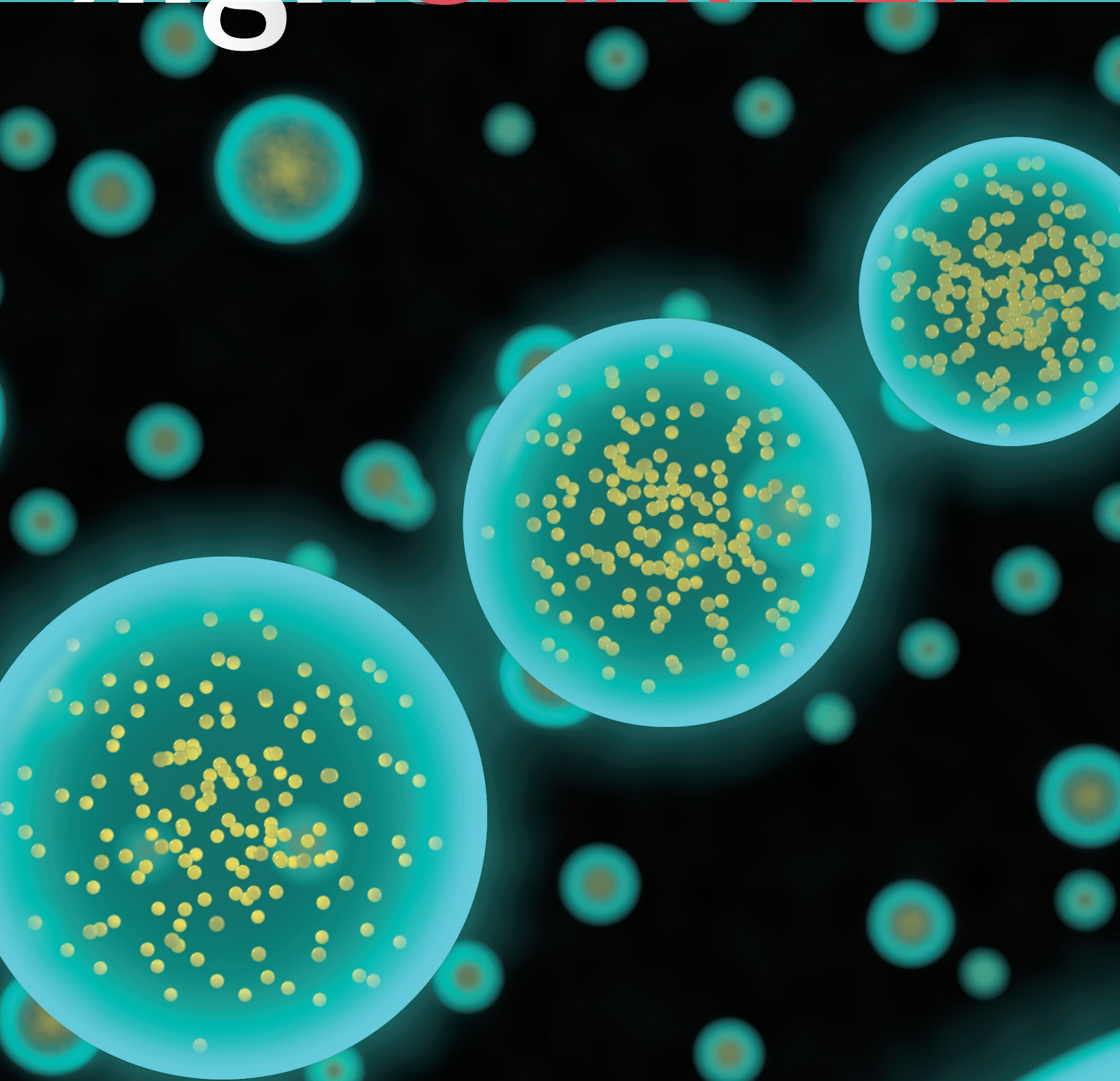
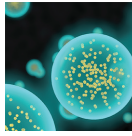


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From **BEC** to **Breathing** Forever p.1

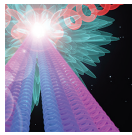
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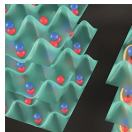
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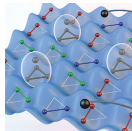
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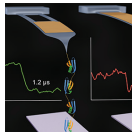
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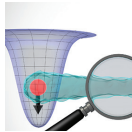
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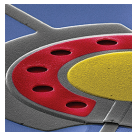
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From BEC to Breathing Forever

The storied history of JILA's Top Trap

It took Eric Cornell three years to build JILA's spherical Top Trap with his own two hands in the lab. The innovative trap relied primarily on magnetic fields and gravity to trap ultracold atoms. In 1995, Cornell and his colleagues used the Top Trap to make the world's first Bose-Einstein condensate (BEC), an achievement that earned Cornell and Carl Wieman the Nobel Prize in 2001.



The Nobel-Prize-winning creation of BEC had been a race to the finish line, as labs all over the world had also been attempting to be the first to validate the 70-year-old prediction of BEC by Satyendra Nath Bose and Albert Einstein. The innovative Top Trap was the key to Wieman and Cornell's great achievement. Afterwards, Cornell, Wieman, and their colleagues conducted a host of Top-Trap experiments, publishing 20 significant papers on the physics of ultracold atoms over the next two decades.

By the end of that 20-year period of discovery, however, the now much older (and more complicated) Top Trap was wearing out. It was time to think about one last experiment. Only one of Cornell's graduate students, Dan Lobser, knew how to operate the complicated apparatus. So Cornell and Lobser enlisted additional help from student assistant Andrew Barentine and Fellow Heather Lewandowski, who had previously worked with Lobser.

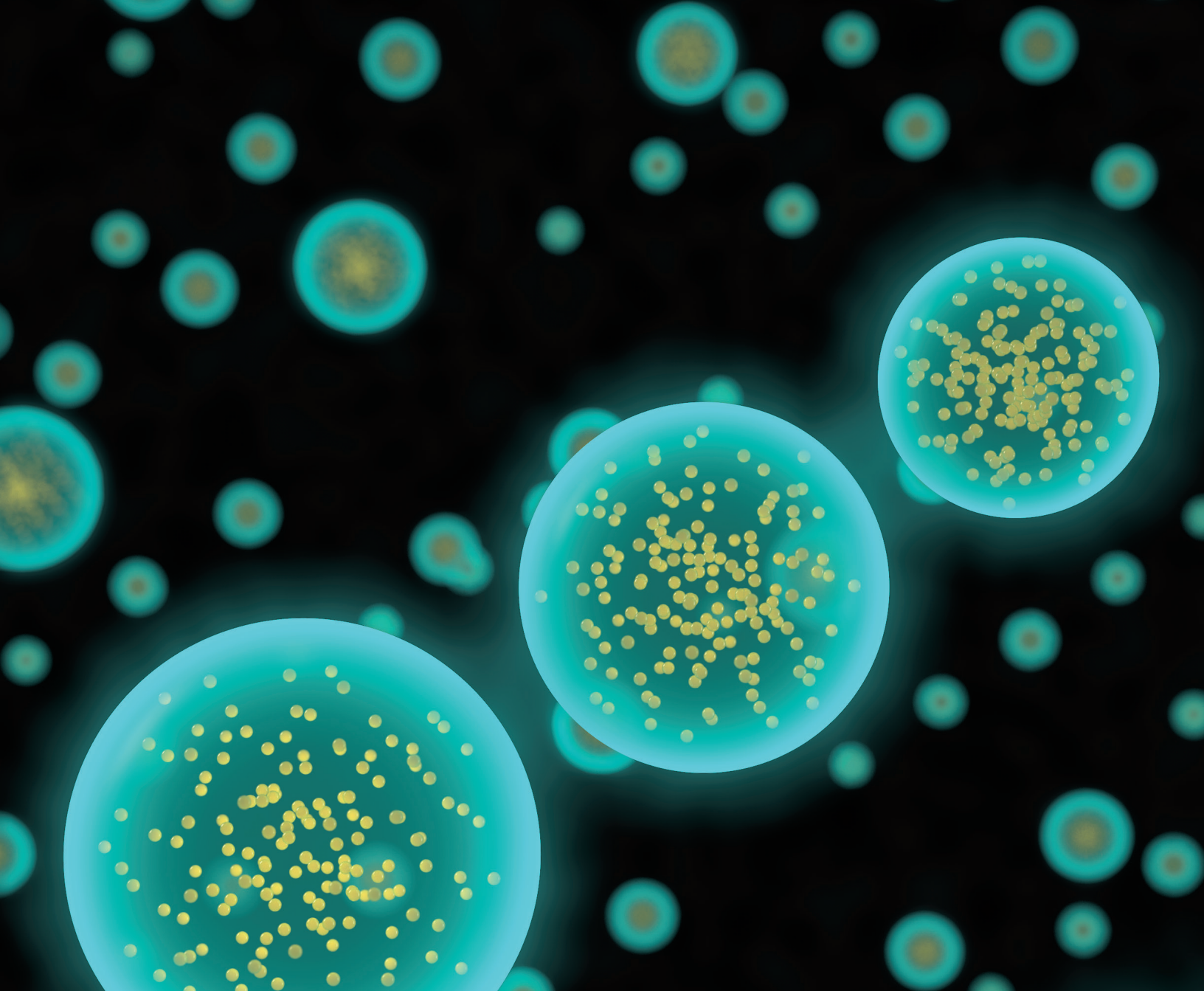
Cornell and Lewandowski decided upon a fitting final experiment for the Top Trap: a test of a special case of Boltzmann's transport equation that had never been proved. This part of Boltzmann's theory predicted that, once set in motion, a cloud of atoms in a perfectly spherical trap would breathe, or oscillate, forever. It was a perfect experiment for the Top Trap despite being somewhat of an historical oddity.

