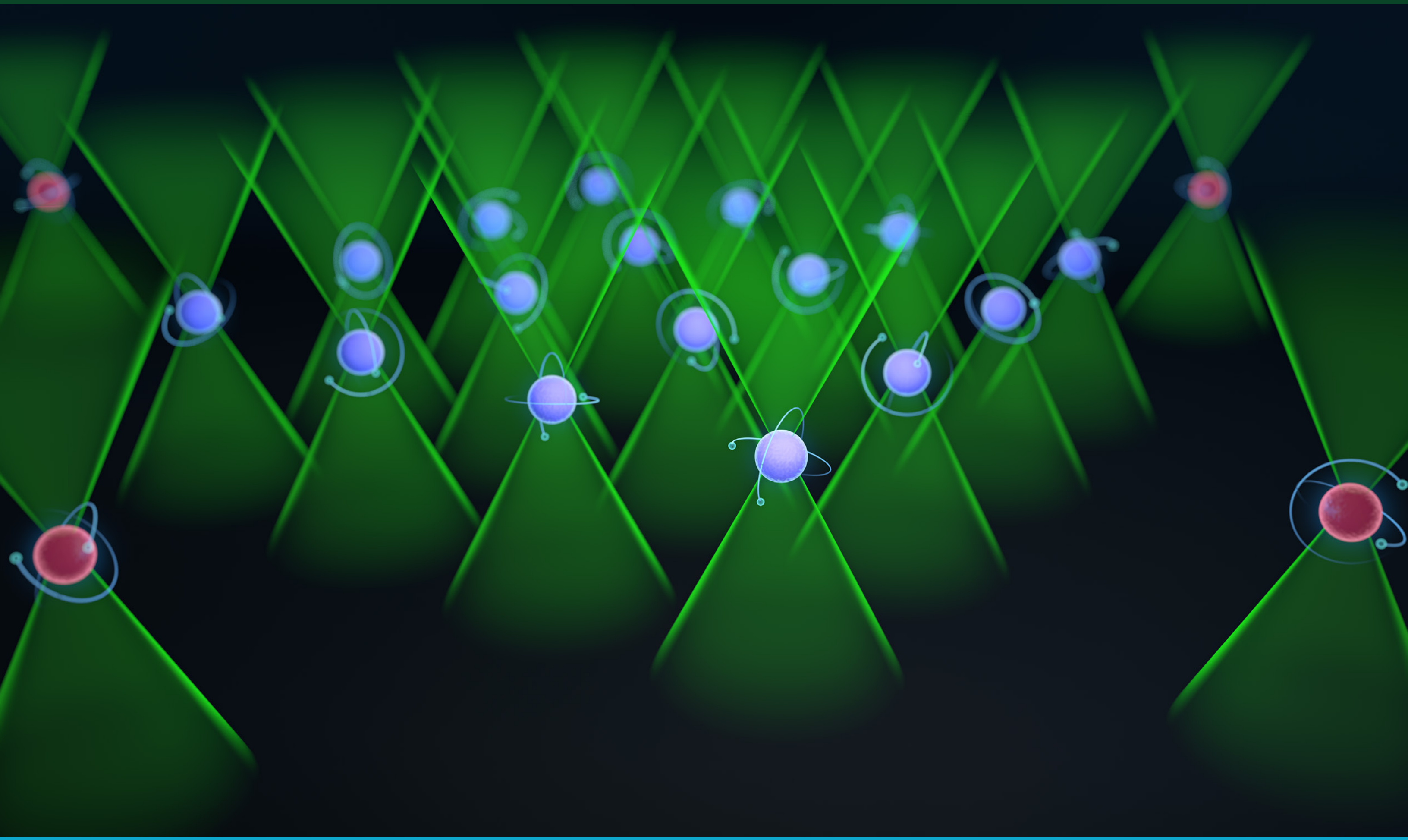


JILA researchers have, for the first time, trapped and cooled single alkaline-earth atoms. Alkaline-earth atoms are more difficult to cool than alkali atoms because of their dual outer electrons. For this experiment, researchers trapped single strontium atoms (red) in optical tweezers (green) before cooling the atoms to their quantum ground state (blue). Credit: Kaufman Group and Steven Burrows / JILA

The Strontium Optical Tweezer

As noted in their recent publication, JILA researchers have, for the first time, trapped a single alkaline-earth atom and cooled it to its ground state. To trap this atom, researchers used an optical tweezer, which is a laser focused to a pinpoint that can hold, move and manipulate atoms. The full motional and electronic control wielded by this tool enables microscopically precise studies of the limiting factors in many of today's forefront physics experiments, especially those in quantum information science and metrology.

Previous to this work, the only singly trapped atoms descended from the alkali family. Unlike alkaline-earth atoms which have dual outer electrons, alkalis are defined by their single outer electron, the simplicity of which makes their interactions with lasers easy to predict. Single-outer-electron atoms are therefore some of the easiest atoms to trap and cool.

But according to Aaron Young, a JILA graduate student working on this experiment, the dual outer electrons are what make alkaline-earths interesting.

"Having these two valence electrons means that there is more richness and complexity in the electronic states," said Young. "It means that there is a broader range of transitions."

Two Electrons—a Blessing and a Curse

Indeed, within the strontium structure there are a plethora of optical transition widths. This variety is key for conducting complex experiments where cooling, imaging, and precision spectroscopy are needed from the same atom. Strontium has been noted for its superb transition selection, which earned strontium its position in the world's most precise atomic clock.

This variety of transitions allows researchers to work around some of strontium's more difficult transitions. For example, unlike most alkalis, strontium's best imaging transition also causes significant heating. According to Young, the heating induced while imaging is enough to push an atom out of its trap. But untrapping can be avoided by toggling a cooling laser between blasts of the imaging laser.

"By chopping these two [lasers] together, you end up being able to keep your atoms cool but also collect a large signal [in your image]," said Young.

In the end, the researchers can cool and detect single strontium atoms with extremely high fidelity. This ability could prove crucial for studying many-body phenomena among complex, dual-electron atoms.

Adam Kaufman, JILA Associate Fellow and principal investigator of this experiment, credits much of this ability to a robust workaround that he calls "magic-trapping" conditions. In response to optical tweezers perturbing—or in other words, distorting—the strontium atoms to such a degree that they can no longer be trapped and cooled, the team developed an imperturbable strontium state by tuning the angle between the tweezer's electric field and the experiment's overall magnetic field. The technique proved to be especially effective, said Kaufman, and reduced the overall distortion to a part in a thousand.

Small Spaces, Big Possibilities

According to Kaufman, this optical tweezer can confine and image strontium atoms to within 480 nanometers—or less than one three-thousandths the size of a pinhead. This size is about 30% smaller than all other optical tweezers, which are currently limited by the trapping transitions of alkali atoms. And size does count here: smaller tweezers can more accurately move atoms in and out of small spaces, like optical lattice sites.

While some proposed experiments can be done with only tweezers (for instance, with the 4 x 4 grid of optical tweezers demonstrated in their latest paper), Kaufman says he sees this tweezer moving quickly towards aiding optical lattice experiments.

"That kind of capability—being able to rearrange atoms in a lattice potential—has never been done before. And the fact that our tweezer is so small is completely critical to, and enabling of, that," said Kaufman.

Given their ability to hold many atoms with stable trapping forces, optical lattices are the basis of some of the today's forefront experiments. And optical tweezers, which allow researchers to quickly trap, untrap and drag around single atoms, could improve upon these experiments.

"When you load into a lattice with 50 percent filling, the distribution is sort of random. But for these experiments involving tunneling, you really care about deterministically preparing a single configuration over and over again. That's the part the tweezers are really good for," explained Young.

This rearrangement technique could allow strontium atoms to test a well-known quantum computation problem called "Boson sampling." The experiment, first proposed for photons, demonstrates the power of quantum computation by creating a configuration that a quantum computer can easily solve, but a classical computer cannot.

"One of the perks of the bosonic isotope of strontium is that you are able to get very clean tunneling and interference. And so, what we have just described—preparing some configuration of strontium atoms and then letting them tunnel around—maps directly onto this boson sampling problem," said Young.

The team currently traps the bosonic isotope of strontium. But in the future, they want to also trap the fermionic isotope, which has a large nuclear spin degree of freedom. Controlling nuclear degrees of freedom, in addition to the electronic and motional degrees of freedom, would allow the creation of spin-orbital exchange gates, which are a vital step in developing a neutral atom quantum computer.