Although physicists today revere Boltzmann as a giant in the field of physics, he was vehemently attacked when he published the transport equation in 1876. For starters, Boltzmann assumed that matter was made of atoms, an idea that was vigorously disputed at the time by many scientists who claimed energy was at the root of the physical world. With respect to the special case showing that it was possible for a physical process to continue forever without damping, or stopping completely, "everyone" knew that was crazy. If something starts moving, it slows down or cools down. Eggs break, for heaven's sake, and they don't reform into eggs. That's just the way the world works!

Boltzmann's controversial idea was that damping happens when you put lots of atoms together, with just one or two exceptions. This idea was heresy to the scientific establishment of his time. It was also right.

Even though physicists today believed the special case is correct because the rest of the transport equation has been validated, Cornell and Lewandowski decided to prove it. The Top Trap was the perfect instrument to use.

The researchers placed an ultracold cloud of rubidium atoms in the Top Trap and started the cloud oscillating. The cloud oscillated in and out in what's known as a "monopole breathe." While it



Rubidium atoms “breathing” endlessly in the Top Trap. Credit: The Lewandowski and Cornell groups and Steve Burrows, JILA

was “breathing,” the cloud changed in volume by about 30%. Most importantly, the breathing continued for a very long time—long enough to vindicate Boltzmann.

When the researchers finished taking the data for the experiment, they disassembled the Top Trap. While this was happening, Eric Cornell walked out of the lab where he’d started an amazing scientific journey at JILA 25 years earlier. It was hard to watch an “old friend” disappear, though perhaps not quite as hard as it had been for Boltzmann to be dismissed and reviled for his stunning insights into the nature of the physical world.

D. S. Lobser, A. E. S. Barentine, E. A. Cornell, and H. J. Lewandowski, *Nature Physics*, **11** 1009–1012 (2015).



Artist's impression of a young star surrounded by an accretion disk. This system is similar to the HD 163296 system theoretically analyzed by Phil Armitage and Jacob Simon before being observed by ALMA. Credit: ALMA(ESO/NAOJ/NRAO)

TURBULENCE:

An Unexpected Journey

Fellow Phil Armitage and his collaborator Jake Simon of the Southwest Research Institute recently conducted a theoretical study of turbulence in the outer reaches of an accretion disk around HD 163296, a nearby young star. Meanwhile, the Atacama Large Millimeter/submillimeter Array (ALMA) in northern Chile observed the same accretion disk. There were intriguing and unexpected differences between what the theory predicted and what the observation revealed. As a result, theorists may need to rethink their understanding of the behavior of an accretion disk at great distances from the central star.



ALMA's 16-antenna Atacama Compact Array, or ACA, enhances imaging fidelity for extended astronomical sources. Credit: ALMA(ESO/NAOJ/NRAO)

"The outer disks we're interested in should have some sort of turbulence, some significant gas motion that departs from the simple rotation (of the disk)," said Simon. Simon explained that something has to remove the disk's angular momentum to allow the gas to move towards the central star. Turbulence was, and still is, the primary explanation for how this happens. However, ALMA detected no clear evidence of turbulence in the outer disk.

"ALMA is a revolutionary instrument," explained Armitage. He said people had predicted that ALMA would overturn some theoretical ideas, but he and Simon hadn't expected it to be *their* ideas. Even so, he and Simon are excited that the new observations are giving them the opportunity to revisit their theory to account for the new observation. And, if this observation holds up with other planet-forming systems, it will be Simon and Armitage's job to figure out exactly what's going on.

Armitage said that there may be a period of confusion on both the observational and theoretical sides before it becomes clear what's happening in the outer region of the accretion disk of HD 163296. An interesting part of this conundrum is that there are observations that clearly show material at 1 astronomical unit, or AU (the distance from the

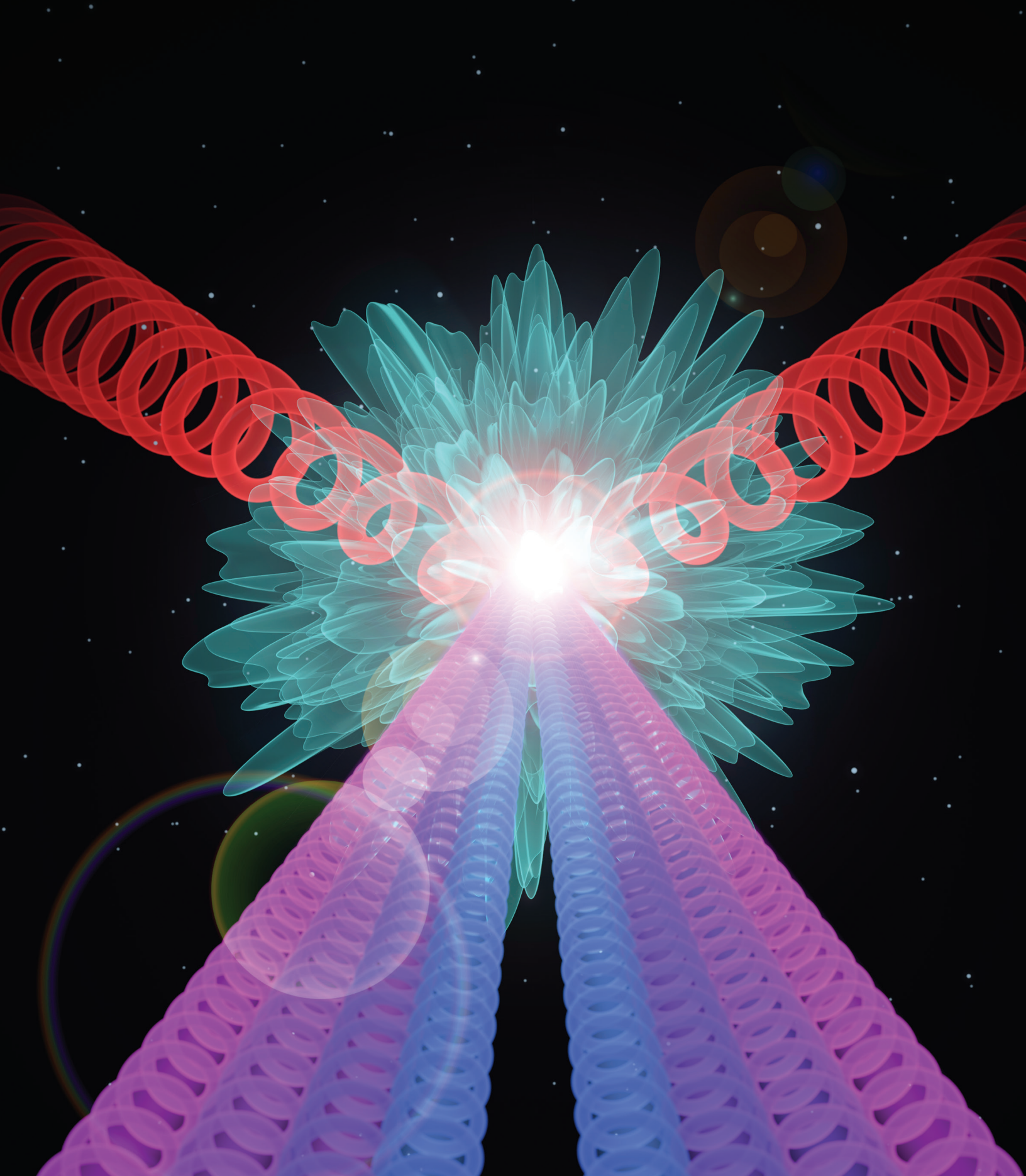
Sun to the Earth) flowing in and accreting onto the star. So something—quite likely turbulence—is removing the angular momentum in the inner disk regions.

However, at 100 AU (two and a half times the distance from the Sun to Pluto), there is no reason, in principle, that the gas has to be turbulent or flowing inward at all. The gas could just be sitting there orbiting the young star until it eventually gets blown away because of heating by x-rays or ultraviolet radiation from the star.

"The new observation is interesting, exciting, and more mysterious now than before," said Armitage. "The issue here is not the precision of the measurements, which is extremely good, but how those measurements are interpreted." He added that there are things in the Universe that may not work in quite the way people currently understand them. And, according to Armitage and Simon, this is the sort of mystery that makes it great fun to do theoretical astrophysics.

Kevin M. Flaherty, A. Meredith Hughes, Katherine A. Rosenfeld, Sean M. Andrews, Eugene Chiang, Jacob B. Simon, Skylar Kerzner, David J. Wilner, *The Astrophysical Journal*, **813**:99 (2015).

Jacob B. Simon, A. Meredith Hughes, Kevin M. Flaherty, Xue-Ning Bai, and Philip J. Armitage, *The Astrophysical Journal* **808**:180 (2015).



When beams of visible light with opposite circular polarizations are crossed in a high-harmonic generation process, an array of harmonics (x-ray laser beams) is produced at different angles, which allows the harmonics to be easily separated. Right and left circularly polarized x-ray laser beams are produced on opposite sides. Credit: The Kapteyn/Murnane group and Steve Burrows, JILA

The Guiding Light

Visible lasers provide exquisite control of x-ray light

The Kapteyn/Murnane group, with Visiting Fellow Charles Durfee, has figured out how to use visible lasers to control x-ray light! The new method not only preserves the beautiful coherence of laser light, but also makes an array of perfect x-ray laser beams with controlled direction and polarization.

Such pulses may soon be used for observing chemical reactions or investigating the electronic motions inside atoms. They are also well suited for studying magnetic materials and chiral molecules like proteins or DNA that come in left- and right-handed versions.

This new discovery has taken tabletop femtosecond (10^{-15} s) and attosecond (10^{-18} s) x-ray bursts to a whole new level. The secret to the discovery: Research associate Dan Hickstein crossed two visible laser beams that were circularly polarized in opposite directions and sent them through a high-harmonic generation (HHG) process. The crossed laser beams entered a gas of argon where the laser field ripped electrons from the noble gas atoms. The laser field then changed direction, smashing the electrons back into their parent ions and producing an array of harmonics (soft x-ray beams of different wavelengths).

The new technique produced different color x-ray beams that emerged at distinct angles. As a result, it was straightforward to isolate and separate beams of different wavelengths and polarizations. And, with this capability came the power to tailor specific x-ray laser beams to individual experiments.

"All the left circularly polarized beams go in one direction, and all the right circularly polarized beams go in the other direction," said Murnane. "This is quite amazing! Nobody thought you could have so much simultaneous control of the direction,

polarization, and spectrum of light in the x-ray region."

The researchers responsible for this breakthrough include Hickstein, former senior research associate Franklin Dollar, research associates Patrik Grychtol and Ronny Knut, former research associate Carlos Hernández-García, graduate students Jennifer Ellis, Dmitriy Zusin, Christian Gentry, Tingting Fan, and Kevin Dorney, Justin Shaw (NIST), Visiting Fellow Charles Durfee (Colorado School of Mines), Associate Fellow Agnieszka Jaron-Becker, and Fellows Andreas Becker, Henry Kapteyn, and Margaret Murnane.

Visible lasers can now be used to precisely control x-rays, opening the door to investigating materials in ways that were never before possible. In fact, the technique is so new that no one yet knows its limits: The researchers don't yet know how high in energy they can make the pulses; nor do they know how short a pulse they can generate or how bright it can be.

"The most dramatic advance here is that we now have the ability to steer x-ray light with visible lasers," Murnane said. "To my knowledge, this is the first time anyone has figured out how to steer an x-ray beam with visible light. It's really beautiful light science."

The new method promises to be a boon to the use of x-ray laser beams in scientific (*cont. pg. 7*)

experiments because good optics are not available to steer x-ray light. Those that are available are expensive, and they don't work very well. Plus, it's very difficult to design optics that preserve the very short bursts generated by HHG. In contrast, the new-found capability of manipulating x-ray light via the HHG generation process circumvents these disadvantages, making it easier to "see" what's happening in experiments.

The nice thing about the new system is that researchers know what's happening in real time, and, if needed, they can adjust the x-rays with a visible laser. So far, the researchers have used their new HHG x-ray beams to investigate magnetic materials. Their goal is to refine the new technique to create an x-ray spectrometer without using any x-ray optics.

Daniel D. Hickstein, Franklin J. Dollar, Patrik Grychtol, Jennifer L. Ellis, Ronny Knut, Carlos Hernández-García, Dmitriy Zusin, Christian Gentry, Justin M Shaw, Tingting Fan, Kevin M. Dorney, Andreas Becker, Agnieszka Jaron-Becker, Henry C. Kapteyn, Margaret M. Murnane, and Charles G. Durfee, *Nature Photonics*, **9** 743–750 (2015).



A quiet and snowy view from JILA while students were away for the holidays.

NIST Boulder Lab Building Renamed for Katharine Blodgett Gebbie

Dr. Katharine Blodgett Gebbie, long-time JILA and former director of the National Institute of Standards and Technology's (NIST's) Physical Measurement Laboratory, was honored by NIST on December 10. The most advanced laboratory building at the NIST campus in Boulder, Colorado, was renamed after legendary laboratory director Gebbie.

This is the first time a NIST Boulder building has been named for a person. Such honors have been rare in NIST's 114-year history across several locations. The last time a NIST building was named for a staff member was in 1962 at the institution's original headquarters in Washington, D.C.

Gebbie, currently a NIST senior advisor, is uniquely deserving of such an honor. An astrophysicist by training, she has worked for NIST for more than 45 years. Among other positions, she directed two large NIST operating units of several hundred researchers each. Under her leadership, NIST staff won four Nobel Prizes in Physics between 1997 and 2012 as well as two MacArthur Fellowships, a.k.a. "genius grants."

Gebbie also played leadership roles in founding NIST's Summer Undergraduate Research Fellowship (SURF) program and the Joint Quantum Institute, and in advocating for women and minorities in science.

"This renaming is our small way of saying thank you, Katharine, for all you've done for this organization over such a long period of time," said Under Secretary of Commerce for Standards and Technology and NIST Director Willie E. May. "This gesture will serve as a reminder for all of us for years to come who Katharine is and was and the remarkable environment that she fostered within NIST and the laboratories that she led."

The renaming was celebrated at a ceremony where Gebbie was presented with many tributes—a standing ovation from an overflow crowd of about 200 staff

and guests; a letter from Colorado Governor John Hickenlooper; and an American flag once flown over the U.S. Capitol in Washington, D.C., provided by local Congressman Jared Polis.

All four NIST Nobel laureates spoke glowingly and told personal anecdotes about Gebbie's quest for excellence, as well as her loyalty and nurturing support that encouraged them to succeed—and remain at NIST throughout their careers.

"Katharine—we revere you, we are in awe of you, and we love you," NIST Fellow and 1997 Nobel laureate William Phillips said.

A typical Gebbie response to such accolades is: "Of course, all I did was hire and retain talented scientists and support staff." (She was unable to attend the ceremony in person.)

The renamed laboratory building, first dedicated in 2012, tightly controls environmental conditions such as vibration and temperature, as required for cutting-edge research and measurements with world-leading atomic clocks and other advanced technologies. The lab also offers capabilities for micro- and nanofabrication of custom research devices and advanced imaging systems. The building is intended to support NIST research needs for the next 50 years.

Although Gebbie spent most of her career based at NIST's current headquarters in Gaithersburg, Maryland, she maintained her roots in Boulder. She began her NIST career as a postdoctoral researcher at JILA, NIST's joint institute with the University of Colorado Boulder. Later, as a lab director, she was responsible for substantial programs at NIST Boulder and JILA.

"At JILA I learned there is no substitute for talent. Hire the highest caliber people, provide them the resources they need, and let them run," Gebbie has said. "I never knew any other way of managing."

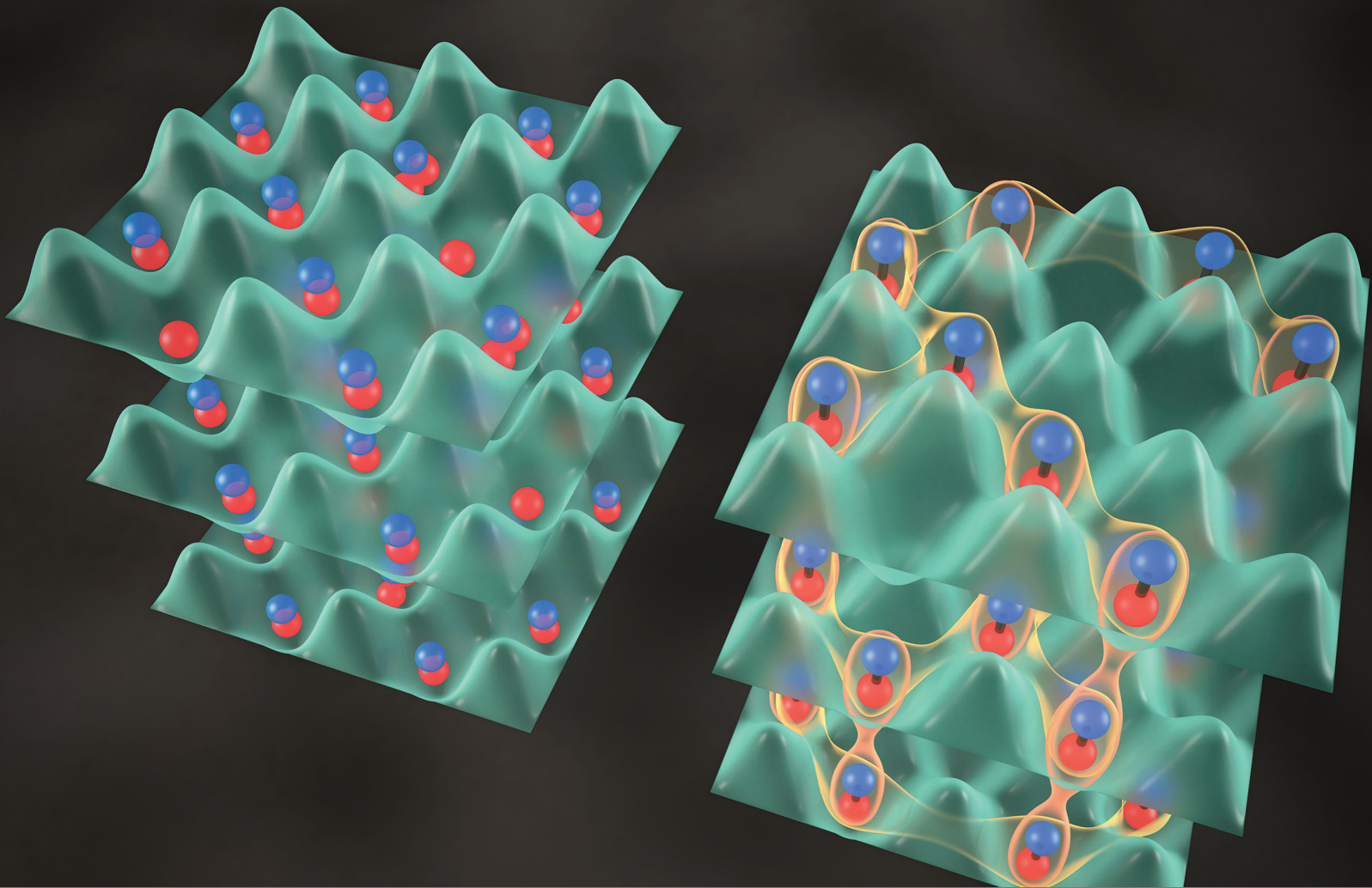
She has fond memories of the Boulder Airport, where she learned to fly her mother's airplane.