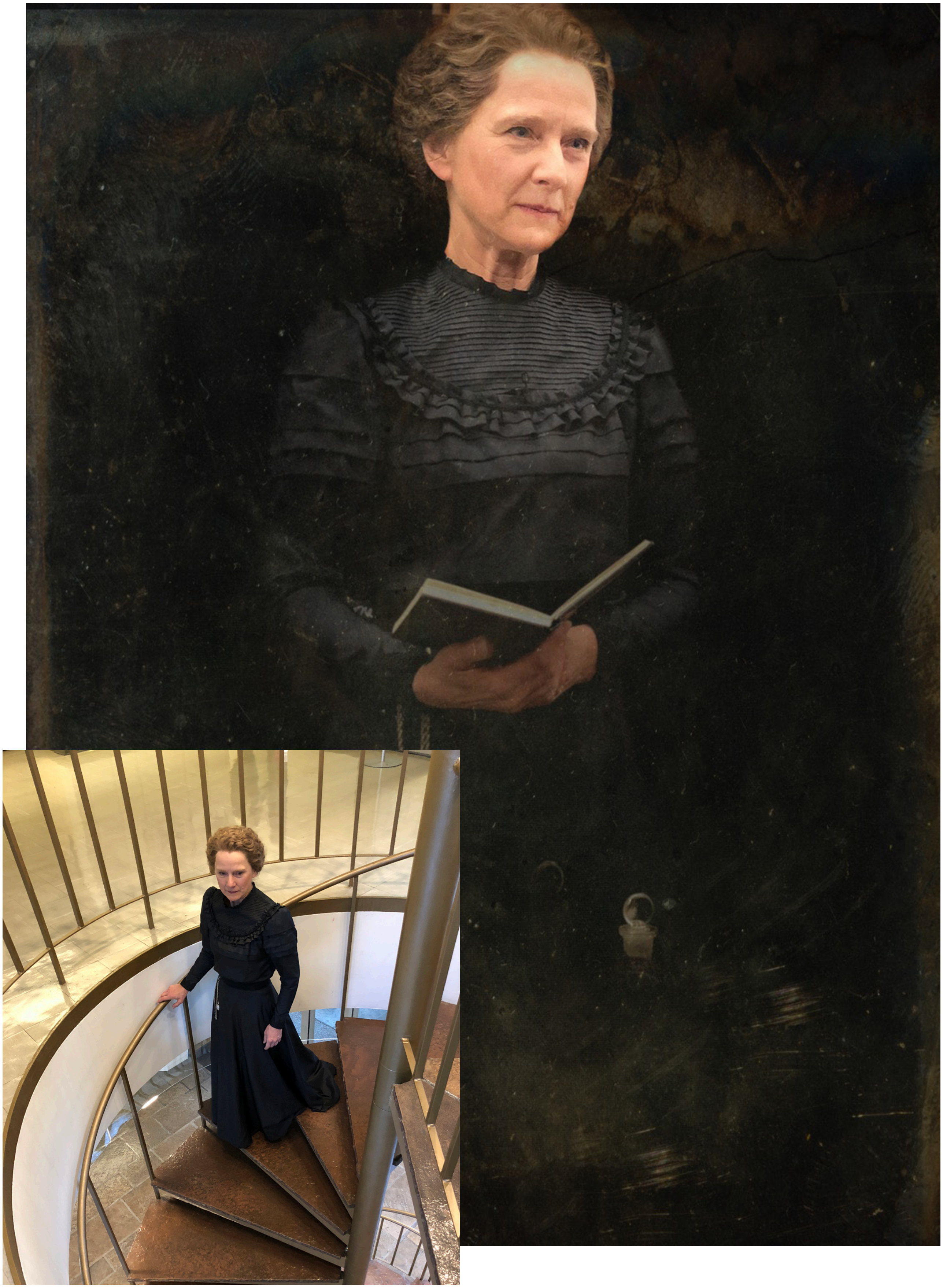
"You can use collisions between atoms in different electronic and nuclear states to entangle the atoms, and then separate them so that the entanglement can be propagated in space," explained Young, "which is exactly what you want for a quantum computer."✺

M. A. Norcia, A. W. Young, and A. M. Kaufman, *Physical Review X* **8**, 041054 (2018).

Women of JILA Event

Right: Actor and storyteller Susan Marie Frontczak portrays Nobel Prize-winning scientist Marie Curie. The performance, held at JILA on November 7, 2018 and open to all, was the first event held by the Women of JILA group. Photo credit: Cynthia Torres, JILA.

The Women of JILA work collaboratively to provide opportunities for all JILAns to gain tools, strategies and knowledge to enhance their current and future professional careers and achievements. They also aim to candidly explore issues related to gender in a proactive manner; in other words, with real-world advice and insight focused on successfully dealing with realities. The Women of JILA also make recommendations related to physical facilities. All JILAns interested are welcome to participate, including JILA Fellows, staff, students, postdocs and visitors.



Buckyballs Play by Quantum Rules

A Full Quantum Measurement of the Buckyball

A water molecule has three atoms—two hydrogens and one oxygen. But stack three water molecules side by side and you've got the width of a buckyball, a complex molecule of 60 carbon atoms. Medium in size and large in atom count, the buckyball has long challenged the idea that only small molecules can play by quantum rules.

We learned that the buckyball plays by full quantum rules when the Ye group measured its total quantum state. Specifically, this measurement resolved the rotational states of the buckyball, making it the largest and most complex molecule to be understood at this level.

Big Molecules, Big Results

The structure of the buckyball, or formally buckminsterfullerene, is elegant in its complexity. A round molecule of 60 carbon atoms, it mixes hexagons and pentagons like a soccer ball. According to Dr. Marissa Weichman, a JILA postdoc and co-author of the recent buckyball publication, this is the most symmetric shape a molecule can take.

Given its 60-atom count, the buckyball is large for the quantum world. But while sometimes difficult, large molecules are worth the effort to study, said Bryan Changala, JILA graduate student and lead author of the recent publication. According to Changala, understanding large molecules could potentially further our understanding of all complex systems.

"A lot of AMO (atomic, molecular, and optical) experiments are focused on creating, controlling, and manipulating quantum many-body systems in complex states," said Changala. "But a molecule is nature's own quantum many-body system."

The Ye group has been pursuing cooling large molecules and performing high-resolution spectroscopy for a number of years, starting when Changala was a first-year graduate student. The first demonstration was achieved in 2016 for molecules such as adamantine (26 atoms).

While the Ye group are not the first to attempt to study buckyballs with spectroscopy, they are the first to attempt to understand it at such a fine quantum level. "Previous structural measurements have been done with X-ray diffraction and electron diffraction," said Changala, "but these are either not done in the gas phase, or they are done warm," both of which directly limit the resolution.

Cold and Combed

To achieve high-resolution measurements, the Ye group both chilled and combed their buckyballs. The former quieted vibrations, and the latter parsed through fine quantum structure.

"Our frequency comb was the reason we were able to measure this and no one else had before," said Weichman.

The cavity-enhanced frequency comb, developed by the Ye lab, is a laser that is simultaneously narrow and broad. Like all frequency combs, this laser has a broad spectrum of precise frequency peaks that can quickly comb through molecular transitions. But it is the cavity enhancement of this particular laser that enables the necessary high sensitivity.

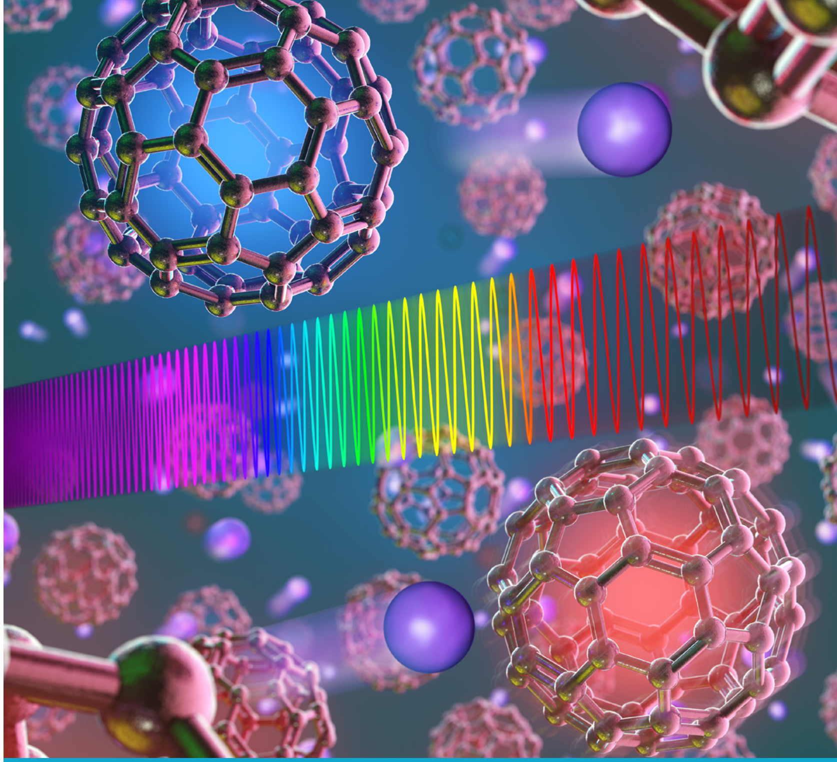
But while both of these factors—the cold gas state and the cavity-enhanced frequency comb—are necessary to probe the buckyballs at a high-resolution (rotational-state) level, they alone are not enough to tackle a molecule with so many atoms.