Katharine Blodgett Gebbie was a JILA Fellow from 1974–1986 and 1988–1991, later becoming the Director of the NIST Physical Measurement Laboratory. Credit: NIST

"My favorite trip was to take people over the Continental Divide and down the Colorado River to Lake Powell and the Grand Canyon. Hard to beat that for scenery. And I still have a house in Boulder at 7,000 feet with a view in one direction to the Divide and in the other to Kansas—including, of course, the Boulder Airport."

The Blodgett in Gebbie's name recalls her famous aunt, Katharine Burr Blodgett, who invented low-reflectance, invisible glass that is the prototype for coatings used today on camera lenses.



The secret to making ultracold KRb molecules inside a 3D optical lattice is create conditions that make it possible to place one atom each of potassium and rubidium on individual lattice sites. Once the atoms are in place, researchers use a change in the magnetic field followed with radiation by a pair of laser beams to form the molecules, which then form communications networks throughout the 3D lattice. Credit: The Jin, Ye, and Rey groups, and Steve Burroughs, JILA

A THOUSAND SPLENDID PAIRS

In making ultracold molecules, the courtship is where the action is

JILA's cold molecule collaboration (Jin and Ye Groups with theory support from the Rey Group) recently made a breakthrough in its efforts to use ultracold polar molecules to study the complex physics of large numbers of interacting quantum particles. By closely packing the molecules into a 3D optical lattice (a sort of "crystal of light"), the team was able to create the first "highly degenerate" gas of ultracold molecules. In other words, the ultracold molecular gas was much closer to the lowest possible entropy than ever before. This accomplishment has made it feasible to use the ultracold polar molecules for practical studies of such complicated phenomena as quantum magnetism.

Because of its goal of studying complex quantum phenomena, the collaboration has learned to produce ultracold molecules in a 3D optical lattice, which resembles a 3D egg carton of regularly spaced energy wells created by intersecting laser beams. When placed inside the energy wells in the lattice, individual ultracold molecules can “talk loudly” to nearby molecules above and below them as well as to their left and right. There’s also some weaker communication with molecules farther away. The team’s recent achievement is to fill enough of these energy wells with cold molecules to establish a working communications network, in which every molecule in the lattice must participate.

With JILA’s potassium-rubidium (KRb) molecules, enough turns out to be approximately one KRb molecule for every three or four lattice sites. At this density, the molecules are able to get well connected with each other, making it feasible to study their complex interacting network. Graduate student Steven Moses and his team from the Jin and Ye collaboration were recently able to create KRb molecules in a large enough fraction of the lattice sites to get the molecules well connected.

To make the molecules inside the lattice, the researchers had to first place atoms inside the lattice in such a way that many sites contained a single potassium atom and a single rubidium atom. Then, with a small change in the magnetic field, they turned pairs of atoms into KRb molecules. However, the first step of getting a pair of different atoms into many sites turned out to be the biggest challenge. But, the cold-molecule collaboration met the challenge of getting the potassium and rubidium atoms to “like” each other well enough to sit side by side on the same site.

To make them sit peacefully together, the researchers had to deal with many issues. First, potassium and rubidium are very different animals, and as different species, they like different things. Potassium atoms are fermions, which prefer to

keep their distance from other atoms, and rubidium atoms are bosons, which don’t mind a lot of close contact. Second, potassium and rubidium have different masses. Plus they experience the trap made by light differently. Finally, the potassium atoms are hotter than rubidium atoms, and harder to cool. With all these differences, it was challenging to place just one Rb atom and one K atom next to each other in the same well. In fact, it turned out it to be best for the K and Rb atoms to completely ignore each other until it was time to turn them into molecules! This unexpected result had to be confirmed experimentally and now has been explained by the Rey theory group.

When it was time to make the molecules, the researchers used a small change in the magnetic field through a Feshbach resonance¹ to create such a strong interaction between atoms that they linked up and formed weakly bound molecules. The weakly bound molecules were converted to long-lived ground-state molecules with a pair of lasers.

In the end, the researchers succeeded in creating a thousand splendid KRb molecules, each snugly tucked away in its own lattice site. And, there were enough pairs to establish a communications network. Now, the Jin and Ye collaboration is building an improved experimental apparatus that will allow them to see the molecules much more clearly. This new ability to watch the behavior of individual molecules in the lattice will lead to future investigations of communication pathways, spin-orbit coupling, and other quantum behaviors.

1. A Feshbach resonance is a special magnetic-field strength where small changes in the magnetic field have dramatic effects on the interactions of atoms in an ultracold gas.

Steven A. Moses, Jacob P. Covey, Matthew T. Miecnikowski, Bo Yan, Bryce Gadway, Jun Ye, and Deborah S. Jin, *Science*, **350** 659–662 (2015).

A. Safavi-Naini, M. L. Wall, and A. M. Rey, *Physical Review A*, **92** 063416 (2015).

Puzzles - It's all about Chemistry!

Be the first to solve 2 puzzles to win a \$25 gift card. The word search answers on the next page can run horizontally, vertically, diagonally and forward or backward.

Turn your correctly-completed puzzle in to Kristin Conrad (room S264) or Julie Phillips (room S211).

Chemistry Word Jumble Puzzle

MICCAUL

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ROPCEP

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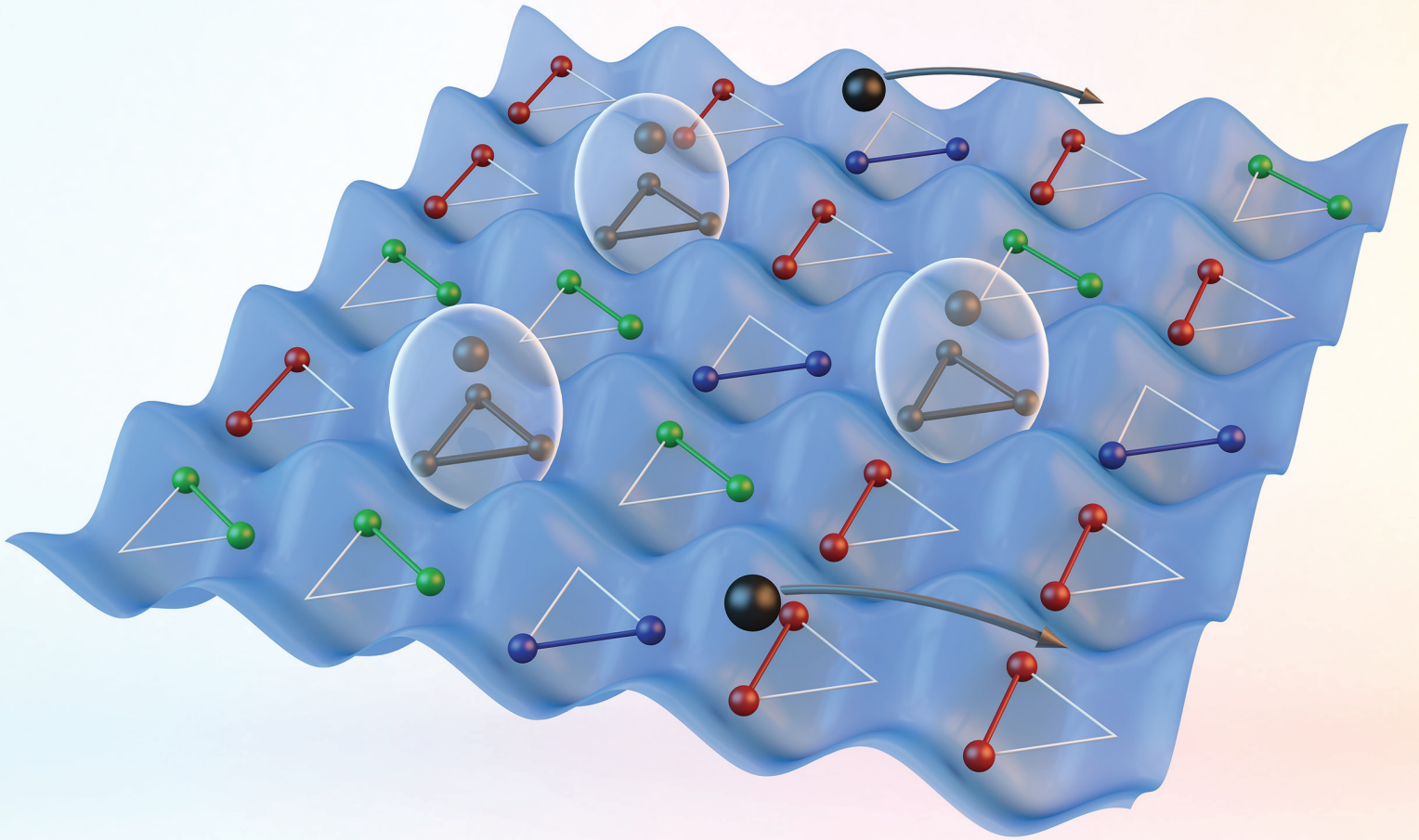
○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○

Unscramble the letters in the clues to find the element names. Use the circled letters to discover where chemists keep all their elements.

Element Word Search

DRMUI DOHRMNRUPBSTCRINUMIHCE TAUU
 MAUUORBYUCLRMAMMRT OOSMIUMGUGMME
 NUHFIEOSILVERIMBMMNPCURIUMIIMGI
 SCIALNYNMSMIOUEPALLADIUMIGTUMMI
 NNEHSUETUUUPIIUHNETS G NUTNASTONS
 BHRPTSSHIMIDOY MOLYNOMITNALHMUON
 MEMLRICRUNDUUTS ATODTTMLRLUUDIC
 MIUAOULUAIBDIPUPWDNPMCINUIMISMA
 URITNEYZMNUMYBOHRYESA AITDUUTORD
 IURITGGNAFDRIIUOESXHU YEAIMAIGNM
 OTENITATSAKIUMERNPGUETRBNOEODMN
 GHCUUHDNCHMIUNPUCRENI TROGENLSMI
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 UOEARMUAUETDPCOEMIYENIROULFLMUB
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|--------------|-------------|--------------|---------------|-------------|--------------|------------|
| Actinium | Aluminum | Americium | Antimony | Argon | Arsenic | Astatine |
| Barium | Berkelium | Beryllium | Bismuth | Bohrium | Boron | Bromine |
| Cadmium | Calcium | Californium | Carbon | Cerium | Cesium | Chlorine |
| Chromium | Cobalt | Copernicium | Copper | Curium | Darmstadtium | Dubnium |
| Dysprosium | Einsteinium | Erbium | Europium | Fermium | Flerovium | Fluorine |
| Francium | Gadolinium | Gallium | Germanium | Gold | Hafnium | Hassium |
| Helium | Holmium | Hydrogen | Indium | Iodine | Iridium | Iron |
| Krypton | Lanthanum | Lawrencium | Lead | Lithium | Livermorium | Lutetium |
| Magnesium | Manganese | Meitnerium | Mendelevium | Mercury | Molybdenum | Neodymium |
| Neon | Neptunium | Nickel | Niobium | Nitrogen | Nobelium | Osmium |
| Oxygen | Palladium | Phosphorus | Platinum | Plutonium | Polonium | Potassium |
| Praseodymium | Promethium | Protactinium | Radium | Radon | Rhenium | Rhodium |
| Roentgenium | Rubidium | Ruthenium | Rutherfordium | Samarium | Scandium | Seaborgium |
| Selenium | Silicon | Silver | Sodium | Strontium | Sulfur | Tantalum |
| Technetium | Tellurium | Terbium | Thallium | Thorium | Thulium | Tin |
| Titanium | Tungsten | Ununoctium | Ununpentium | Ununseptium | Ununtrium | Uranium |
| Vanadium | Xenon | Ytterbium | Yttrium | Zinc | Zirconium | |



In an optical lattice, quantum frustration caused by the entanglement (grey shadows) of molecule-like atom pairs and freely moving itinerant atoms (of the same kind) can result in the itinerant atoms appearing to be heavier than they really are. Because the itinerant electrons play the same role as conduction electrons in metals, this behavior may shed light on the conduction properties of magnetic metals. Credit: The Rey group and Steve Burrows, JILA

Born of Frustration

Scientists often use ultracold atoms to study the behavior of atoms and electrons in solids and liquids (a.k.a. condensed matter). Their goal is to uncover microscopic quantum behavior of these condensed matter systems and develop a controlled environment to model materials with new and advanced functionality.

In an exciting new theory investigation, Fellow Ana Maria Rey and research associate Leonid Isaev have showed how ultracold atoms in optical lattices (created with intersecting laser beams) can model the interplay of two fundamental factors affecting the flow of electrons in metals: (1) localized magnetic impurities that behave as tiny magnets and (2) quantum frustration that occurs when the spins of the impurities cannot decide whether to point up or down.

When mobile electrons collide with impurities, their flow that generates a current is distorted, similarly to how obstacles distort waves in the sea. This process is how ordinary metals acquire resistance. However, when the impurities are magnetic and have a permanent magnetic moment, or spin, there is an additional contribution to resistance due to electron collisions accompanied by spin flips. (This behavior can occur because electrons also have their own spin.) This purely quantum effect profoundly modifies the properties of a metal. For instance, to an outside observer, mobile electrons appear a thousand times heavier than they really are because they tend to spend more time talking to the local spins and hence move slower.

Naturally, the spin-flipping collisions of electrons depend on how easily the electrons can modify the state of magnetic impurities. If the local spins are rigid and cannot be flipped, the system behaves as an ordinary metal. An especially interesting situation occurs when this rigidity arises because of competing spin-spin interactions with other nearby impurities. Whenever these interactions occur, the magnet is said to be frustrated because a magnetic impurity does not know if it should allow the mobile electron to flip its spin, or if instead it should remain rigid, obeying its surrounding localized partners. As a result of this confusion, the individual spins experience wild quantum fluctuations. Clearly, magnetic frustration should prevent electrons from efficiently communicating to the local spins, hence making them lighter. But figuring out which tendency wins remains a puzzle for scientists.

Interestingly, observing ultracold alkaline-earth atoms in an optical lattice can shed some light on this issue. The ultracold atoms can move and their nuclei have spins: the former allows scientists to model the flow of conduction electrons, while the latter can be used to capture the effects of magnetic frustration by building bound molecule-like states of two atoms and confining them in deep energy wells of the lattice. These molecules are

In an exciting new theory investigation, Fellow Ana Maria Rey and research associate Leonid Isaev have showed how ultracold atoms in optical lattices can model the interplay of two fundamental factors affecting the flow of electrons in metals.

not featureless, however: the same nuclear spins that enable their creation also give them an internal structure with different states encoded by red, green and blue colors in the figure.

When an itinerant atom (represented by black spheres in the figure) hops into an energy well, it can rapidly change the state (color) of the bound pair sitting in that well. As itinerant atoms move around the lattice they mix the colors of the local molecules, thus making them appear white and entangled.¹ But at the same time, this process slows down the atoms and makes them appear heavier than they really are, similar to the electrons described earlier. Thus, studying a cold-atom system reveals a peculiar regime in which heavy electrons (modeled by the freely hopping, but heavy, itinerant atoms) can happily exist in a frustrated magnetic system.

Fortunately, the Ye lab will soon be ready to test this complex new theory of conduction in the laboratory with ultracold alkaline-earth atoms in an optical lattice. Stay tuned.

1. When particles are entangled, it means that when something happens to one of them, the other responds.

L. Isaev and A. M. Rey, *Physical Review Letters* **115**, 165302 (2015).

The Land of Enhancement: AFM Spectroscopy

Custom AFM cantilevers open the door to watching the process of protein folding/unfolding

The Perkins Group has demonstrated a 50-to-100 times improvement in the time resolution for studying the details of protein folding and unfolding on a commercial Atomic Force Microscope (AFM).

This enhanced real time probing of protein folding is revealing details in these complex processes never seen before. This substantial enhancement in AFM force spectroscopy may one day have powerful clinical applications, including in the development of drugs to treat disease caused by misfolded proteins. Misfolded proteins are implicated in such fatal maladies as Creutzfeldt-Jakob disease and mad cow disease, both of which are caused by prions.

The Perkins Group has been continually improving AFM as a powerful tool to understand the structure and function of proteins through force spectroscopy, measuring the tiny changes in forces as proteins fold and unfold. These folding processes lead to protein function. To get better real-time force spectroscopy, Devin Edwards made a significant breakthrough in optimizing AFM cantilevers for force spectroscopy. The cantilever is the diving-board-like structure that pulls on the proteins.