"In a normal molecule, there are can be hundreds to thousands of rotational states," said Weichman. "But bigger molecules mean denser rotational states." For a molecule with as many atoms as the buckyball, Weichman said there can be more than a million rotational states in the ground vibrational state alone.

From Grass to Trees

Even with the cavity-enhanced frequency comb, a million rotational states are too dense to resolve. Weichman likens the signal to an overgrown field of grass, where it is hard to differentiate a single blade from another.

"It's all moving towards a classical structure," said Weichman. "Where the individual states become so dense that they blur into a continuum."



The Ye group has successfully measured the total quantum state of buckyballs (buckminsterfullerene), a molecule comprised of 60 carbon atoms. This measurement marks buckyballs as the largest and most complex molecule to be understood at this level. Image Credit: Ye Group and Steven Burrows / JILA

But the buckyball is no ordinary large molecule. "It's perfectly symmetric," Weichman reminded, "and it is this symmetry of buckyballs that allows us to use small-molecule tools."

When the research team combed through the buckyball's spectroscopic signal, they saw not a grass field of fuzzy states, but clear, specific states, "like a forest of trees that were pruned in a very specific way" said Weichman.

And according to Weichman, this pruning is due to the buckyball having a perfect icosahedral structure. "The atoms are all exactly spaced. It's not approximate, it's exact."

Because of this exact spacing, the atoms are indistinguishable, much like how one hexagon corner on a perfect soccer ball looks just like any other hexagon corner. And when the atoms are indistinguishable, quantum statistics declares many rotation states are forbidden, thereby pruning the forest. In the end, only one for every 60 states remain, said Changala, or a little less than 2%.

In future experiments, the Ye group hopes to observe the spectrum of imperfect buckyballs, in which a single carbon-13 atom replaces a typical carbon-12 atom.

"The indistinguishability would completely disappear, because all of the atoms will now be distinguishable based on their distance and location relative to the impurity. So you would see the spectroscopy signal change from individual trees back to grass," said Weichman.✺

P. Bryan Changala, M. L. Weichman, K. F. Lee, M. E. Fermann and J. Ye, *Science* **363**, 49–54 (2019).

Taming Chemistry at the Quantum Level

In the vast stretches between solar systems, heat does not flow and sound does not exist. Action seems to stop, but only if you don't look long enough.

Violent and chaotic actions occur in the long stretches of outer space. These chemical reactions between radicals and ions are the same reactions underlying the burn of a flame and floating the ozone above our planet. But they're easy to miss in outer space because they're very rare.

"It's very low density in the interstellar medium, so the probability of seeing another atom or molecule is very low," said JILA Fellow Dr. Heather Lewandowski. "They could go for kilometers before seeing another particle."

And when meetings are that rare, the particles must be reactive. "If you do run into another particle, you want to have a high probability of reaction if you are ever going to react," said Lewandowski.

Radicals and ions are both very reactive. Their reaction enthusiasm stems from a lack of an electron. The ions involved are positively charged atoms missing an electron; the radicals are molecules with an unpaired electron, that is, an electron seeking an orbital mate.

Lewandowski, a molecular physicist at JILA and an Associate Professor of Physics at the University of Colorado Boulder, studies the reactions of ions and molecular radicals. In their latest publication, Lewandowski and her group demonstrate control of the reaction rate at the quantum level, bringing new insights into these elusive yet eager reactions.

Difficult Reactants

The complications of this experiment start with the reactants themselves. Even getting both reactants into an experiment can be a challenge. The radicals, for instance, are so reactive that most react with each other before the experiment begins.

"If you were to have a bottle of OH, the molecules would react with each other very rapidly, forming water and other things," Lewandowski explained, "so you would not have a bottle of OH for very long."

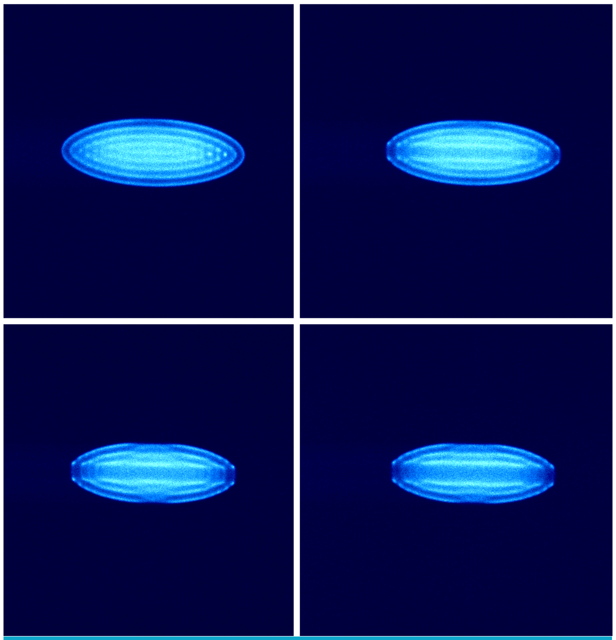
And while radicals are easily distracted, ions are pushy. "You can't get a high density of ions because they repel one another," explained Lewandowski, citing the Coulomb repulsion, or pushing away, that stems from electric charge.

The low densities that result from this repulsion lower the probability that ions and radicals will meet within an experiment. And for most experiments, which have only a thousandth of a second to operate, that can mean zero or few reactions.

Lewandowski's group overcomes this problem by squeezing calcium ions together using electromagnetic fields, and then cooling them with lasers to squeeze them even closer. By packing the ions closer together, the team increases the chance of radicals colliding with their ions.

"And when you get them cold enough, these ions form a crystal," said Lewandowski, meaning that the balance of pushing and squeezing forces the ions to pattern their positions. Once the ions are frozen into position, the team then has a million times longer than most other experiments to observe reactions.

But one can only learn so much by just observing reactions. Lewandowski knew she could learn even more by controlling them too.



Lewandowski and her team of researchers are using lasers to control chemical reactions at the quantum level. Specifically, they are electrodynamically trapping calcium ions and then cooling them with lasers until they form a Coulomb crystal, in which the ions evenly pattern themselves. The team can then use this laser to control whether the ions react with radicals. Above we see four images of various Coulomb crystals, where ions that have not yet reacted with radicals brightly glow. Credit: The Lewandowski Group and Steven Burrows / JILA

Quantum Control

Lewandowski's team uses lasers to not only command the ions' movements, but to command their reactivity as well. Specifically, they use lasers to control the ions' quantum states. While usually in the ground state, a laser can impart energy to the ions' electrons and put them into an excited state.

"When calcium ions are in the ground state, they don't have enough energy to react with the radicals," explained Lewandowski. "When we put them into the excited state, now they have all that energy from the excitation that can be used in the reaction."

Because the ions only react with radicals in the excited state, Lewandowski can control how fast the ions and radicals react. Ultimately, she can vary the reaction rate by a factor of four, and wholly turn off the reactions by simply turning off the laser.

This quantum control made it possible to extensively study the reaction of calcium ions and nitric oxide radicals down to the reaction pathways. This chemical precision affords new understanding in modeling future reactions. But ultimately, Lewandowski would like to apply the techniques of quantum control to more exciting reactions, like those including hydroxide (otherwise known as OH).