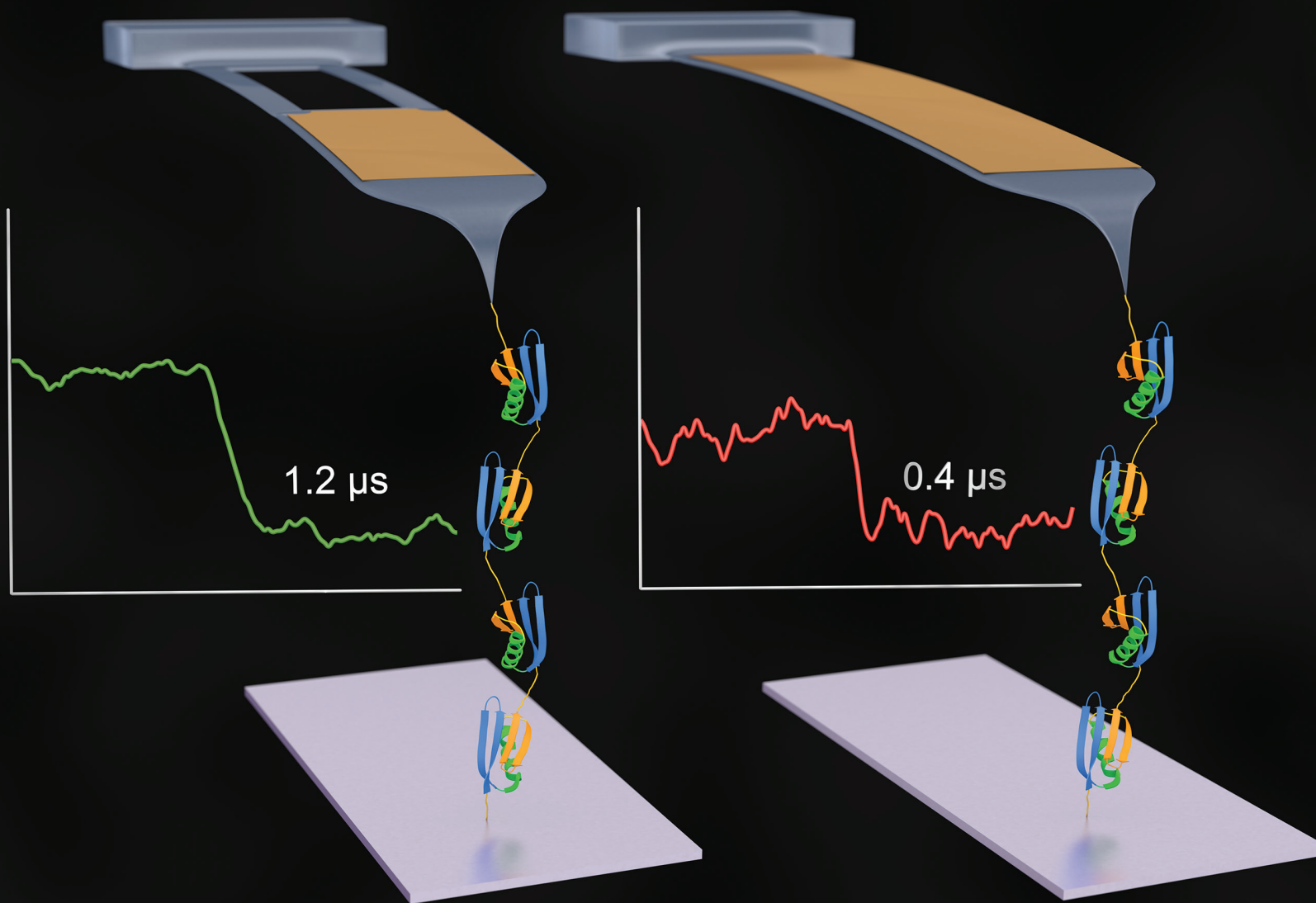
The first step for Edwards and his colleagues was to start with very small, commercially available cantilevers that would respond quickly to changes in protein structure. The key advancement was to substantially reduce the tendency of these small cantilevers to bounce up and down, or ring, in response to normal random movements of the surrounding liquid molecules (Brownian motion). To do so, the team used a focused-ion beam micro-fabrication tool to modify specialized cantilevers that are simultaneously very small (9 nm long) but do not ring. However, these modified cantilevers

were initially too curved for use. The team then developed an innovative and efficient way to straighten out these diving board-like structures, thereby dramatically enhancing the yield of the fabrication process.

The new AFM system is optimized for single-molecule force spectroscopy, a technique used to mechanically measure the folding and unfolding of proteins. The system is capable of detecting changes in a protein's configuration during the folding or unfolding process because it has an amazing resolution in time of less than 1 μ s. The researchers responsible for this feat of nano-engineering included research associates Devin Edwards and Robert Walder, undergraduate students Jaevyn Faulk and Matthew Bull (now a graduate student at Stanford), Aric Sanders of NIST, Marc-Andre LeBlanc and Prof. Marcelo Sousa of the University of Colorado Boulder, and Fellow Tom Perkins.

The researchers used their new custom AFM system to monitor the unfolding of a single polypeptide consisting of 59 amino acid subunits. They found they were able to measure the process with 50-100 times better time resolution than traditional AFM-based force spectroscopy and see small changes better than ever before. The new capability bodes well for future work in the Perkins Lab.

"We want to watch biological processes like protein folding on ever faster time scales," Perkins said. "Now we can do this more easily (than before) with



During AFM spectroscopy of protein unfolding, the 9- μm -long micromachined cantilever (left) custommade in the Perkins Lab significantly reduced the bouncing (ringing) that occurred with a commercially available cantilever (right). Credit: The Perkins group and Steve Burrows, JILA

a lot more precision. We are at the point where we can actually watch proteins fold and unfold with microsecond time resolution.”

The researchers proved that their new cantilevers work well on a commercial AFM, which can process more samples and work faster than a custom system. The commercial AFM was retrofitted with a special small laser detection system with a tiny 3- μm circular spot size that just fit on the tiny reflective gold surface on the top of the cantilever. Using this system on a commercial AFM opens

the door to other labs adopting the new cantilever technology for biological assays, potentially leading to better understanding of the complex roles protein folding plays in various diseases, and perhaps leading to new drug treatments.

Devin T. Edwards, Jaevyn K. Faulk, Aric W. Sanders, Matthew S. Bull, Robert Walder, Marc-Andre LeBlanc, Marcelo C. Sousa, and Thomas T. Perkins, *Nano Letters*, 15 7091–7098 (2015).

Natural Born Entanglers

The Regal and Rey groups have come up with a novel way to generate and propagate quantum entanglement,¹ a key feature required for quantum computing. Quantum computing requires that bits of information called qubits be moved from one location to another, be available to interact in prescribed ways, and then be isolated for storage or subsequent interactions. The group showed that single neutral atoms carried in tiny traps called optical tweezers may be a promising technology for the job!

To prove this, the group prepared two ultracold neutral atoms of rubidium, then moved them until they were on top of one another. This positioning caused the spins of the atoms to become entangled after a bit of time. The group then separated the atoms while preserving their entanglement. The researchers were able to prove the enduring entanglement via measurements of the spin states of the separated atoms: When one of the atoms was spin up, the other was always spin down. However, the direction of each spin fluctuated from one experiment to the next.

This exciting work was reported online in *Nature* on November 2, 2015. The researchers responsible for it included recently minted Ph.D. Adam Kaufman, graduate student Brian Lester, research associate Michael Wall, Fellows Ana Maria Rey and Cindy Regal, and former JILA Michael Foss-Feig of the Joint Quantum Institute.

One of the most interesting parts of this work was that just moving two almost identical atoms in different spin states on top of one another was sufficient to cause them to become entangled.

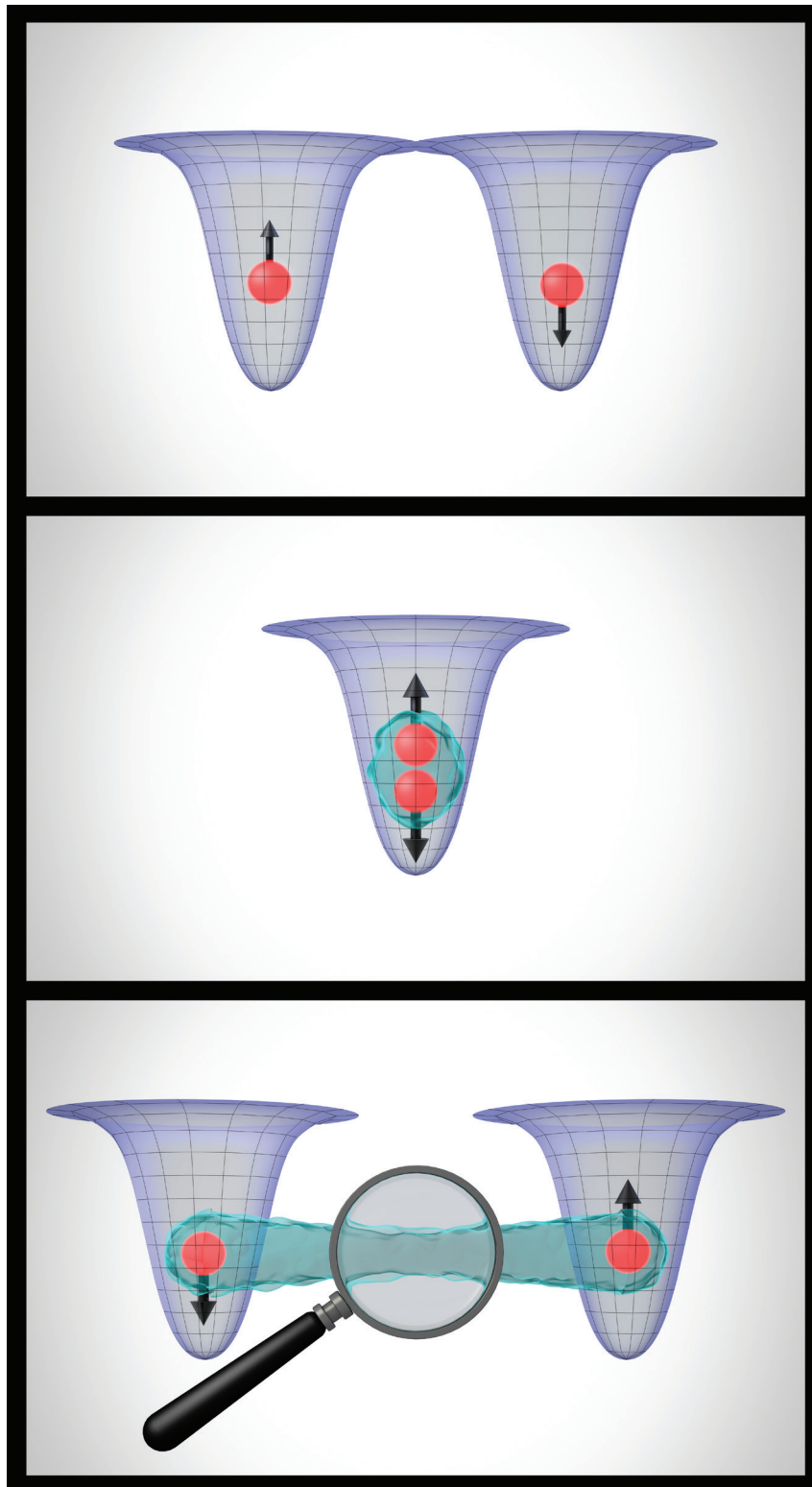
One of the most interesting parts of this work was that just moving two almost-identical atoms in different spin states on top of one another was sufficient to cause them to become entangled. When atoms (which exist as waves in the quantum world) get this close together, their waves overlap. As the atom waves “talk” to each other, they discover neither one of them is staying in one of their natural spin states, which they are normally happy to remain in indefinitely. Both atoms start flipping back and forth between spin up and spin down. It’s impossible to know which atom is spin up and which one is spin down at any give moment. Thus, the probability of measuring a particular configuration oscillates in time. This process leads to entanglement at certain times.

“All you have to do is place the atoms on top of one another, and they evolve into the state we want,” explained Regal. “You could say it occurs naturally.” In fact, the process used by the researchers happens in real materials with identical electrons.

And, if the researchers then separated the atoms, the atoms stayed entangled.

1. When two atoms are entangled, it means the behavior of one atom is correlated with the other.

A.M. Kaufman, B. J. Lester, M. Foss-Feig, M. L. Wall, A. M. Rey, and Cindy Regal, *Nature* 527 208–211 (2015).



Placing two rubidium atoms on top of each other results in their naturally evolving into an entangled state. When the atoms are separated, the entanglement is preserved. These characteristics will be important for building a quantum computer. Credit: The Regal group and Steve Burrows, JILA

DANCING to the Quantum Drum Song

In the future, quantum microwave networks may handle quantum information transfer via optical fibers or microwave cables. The evolution of a quantum microwave network will rely on innovative microwave circuits currently being developed and characterized by the Lehnert group. Applications for this innovative technology could one day include quantum computing, converters that transform microwave signals to optical light while preserving any encoded quantum information, and advanced quantum electronics devices.

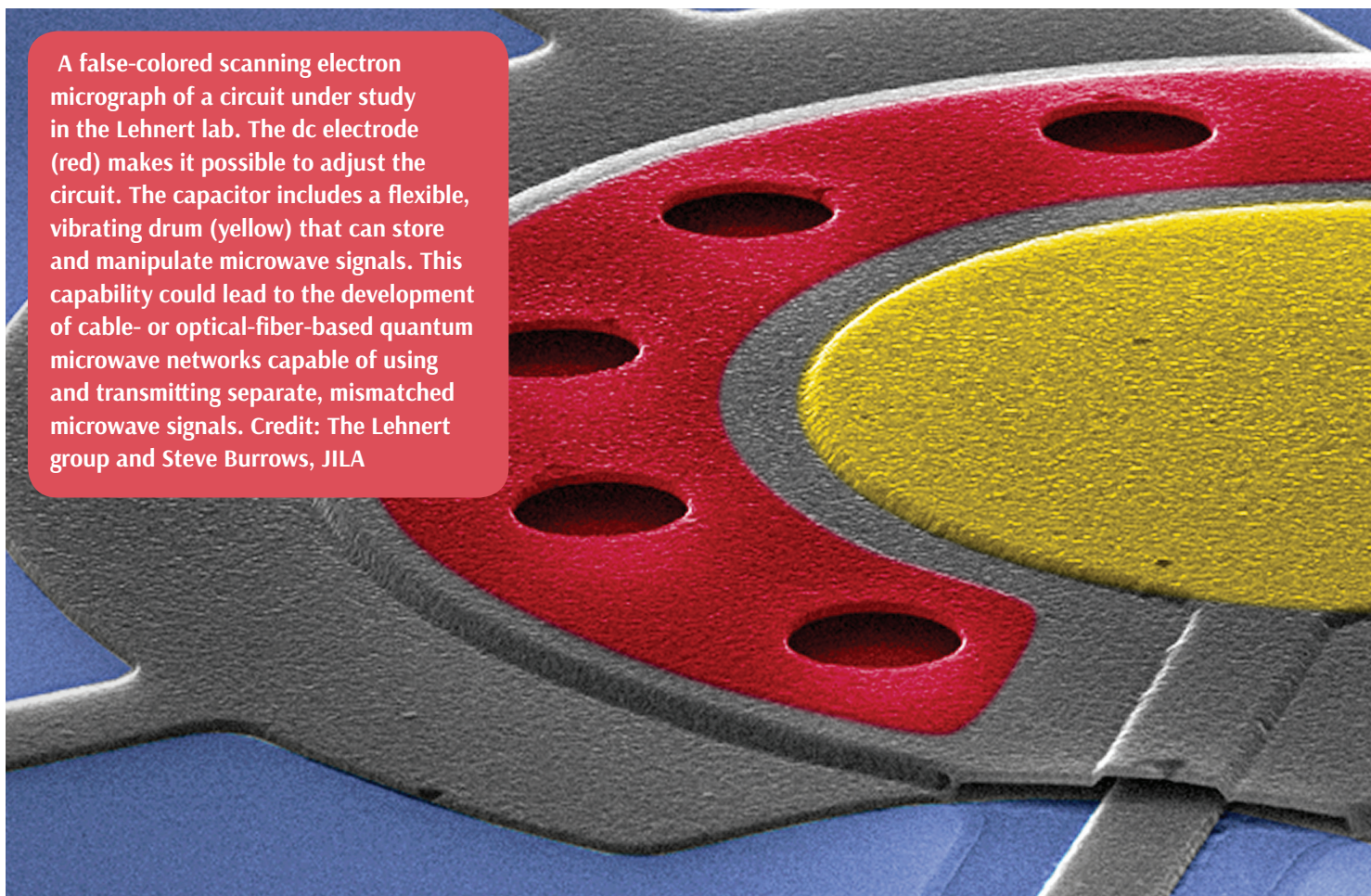
In recent work, the group demonstrated that a flexible aluminum drumhead embedded in a microwave circuit made it possible for researchers

to manipulate the timing and shape of microwave signals while preserving their quantum nature. The oscillating drumhead (yellow in the picture) is actually part of the microwave circuit's capacitor, whose two charge-conducting surfaces are just 40 nm apart.

The capacitor's job is to accumulate and hold electrical charge. The dc electrode (red in the picture) allows the researchers to adjust the capacitor, which in turn allows them to change the circuit's resonant frequency, making it possible to connect the circuit to other microwave quantum devices.

The drumhead's job is to encode the quantum information in the microwave signal as mechanical

A false-colored scanning electron micrograph of a circuit under study in the Lehnert lab. The dc electrode (red) makes it possible to adjust the circuit. The capacitor includes a flexible, vibrating drum (yellow) that can store and manipulate microwave signals. This capability could lead to the development of cable- or optical-fiber-based quantum microwave networks capable of using and transmitting separate, mismatched microwave signals. Credit: The Lehnert group and Steve Burrows, JILA



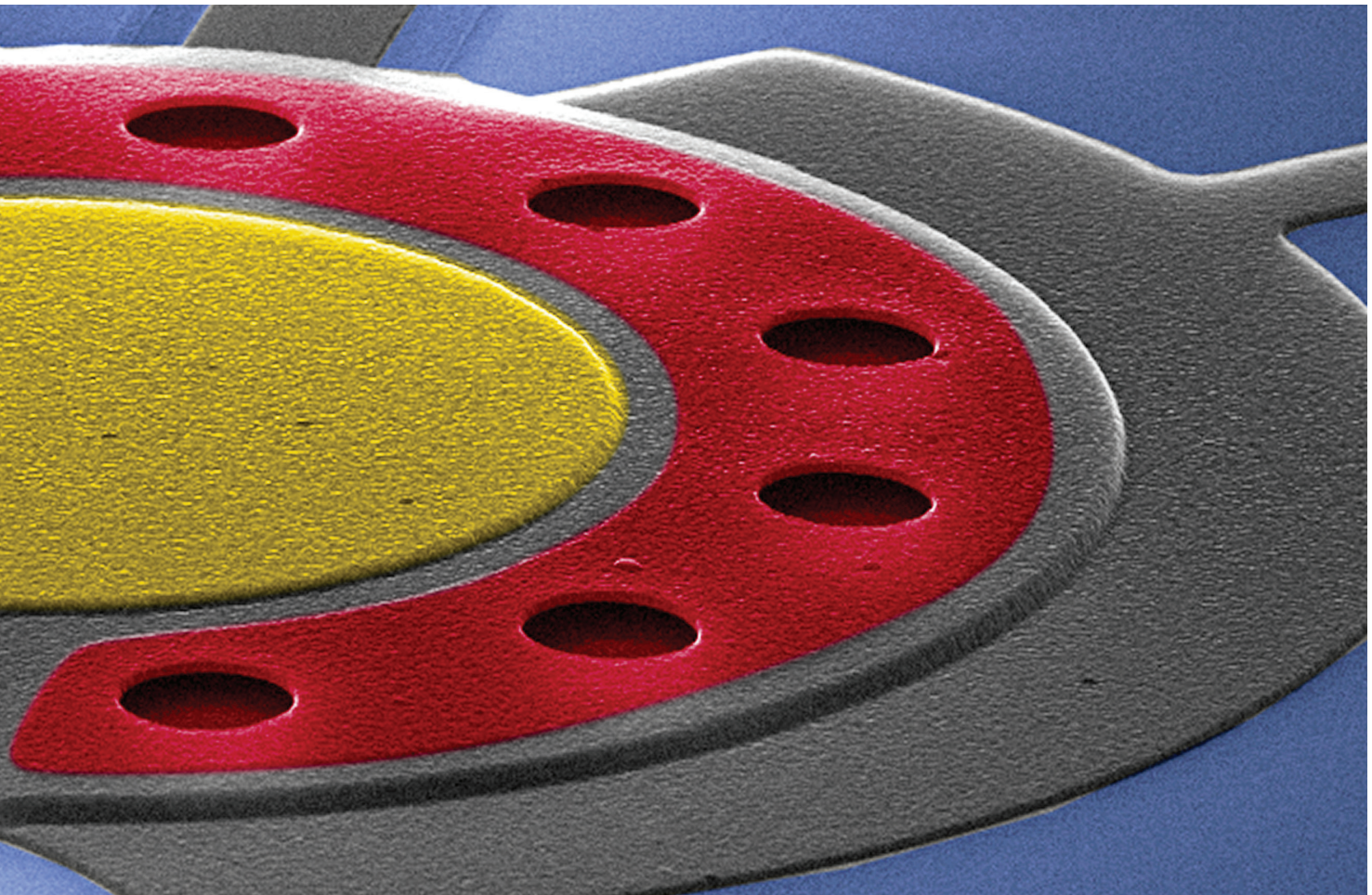
motion and store the quantum information intact until the drumhead's mechanical motion can be reconverted back into microwave radiation. After reconversion, the researchers verified that the quantum information had indeed come through in good shape.