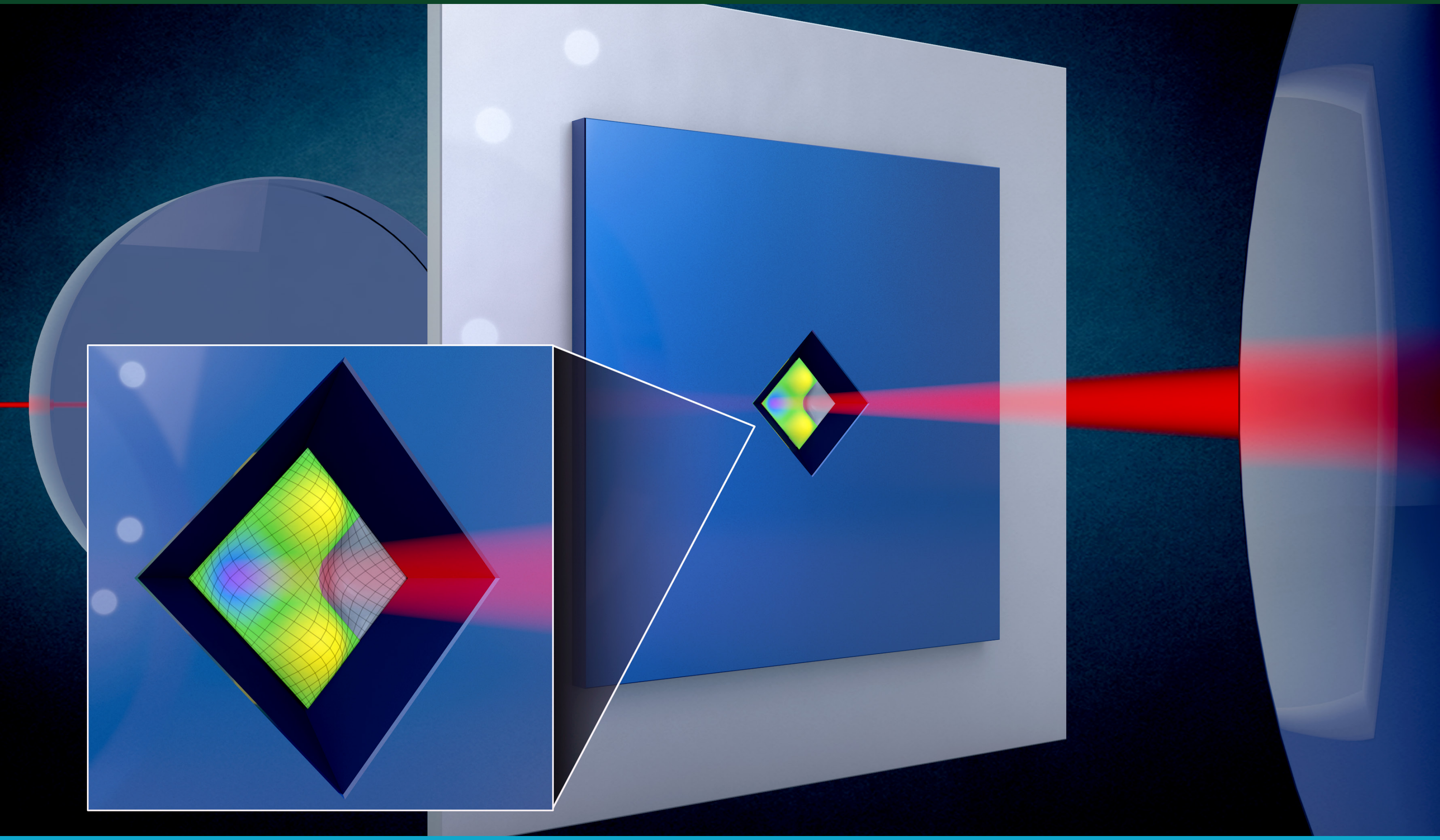
"OH is everybody's favorite radical, but you have to break apart other molecules inside your chamber to get the OH," said Lewandowski. Always a step ahead, she already has plans to make this experiment a reality.

Future Combinations

While developing quantum control over ions with lasers, Lewandowski was also developing techniques for quantum control of molecules. The latter experiment uses strong electric fields to control the speed and quantum states of molecular radicals.

In the near future, Lewandowski hopes to combine these two major experiments and obtain full quantum control of molecular radical and ion collisions. This development will allow researchers to determine how rotations and vibrations within molecules affect reactions, bringing a new level of precision to our understanding of chemical processes.

J. Greenberg, P. C. Schmid, M. Miller, J. F. Stanton, and H. J. Lewandowski, *Physical Review A* **98**, 032702 (2018).



Microwave signals are translated into optical signals (red) through a microscopic quantum drum (center). Recently, JILA researchers used strategic measurements of the microwave and optical signals to significantly reduced the added noise. Credit: Lehnert and Regal Labs, and Steven Burrows / JILA

Quiet Drumming: Reducing Noise for the Quantum Internet

Quantum computers are set to revolutionize society. With their expansive power and speed, quantum computers could reduce today's impossibly complex problems, like artificial intelligence and weather forecasts, to mere algorithms.

But as revolutionary as the quantum computer will be, its promises will be stifled without the right connections. Peter Burns, a JILA graduate student in the Lehnert/Regal lab, likens this stifling to a world without Wi-Fi.

Burns is part of a JILA research team hoping to jumpstart the "quantum internet," or the ability to network quantum computers. These networks would use the uniquely quantum property of entanglement to transfer inherently fragile quantum information between computers. Currently, the development of quantum networks is plagued by noise, but the JILA team recently implemented a new protocol which uses strategic measurements to reduce this impediment.

Fragile Information

Just as it is difficult to build a quantum computer, it's also difficult to build a quantum network. This difficultly arises from the inherent fragility of quantum information. Even the smallest interference from the outside world, like a warm touch or an observing glance, can collapse quantum properties.

This is why most quantum-computer prototypes are kept inside dilution refrigerators, which are the quantum equivalent of an isolation chamber. Sheltered from the outside world, and ultimately from each other, these computers cannot pass information, "unless you are going to make a really, really big dilution refrigerator," joked Burns. Instead, researchers are working to translate quantum information into a portable form.

While in a computer, quantum information is stored in microwave signals, which are easy to process, but terrible at traveling. To travel long distances, optical signals are the better carrier. JILA researchers therefore invented a quantum drum to translate quantum information between microwave and optical signals.

The Quantum Drum

Measuring only half a millimeter wide on either side, the drum is comparably sized to a grain of salt. The drumhead, however, is only a ten-thousandth of a millimeter (100 nanometers) thick, which is thinner than most bacteria and viruses. When the drum is excited by either optical or microwave frequencies, "it vibrates at a fundamental frequency," explained Burns.

This fundamental frequency is the common language the drum uses to translate optical and microwave signals. It does this with the help of "carrier tones", or additional microwave and optical frequencies which, when contrasted to the signal frequency, differ by the drum's vibrational frequency. Ultimately, the process is like that of a radio. "There's one frequency, or carrier tone, that you tune your radio to, and then the actual information [e.g., music or talk radio] is a frequency modulation [FM] on that," explained Burns.

The drum has successfully translated microwave signals into optical, and optical signals into microwave, with nearly 50% efficiency. But translating actual quantum signals is currently impeded by noise, said Burns.

Quieting Noise to Hear the Music

This noise presents itself as extra photons, which are erroneous packets of microwave and optical energies that wash out the signal photons. These extra photons are produced by the drum itself, as heat and other external energies whisper through the quantum translator. "The problem is, all those extra photons don't carry any of the information, so you lose your signal in the noise," said Burns.

Originally, the quantum drum produced nearly 100 extra photons for every translated signal photon. But soon the team discovered that extra photons emerged simultaneously in the optical and microwave signals, like a game of telephone where the malefactor not only throws in extra words, but whispers their misdoings back down the line. By measuring both the microwave and optical signals, the team could identify and remove 3 of every 5 extra photons, thereby significantly reducing the added noise.

While current drum prototypes produce around 10 to 40 extra photons, the ultimate goal is to reduce this number to less than one, said Burns.

A. P. Higginbotham, P. S. Burns, M. D. Urmey, R. W. Peterson, N. S. Kampel, B. M. Brubaker, G. Smith, K. W. Lehnert and C. A. Regal, *Nature Physics* **14** 1038–1042 (2018).

Turn it Up to 11—The XUV Comb

With the advent of the laser, the fuzzy bands glowing from atoms transformed into narrow lines of distinct color. These spectral lines became guiding beacons visible from the quantum frontier.

More than a half century later, we stand at the next frontier. The elegant physics that will decode today's mysteries (such as dark matter, dark energy, and the stability of our fundamental constants, to name a few) is still shrouded in shadows. But a new tool promises illumination.

Whereas the monochrome glow of the laser illumed the mysteries of the quantum frontier, today's frontier is lit by the frequency comb—a revolutionary laser source that emits not one, but over one-million distinct colors.

"Like the teeth of a comb that you could comb your hair with," is how Stephen Schoun, a postdoc in the Ye group, describes the comb's evenly spaced frequency (color) prongs. These prongs act like ticks on a ruler, allowing physicists to measure frequency distances and thus enabling the most precise measurements of atomic and molecular dynamics.

"The idea is to take this highly successful comb concept, which has been applied for years in the infrared and the visible, and now apply it to the extreme ultraviolet," said Schoun.

Extreme ultraviolet (XUV) is the region of the electromagnetic spectrum between ultraviolet (which travels just deep enough to burn skin) and X-rays (which travels past skin, imaging bones). With an XUV comb, we could potentially probe new atomic structures and observe wobbles in the fine structure constant (the strength of the electromagnetic attraction holding atoms, and therefore most other things, together). But when transformed into a comb, XUV lacks power.

"It was a major setback for spectroscopy that the power was very low," said Gil Porat, another Ye group postdoc on the team. "You need enough power to be able to observe the results of spectroscopy precisely."

Unfortunately, increasing power was not as simple as adding an amplifier. The real problem was pollution—plasma pollution, to be exact.

To generate XUV light, the group must blast Xenon atoms with infrared (IR) light, which lobs away the atoms' electrons. When the electrons eventually smash back into their parent ion, an XUV photon emerges.

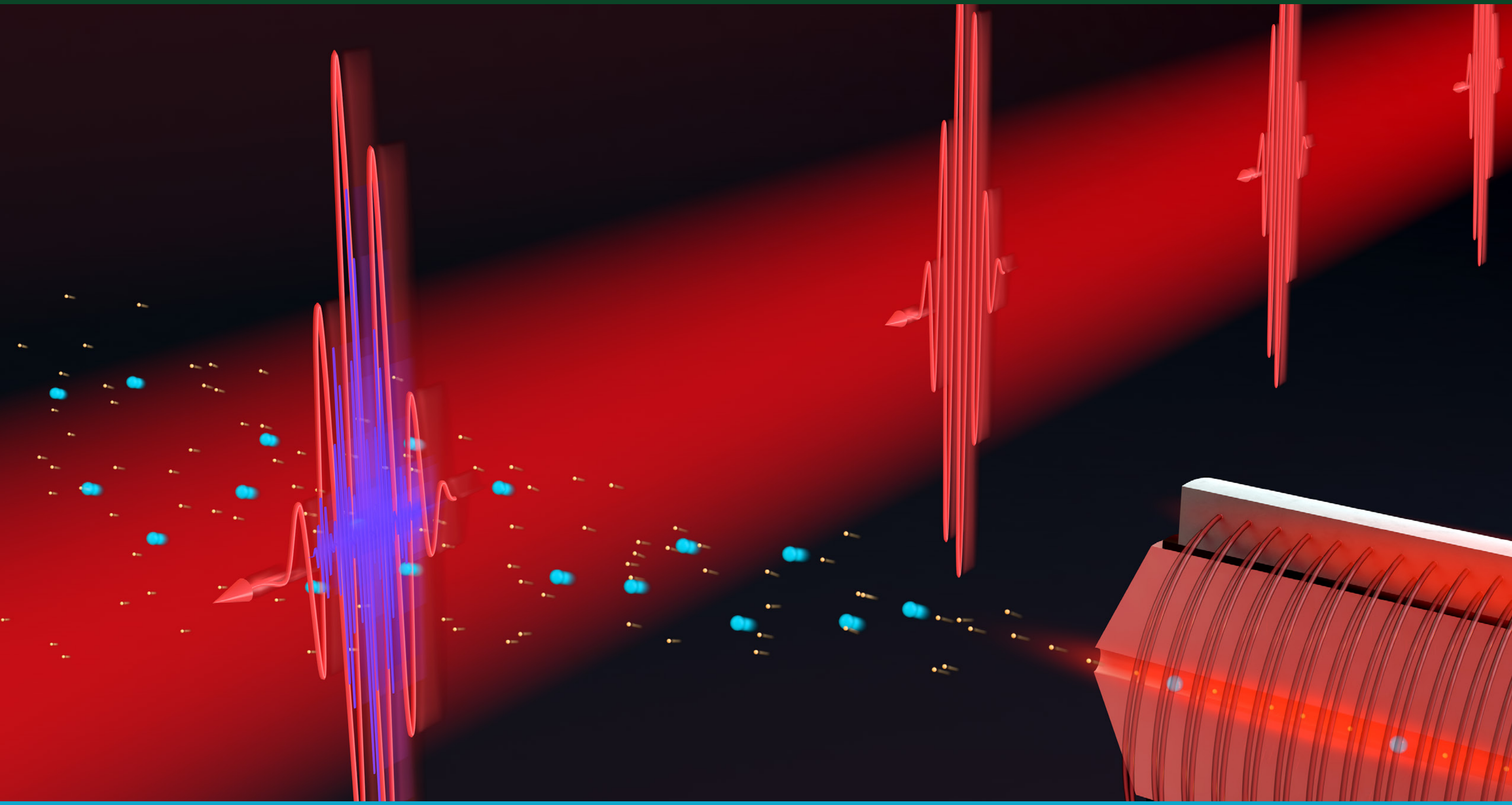
"The problem is most electrons don't recombine," explained Porat. "They miss their parent ion, and then you have a lot of electrons flying around their parent ions and not recombining, and that is what we call plasma."

In standard XUV generation, plasma naturally dissipates. But to translate the bristly "comb structure" from IR to XUV, atoms must be blasted a thousand times more frequently. Lacking adequate time to dissipate, the plasma will accumulate into a thick smog.

Amidst this plasma smog, XUV will dwindle to a weak glow. This dwindling is caused by the same process that separates violet from red within a prism. Traveling at different speeds, the XUV lags behind IR within plasma, and this lag prevents XUV photons from accumulating into a powerful beam (i.e., the interference shifts from constructive to destructive).

To increase XUV power "[we needed] to push the plasma out of the way," said Porat.

But push quickly turned to shove as the team resolved to remove the plasma by any means necessary. First, they mixed helium into their gas to make



Researchers in the Ye Group at JILA have generated the most powerful extreme ultraviolet (XUV) frequency comb yet. Here we see xenon atoms (blue) mixed with Helium atoms (orange) blast out of a heated nozzle and crash into a pulse of coherent infrared light (red), ultimately generating a coherent XUV pulse (purple). Credit: Jun Ye and Steven Burrows / JILA

the xenon atoms squeak across the chamber like a high-pitched balloon voice. But they found this new gas mixture demanded higher pressures, and soon their gas faucet was puffing as hard as an air gun. Finally, the plasma could be pushed even faster with heat, they concurred, as they increased the temperature to near molten lava.

Many designs later (five, said Schoun, but Porat estimated eight), the group assembled their stable XUV volcano. With gale-force xenon winds whisking away the plasma smog, XUV photons could accumulate into a coherent beam, totaling a couple of milliwatts in power.

Although this power is comparable to a commercial laser pointer, this achievement is still astonishing. The only other facilities capable of producing milliwatts of XUV are huge, billion-dollar particle accelerators called synchrotrons and free-electron lasers. In contrast, Porat and Schoun's experiment sits on a tabletop no more than 30 feet square.

"And our XUV light is very stable and controlled," added Porat. It is this stability, which synchrotrons and free-electron lasers lack, that marks ticks along their frequency ruler, enabling the most precise measurements of atomic and molecular dynamics. Without these ticks, the ruler is just a stick.

G. Porat, C. M. Heyl, S. B. Schoun, C. Benko, N. Dörre, K. L. Corwin and J. Ye, *Nature Photonics* **12**, 387–391 (2019).

The First Quantum Degenerate Polar Molecules

Understanding chemistry requires understanding both molecules and quantum physics. The former defines the start and end of chemical reactions, the latter dictates the dynamics in between. JILA researchers now have a better understanding of both.

For the last decade, JILA researchers have expertly chilled, and then combined, atoms into ultracold polar molecules. But today, researchers in the Ye group announced achievement of the next step: combining cold atoms into quantum degenerate polar molecules. This new form of molecular matter amplifies many-body quantum effects between molecules and has already furthered our understanding of chemistry at the quantum level.

Calm Cool Down

Studying molecules is not easy. At room temperature, they rotate, vibrate, and run around—and into each other—like caffeinated school children. But researchers can create calm molecules, and therefore easier-to-study molecules, through cooling.

In 2008, JILA Fellows Deborah Jin and Jun Ye created the first gas of ultracold polar molecules by cooling and combining two ultracold atoms (http://science.sciencemag.org/content/322/5899/231). At 500-million times colder than the average temperature of Earth, these polar molecules no longer rotate or vibrate, but they can collide—if researchers permit it.

Obtaining this level of control for any molecule is fascinating, but it is particularly so for polar molecules. Polar molecules, such as H2O, have an electric charge difference across either end. This small charge difference manifests into large-scale physical properties, such as solubility, melting and boiling points, and surface tension.

But this control, however fascinating, was only surface deep. While Jin and Ye could control how the molecules interacted with their nearest neighbor, they could not control how a molecule might interact with farther neighbors. To achieve that control, they'd need to create degenerate polar molecules.