"We've learned how to manipulate the information in a microwave signal in a unique way" explains graduate student Adam Reed. "We do this by taking the energy in a propagating electrical signal and transferring it into a drum that's vibrating at megahertz frequencies even though our electrical signal is vibrating at gigahertz frequencies."

Reed's collaborators on this amazing project included former research associate Reed Andrews, Fellow Konrad Lehnert as well as Katarina Cicak and John Teufel of NIST Boulder's Advanced

Microwave Photonics group. The researchers believe their drumhead-containing capacitor and its microwave circuit hold great promise for the future of quantum electronics. The device may allow engineers to build quantum microwave networks from separate and even mismatched components that can be synchronized via the transfer of quantum information in and out of the drumhead. The device could one day make it possible to prepare quantum states of motion in an object large enough to visible to the naked eye. This process would rely on capturing quantum microwave signals prepared by artificial atoms or superconducting qubits, which are the fundamental units of information in a quantum computer.

R. W. Andrews, A. P. Reed, K. Cicak, J. D. Teufel, and K. W. Lehnert, *Nature Communications* **6** 10021 (2015).



IN THE NEWS IN THE NEWS?

A selection of news, awards, and what is happening around JILA

JUN YE SELECTED FOR 2015 PRESIDENTIAL RANK AWARD

President Obama has selected JILA Fellow Jun Ye of NIST's Quantum Physics Division to receive a 2015 Presidential Rank Award. The award cited Ye's work advancing "the frontier of light-matter interaction and focusing on precision measurement, quantum physics and ultracold matter, optical frequency metrology, and ultrafast science."

The Presidential Rank Awards honor a select group of senior Federal employees for "sustained extraordinary accomplishment." These employees are "strong leaders, professionals, and scientists who achieve results and consistently demonstrate strength, integrity, industry and a relentless commitment to excellence in public service."

Ye was awarded the highest of the two Rank Award levels, the Distinguished Executive, which can be given to no more than 1% of the approximately 6,800 senior Federal employees across the nation. The Award includes a monetary prize equal to 35% of the employee's base pay, plus a certificate signed by the President.

The award recognizes Ye as a world leader in laser and atomic physics. He has a long and diverse list of major accomplishments, including the world's most accurate atomic clock, the world's most stable laser, extreme ultraviolet frequency combs, major advances with ultracold molecules and chemistry (partly with Debbie Jin), pioneering novel quantum many-body phenomena, and many other breakthroughs.

Congratulations to Jun Ye!

SCIENCE BUFFS FEATURES JILA'S INNOVATIVE PLATFORM FOR OBSERVING THE ULTRAFAST AND ULTRASMAALL

Graduate student Chris Mancuso and senior research associate Dan Hickstein of the Kapteyn/Murnane group recently spoke with Amanda Grennell, a 5th year Ph.D. candidate in Chemistry at the University of Colorado Boulder. The researchers discussed the K/M group's paper "Strong-field ionization with two-color circularly polarized laser fields," which appeared in *Physical Review A* in March, 2015. The result is a delightful blog post of the K/M group's groundbreaking research on imaging with circularly polarized laser fields. The story includes terrific animations prepared by Hickstein. The story was posted by the BioFrontiers Science Alliance.

Enjoy learning about two-color circularly polarized laser fields at <http://www.sciencebuffs.org/>

JAN HALL SPEAKS ABOUT LIGHT, ATOMIC CLOCKS, AND TESTING EINSTEIN'S ASSUMPTIONS AT THE KECK INSTITUTE FOR SPACE STUDIES

JILA's laser guru Jan Hall spoke about light, atomic clocks, and testing Einstein's assumptions on Nov. 4, 2015, at the Keck Institute for Space Studies. A lively video of the talk can be found at http://kiss.caltech.edu/new_website/lectures/Hall_Lecture_2015.html

Jan's abstract is a good synopsis of the video talk: "Even though this is the 55th year of the laser, progress in its control and application in precision measurements is still accelerating. The optical frequency comb technology exploded in 1999-2000 from the synthesis of advances in independent fields of laser stabilization, ultrafast lasers, and nonlinear optical fibers, enabling a thousand-fold advance in optical frequency measurement, and searches (in the 17th digit) for time-variation of physical "constants." Several optical frequency standards now have far better performance than the well-established Cs clock that defines time in the SI (metric system) measurement system. But adopting a new "atomic clock" to "tick out the seconds" will be daunting in many ways. Current advances in ultraprecise locking are also making possible stable optical frequencies defined by length and the speed of light, as well as by locking lasers to the resonant

How Did They Get Here?

Fellow and physicist **Andreas Becker** joined the JILA faculty as an Associate Fellow in August of 2008. He became a Fellow in 2012. His specialty is ultrafast laser theory, a topic of interest to several JILA labs, including the Kapteyn/Murnane group. His wife, theorist Agnieszka Jaron-Becker, also arrived in 2008. She is an Associate Fellow of JILA. They are the proud parents of Anna Sophie, who has yet to decide whether she wants to be a physicist when she grows up.

Anna Sophie's father decided to turn his strong interests in physics and math into a career in physics while still in high school. Soon after starting work at the Universität Bielefeld (Germany), he decided to become a theoretician. He liked interpreting experimental results and making calculations that predict experimental findings, then getting to see the pertinent experiments actually happen a few years later. Becker received his Diploma (equivalent to a Master's degree) from Bielefeld in 1993 for studies of electron/atom collisions and a Ph.D. from the same institution in 1997 for his work on ultrafast laser theory.

Armed with a Feodor Lynen Research Fellowship from the Alexander von Humboldt Foundation, Becker came to the Université Laval in Quebec, Canada, in 1999 for postdoctoral studies with See Leang Chin. There Chin advised him, "Don't do only theory. Go into the lab and get your hands dirty." Becker argued that he'd break everything in the lab and then Chin would have to buy more equipment. Chin retorted, "Don't worry, all graduate students do this."



For 12 months Becker worked with an experimental team studying the effect of intense lasers on the ionization of atoms and molecules and the propagation of ultrashort laser pulses in air and other materials. He not only learned how to gather, read, and interpret data, but also became the first author on the experimental part of a paper that explored both experiment and theory.

In 2001, Becker returned to Germany to obtain his Habilitation, the highest academic qualification one can achieve in Germany. He worked on ultrafast-laser theory both at Bielefeld and at the Max Planck Institute for the Physics of Complex Systems in Dresden. He became head of his own research group in 2002 and completed his Habilitation in June of 2003. Becker worked at Dresden until he and his family came to JILA in 2008.

At JILA, Becker is working on several projects. He is continuing his exploration of the role of Coulomb interactions in the simultaneous removal of two electrons from an atom—a complex topic he has now successfully modeled after more than a decade of work. In collaboration with his wife Agnieszka, he is also studying the use of ultrafast lasers to image electron wave distributions in molecules and deduce the molecular radius of fullerenes (C^{60} – C^{180}). Other theoreticians predict that under an intense laser pulse C^{60} will breathe—a prediction the Beckers hope can be imaged with their theory and tested experimentally at JILA. Finally, he is exploring the interaction of attosecond laser pulses with electrons in atoms and molecules as well as investigating the control of these dynamics with coherent ultrashort laser pulses.

Becker says he's excited to be exploring all these ideas here at JILA. "What's great about being a theorist at JILA is that you can knock, for example, on Henry and Margaret's door and say, hey I have this crazy idea," he explains. "Then we can discuss it and hopefully come up with something new."



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 in the Duane Physics complex.

JILA's faculty includes two Nobel laureates, Eric Cornell and John Hall, as well as three John D. and Catherine T. MacArthur Fellows, Margaret Murnane, Deborah Jin, and Ana Maria Rey. JILA's CU members hold faculty appointments in the Departments of Physics; Chemistry and Biochemistry; and Molecular, Cellular, and Developmental Biology as well as in the School of Engineering. NIST's Quantum Physics Division members hold adjoint faculty appointments at CU in the same departments.

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 seven broad categories: Astrophysics, Atomic & Molecular physics, Biophysics, Chemical physics, Laser Physics, Nanoscience, Precision Measurement, and Quantum Information.

To learn more visit:
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