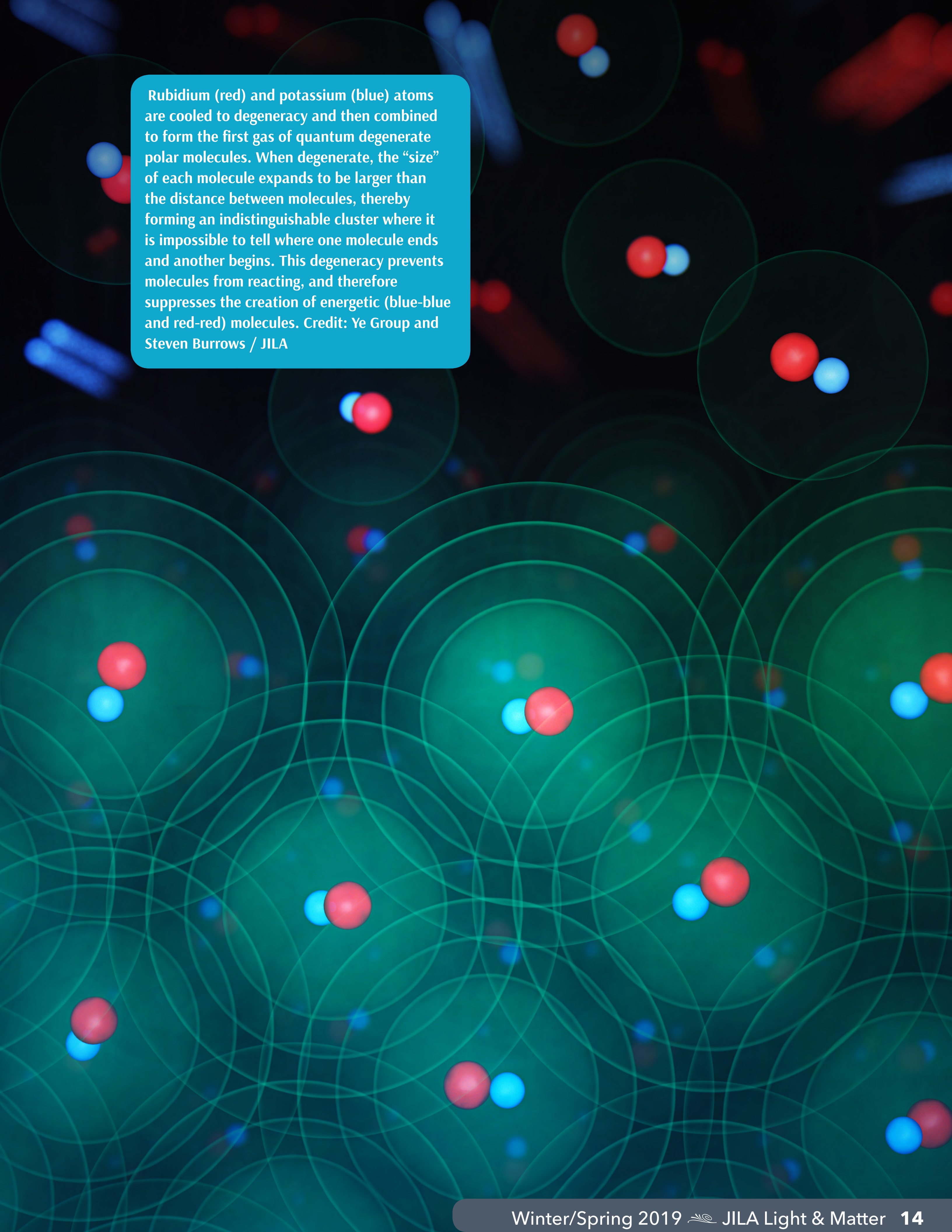
Cold, Ultracold… Degenerate?

Quantum degeneracy is not simply colder than ultracold. With degeneracy, it's no longer temperature that is important, but space, or lack thereof.

For a gas of molecules to be degenerate, the "size" of each molecule must be larger than the distance between nearest neighbors. This means that the molecules overlap, thereby creating a big pile of indistinguishability where it is impossible to tell where one molecule ends and another begins.

There are two ways to make molecules degenerate. The first is to squeeze molecules together so hard they are forced to overlap, which is what happens in very dense places, like the centers of neutron stars. The other way is to cool the molecules, thereby expanding their quantum size (defined by the de Broglie wavelength) .

JILA researchers opted for the cold route. Specifically, our researchers opted to cool their polar molecules down to their "ground-state," or as cold as physics permits. This decision meant nearly a decade of developing laser and atom trapping



Rubidium (red) and potassium (blue) atoms are cooled to degeneracy and then combined to form the first gas of quantum degenerate polar molecules. When degenerate, the “size” of each molecule expands to be larger than the distance between molecules, thereby forming an indistinguishable cluster where it is impossible to tell where one molecule ends and another begins. This degeneracy prevents molecules from reacting, and therefore suppresses the creation of energetic (blue-blue and red-red) molecules. Credit: Ye Group and Steven Burrows / JILA technologies and years of fine-tuning ratios of temperature and atom quantities, but according to Luigi De Marco, the lead postdoc of this research, these challenges did not hamper ambition.

"Pushing molecules into this regime of quantum degeneracy is something that people have talked about doing with ultracold [polar] molecules since they were first made ten years ago," said De Marco with an eager grin.

To make their degenerate molecules, De Marco and his team cooled rubidium and potassium atoms to degeneracy and then combined them. This process was similar to the process to create ultracold molecules, but much colder. An early hurdle that the group had to jump was the number of cold rubidium atoms.

"In our experiment, rubidium atoms do all the cooling for potassium atoms," said De Marco. "So, if you don't have enough rubidium atoms, and keep trying to make it colder and colder, eventually your potassium is going to stop getting colder, and you are going to lose all your rubidium."

Degeneracy Brings About Quantum Surprises

Upon creating their ground-state polar molecules, the team observed a stark chemical change.

Within ultracold molecules, the group had long observed an uncontrollable chemical reaction that slowly destroyed their molecules, resulting in loss.

"What we measured in the past was that if we made the molecules cooler, the loss rate linearly dropped, and if we made them hotter, it linearly increased," said De Marco.

But when the molecules became degenerate, De Marco and his team saw a surprising change.

"As we brought the temperature lower and lower, further and further into the degenerate regime, the suppression of chemical reactions was more than linear," said De Marco. In fact, they were able to lower the reaction rate by a factor of four times than would be possible when not degenerate.

"And we confirmed that is not an effect of just the temperature itself," De Marco added. Because degeneracy depends on overlap, not just temperature, the team was able to create nondegenerate clouds of the same temperature by using fewer molecules. Without the degeneracy, the chemical reaction rate remained linear.

"It was really surprising that the degenerate regime allowed us to beat this linear scaling and suppress these reactions."

According to De Marco, the molecule reaction is suppressed by quantum effects that are enhanced in the degenerate regime. Whereas classical molecules interact with only nearest neighbors, quantum molecules are influenced by all surrounding molecules. These influences can prevent reactions because of certain quantum exclusion rules.

"We see that chemical reactions turn off as the gas becomes more and more degenerate. That was exciting for us, as no one has ever seen that sort of direct interplay between quantum correlations and chemistry."

De Marco and his team have not only created the first degenerate gas of molecules, but demonstrated its powerful ability to enhance quantum effects. With further study of gases like this, De Marco says that quantum computers using molecular chemistry for data storage and more precise measurements of our universe's fundamental symmetries may be possible.✺

L. De Marco, G. Valtolina, K. Matsuda, W. G. Tobias, J. P. Covey, and J. Ye, *Science* **363**, 853–856 (2018).

IN THE NEWS

Anna McAuliffe wins APS CUWiP Poster Award

CU Boulder student and JILA undergraduate researcher Anna McAuliffe won the poster competition at the *2019 Conference for Undergraduate Women in Physics* held at Utah State University.

McAuliffe's poster detailed the build and installation of a cryogenic hexapole designed to mitigate clog issues in an OH decelerator.

McAuliffe began working in Jun Ye's group over a year ago as a freshman. Said Ye of her early career, "This is quite unusual for an undergraduate student to start their research work at such an early stage, but Anna is very mature, and she works well with graduate students and postdocs. We are very proud of Anna's achievement as a young undergraduate student," said Ye.

Jan Hall named National Academy of Inventors Fellow

JILA Fellow John "Jan" Hall was named a 2018 Fellow of the National Academy of Inventors (NAI).

Inventors of U.S. patents are nominated to NAI fellowship by their peers. To be named a NAI fellow is to receive recognition for outstanding inventions that have had a tangible impact on quality of life, economic development and the welfare of society.

The NAI named 148 fellows in 2018, representing research universities and government and non-profit research institutes. Collectively, the 2018 fellows hold nearly 4,000 issued U.S. patents.

Hall was elected for his innovative work on laser-based precision spectroscopy. Hall has at least 11 issued U.S. patents, including "An external laser frequency stabilizer," "Comb generating optical cavity that includes an optical amplifier and an optical modulator," and "Mode-locked pulsed laser system and method." Hall's inventions helped usher physics research to a new level of precision, thus improving everyday technologies from time-keeping to GPS satellites.

The National Academy of Inventors is a member organization comprising U.S. and international universities, and governmental and non-profit research institutes, with over 4,000 individual inventor members and Fellows spanning more than 250 institutions worldwide.

Margaret Murnane Presented Presidential Distinguished Service Award for the Irish Abroad

JILA Fellow Margaret Murnane was one of 10 recipients of the Presidential Distinguished Service Award for the Irish Abroad.

Tánaiste and Minister for Foreign Affairs Simon Coveney announced the names of the award winners on the 28th of November 2018. These awards, established in 2012, are meant to recognize the contributions of members of the Irish diaspora.

Each of the awards is for contributions to a specific category. Murnane received the science, technology and innovation award for her work as "one of the leading optical physicists of her generation," according to The Irish Times.

The awards were presented on Thursday, November 29th, 2018, by Ireland's President Michael D. Higgens.

Other recipients of the award include Novelist Edna O'Brien and Irish-American Pulitzer Prize-winning author William Kennedy.

Zetong Xue wins Stephen Halley White Undergraduate Research Award

Zetong Xue, a JILA undergraduate researcher and recent CU Boulder Honors graduate, was awarded the Stephen Halley White Undergraduate Research Award at the CU Physics graduation ceremony in December 2018.

Xue completed his Honors thesis by working with JILA Fellows Agnieszka Jaron-Becker and Andreas Becker for over a year on an ultrafast AMO theory project. He was also a co-author on two papers which were published in *Physical Review A* earlier this year. Xue's work at JILA was supported by the PFC.

Tom Perkins elected AAAS Fellow

JILA Fellow Tom Perkins has been elected a Fellow of the American Association for the Advancement of Science (AAAS). Perkins was elected for his pioneering advances in high-resolution studies of single biological molecules.

Perkins is among the 416 AAAS members elected Fellows by their peers. The honor recognizes distinguished efforts to advance science, either scientifically or socially. The newly elected fellows were presented with an official certificate and a gold and blue (representing science and engineering, respectively) rosette pin at a ceremony on February 16, 2019 at the AAAS Annual Meeting in Washington, DC.

Fellow Earl Beaty passed away (1930-2018)

JILA Fellow Dr. Earl Beaty passed away on November 3, 2018. Beaty was one of the original JILA Fellows who moved from the National Bureau of Standards (now the National Institute of Standards and Technology) in Washington D.C. to Boulder, Colorado. Beaty helped shape the foundation of JILA as one of the four Fellows to serve on the by-laws committee.

Earl was a JILA Fellow from 1962–1981 with expertise in the area of atomic and molecular physics. After leaving JILA, he ended his professional career with the Bureau of Standards (now known as NIST) in Boulder.

Jun Ye awarded APS Ramsey Prize

The American Physical Society announced JILA Fellow Jun Ye as the recipient of the 2019 Norman F. Ramsey Prize in Atomic, Molecular and Optical Physics, and in Precision Tests of Fundamental Laws and Symmetries. Ye was recognized for his ground-breaking contributions to precision measurements and the quantum control of atomic and molecular systems, including atomic clocks.

The Ramsey Prize is awarded annually for outstanding accomplishments in precision tests of fundamental laws and symmetries or in atomic, molecular and optical physics. Ye's award, which recognizes his work in both precision measurement and quantum control, highlights the increasingly important connections between precision measurement and quantum state control, from which future quantum technologies will grow.

Ben Brubaker wins Particle Physics Dissertation Award

Dr. Benjamin Brubaker won the 2019 Mitsuyoshi Tanaka Dissertation Award in Experimental Particle Physics from the American Physics Society (APS).

Dr. Brubaker is currently a postdoctoral research associate at JILA working with Dr. Konrad Lehnert. Brubaker completed his doctoral thesis work at Yale, where he made outstanding contributions to the design and construction of, and detailed the first results from, the HAYSTAC (Haloscope at Yale Sensitive to Axion Cold) dark matter experimental detector. Brubaker's thesis reports a major milestone in the progress to detect hypothetical particles called axions, which are leading candidates for "cold dark matter."

"I'm very honored for this recognition of my dissertation, which would not have been possible without the support of collaborators from Yale, Berkeley, and JILA," said Brubaker. "I'm gratified that the APS Division of Particles and Fields has chosen to highlight the kind of particle physics that can be explored with tabletop experiments, and I hope this will encourage more research in the application of quantum technologies to problems in fundamental physics."

Heather Lewandowski awarded APS Advanced Lab Instruction Prize

The American Physical Society announced JILA Fellow Heather Lewandowski as the 2019 recipient of the

F. Reichert and Barbara Wolff-Reichert Award for Excellence in Advanced Laboratory Instruction.

Lewandowski was recognized for her systemic and scholarly transformation of advanced laboratories in physics, her building of leading assessment tools of laboratories, and for her national service advancing the laboratory educational community.

The F. Reichert and Barabara Wolff-Reichert Award for Excellence in Advanced Laboratory Instruction was established in 2012 to recognize and honor outstanding achievement in teaching, sustaining, and enhancing advanced undergraduate laboratory courses at U.S. institutions.

Lewandowski has long been an advocate for, and enabler of, improved physics education. In addition to her research on cold molecules, Lewandowski researchers the effectiveness of laboratory instruction. This research has been published in numerous journals, such as *Physics Review*, *Physics Education Research* and the *American Journal of Physics*, and her advocacy for advanced lab classes was recently shared on the back page of an *APS News*.

Ann-Marie Madigan named 2018 Packard Fellow

JILA Fellow Ann-Marie Madigan, a CU Boulder researcher who investigates the unusual behavior of icy objects at the outermost edges of the solar system, has been named a 2018 Packard Fellow. Madigan is one of 18 scientists and engineers receiving this honor, which is handed out annually by the David and Lucile Packard Foundation. The award comes with a no-strings-attached, 5-year grant of $875,000 to support "the blue-sky thinking" of researchers across the country.

Madigan, an Assistant Professor in the Department of Astrophysics and Planetary Sciences (APS) and an Associate Fellow of JILA, said that she will use the award to explore the motion of "trans-Neptunian objects"—icy bodies that orbit the sun billions of miles from Earth.

Murnane and Kapteyn Presented 2018 Governor's Award

CO-LABS presented JILA's ultrafast imaging team, led by Fellows Margaret Murnane and Henry Kapteyn, the 2018 Governor's Award for High-Impact Research.

Murnane and Kapteyn were honored for their work in revolutionizing ultrafast and nanoscale imaging through the research and development of tabletop x-ray sources. These advancements enable real-time imaging of the structure, chemistry, and dynamics of materials at the level of small collections of atoms. The applications range from improving semiconductor devices and magnetic storage to understanding the fundamental physics and chemistry of complex materials. By designing, developing, and eventually enabling the availability of this technology through KM-Labs, Murnane and Kapteyn have enabled many curious researchers to further their discoveries.

CO-LABS was started in 2007 as a non-profit consortium of federal research labs, research universities, businesses and economic development organizations with a mission to support and expand the positive impacts of Colorado's science and technology resources.

Three JILA Fellows named 2018 APS Fellows

Three JILA Fellows have been named 2018 Fellows of the American Physical Society. The three new Fellows—Andreas Becker, Heather J. Lewandowski, and James K. Thompson—were nominated from varying divisions of APS.

Andreas Becker was nominated by the APS Division of Atomic, Molecular & Optical physics for his contributions to the understanding of the behavior of atoms and molecules in intense light fields, including seminal theoretical studies of attosecond dynamics, photoionization, complex electron dynamics in simple systems such as H2, and a better understanding of high-harmonic generation.

Heather J. Lewandowski was nominated by the APS Forum on Education for her pioneering and comprehensive research on, and leading development of resources for, teaching and learning in advanced physics instructional lab courses.

James K. Thompson was nominated by the APS Topical Precision Measurements & Fundamental Constants for his development of precision measurement techniques, in particular for atomic mass and for measurements with atomic ensembles beyond the standard quantum limit.

Heather Lewandowski to Receive 2018 Homer L. Dodge Citation for Distinguished Service to AAPT

The American Association of Physics Teachers (AAPT) announced last week that JILA Fellow Heather Lewandowski will receive the association's Homer L. Dodge Citation for Distinguished Service to AAPT.

Lewandowski's dual research areas are in fundamental experimental molecular physics and Physics Education Research (PER). Within PER, Lewandowski studies how the structures of upper-level labs for undergraduates can best transition students into research lab environments.

Lewandowski is a Fellow of JILA and an Associate Professor of Physics, as well as the Associate Chair and Director of the Engineering Physics Program, at the University of Colorado Boulder. She has been an active member of AAPT since 2007.

The Homer L. Dodge Citation for Distinguished Service to AAPT is presented to members in recognition of exceptional contributions at the national, sectional, or local level.

Emma Simmerman Awarded Prestigious Astronaut Scholarship

Emma Simmerman, a senior physics major, has been awarded a $10,000 scholarship from the Astronaut Scholarship Foundation (ASF).

NASA astronaut and CU instructor Joe Tanner was presented with the award during a ceremony at 1:15 p.m. Friday, September 28th.

Simmerman is a research assistant at JILA working in the Ralph Jimenez Lab studying fluorescent proteins used in biological imaging.

Perkins and Lehnert Awarded Department of Commerce Medals

JILA Fellows Tom Perkins and Konrad Lehnert both received medals from the Department of Commerce.

Perkins received the Gold Medal, which is the highest honorary award given by the United States Department of Commerce. Perkins was recognized for creating the world's best atomic force microscope tailored to biological measurements. The device can "grab" onto biological molecules, such as proteins, and measure the tiny forces involved in their folding and unfolding.

Perkins was also recognized for using this technology to study the structure and dynamics of key membrane proteins, which are proteins that control the exchange of chemicals into and out of cells that will lead to better understanding, and subsequently diagnosing and treating the diseases developed through protein misfoldings, such as Alzheimer's, Parkinson's, and cystic fibrosis.

"I am honored to receive this award," said Perkins. "It reflects a decade of efforts by my students and post-docs as we sequentially addressed a set of metrological limitations to bioAFM. We successfully demonstrated our metrological improvements by resolving a multitude of hidden dynamics of bacteriorhodopsin, a result that biologist and biochemists cared about."

Dr. Lehnert received the Silver Medal as part of a team of NIST scientists building the components of a quantum communications network. The team was recognized for the first realization of the complex components needed for future quantum networks.

"It was exhilarating to get out in front of this highly competitive new research area," said Lehnert. "By working together, [we] were able to quickly make great progress."

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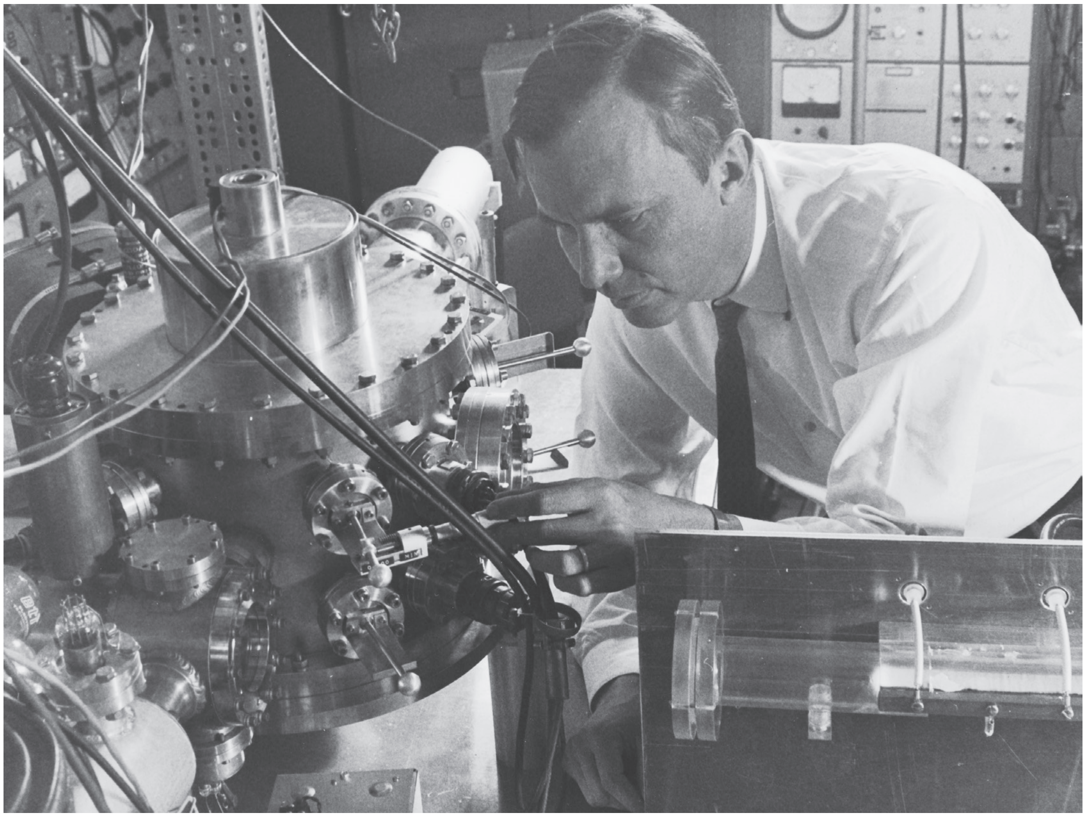

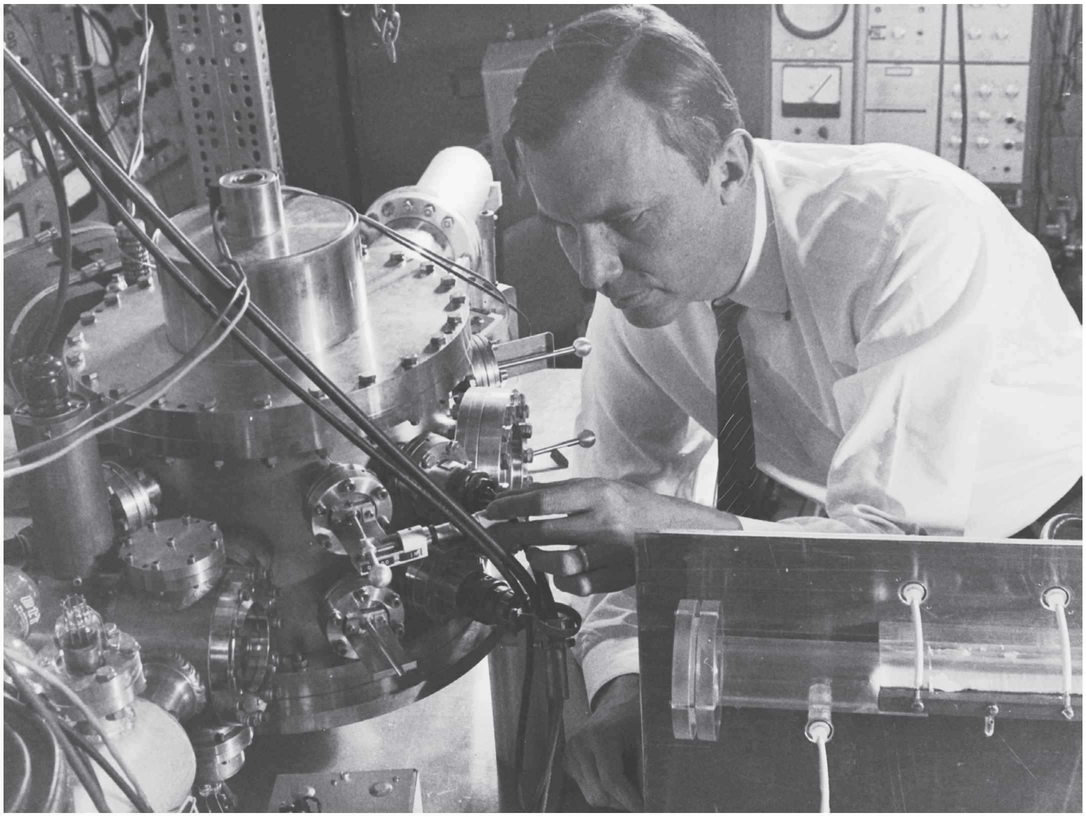

Fellow Lewis Branscomb working in his laboratory at JILA, circa 1966.

JILA is a joint institute of the University of Colorado Boulder and the National Institute of Standards and Technology

University of Colorado **Boulder**

National Institute of Standards and Technology
U.S. Department of Commerce

About JILA

JILA was founded in 1962 as a joint institute of CU Boulder and NIST. JILA is located at the base of the Rocky Mountains on the CU Boulder campus, next to the Duane Physics complex.

JILA's faculty includes two Nobel laureates, Eric Cornell and John Hall, as well as two John D. and Catherine T. MacArthur Fellows, Margaret Murnane and Ana Maria Rey. JILA's faculty hold appointments in the Departments of Physics; Astrophysical & Planetary Science; Chemistry; Biochemistry; and Molecular, Cellular & Developmental Biology as well as in the School of Engineering.

The wide-ranging interests of our scientists have made JILA one of the nation's leading research institutes in the physical sciences. They explore some of today's most challenging and fundamental scientific questions about quantum physics, the design of precision optical and x-ray lasers, the fundamental principles underlying the interaction of light and matter, and processes that have governed the evolution of the Universe for nearly 14 billion years. Research topics range from the small, frigid world governed by the laws of quantum mechanics through the physics of biological and chemical systems to the processes that shape the stars and galaxies. JILA science encompasses eight broad categories: Astrophysics, Atomic & Molecular Physics, Biophysics, Chemical Physics, Laser Physics, Nanoscience, Precision Measurement, and Quantum Information Science & Technology.

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