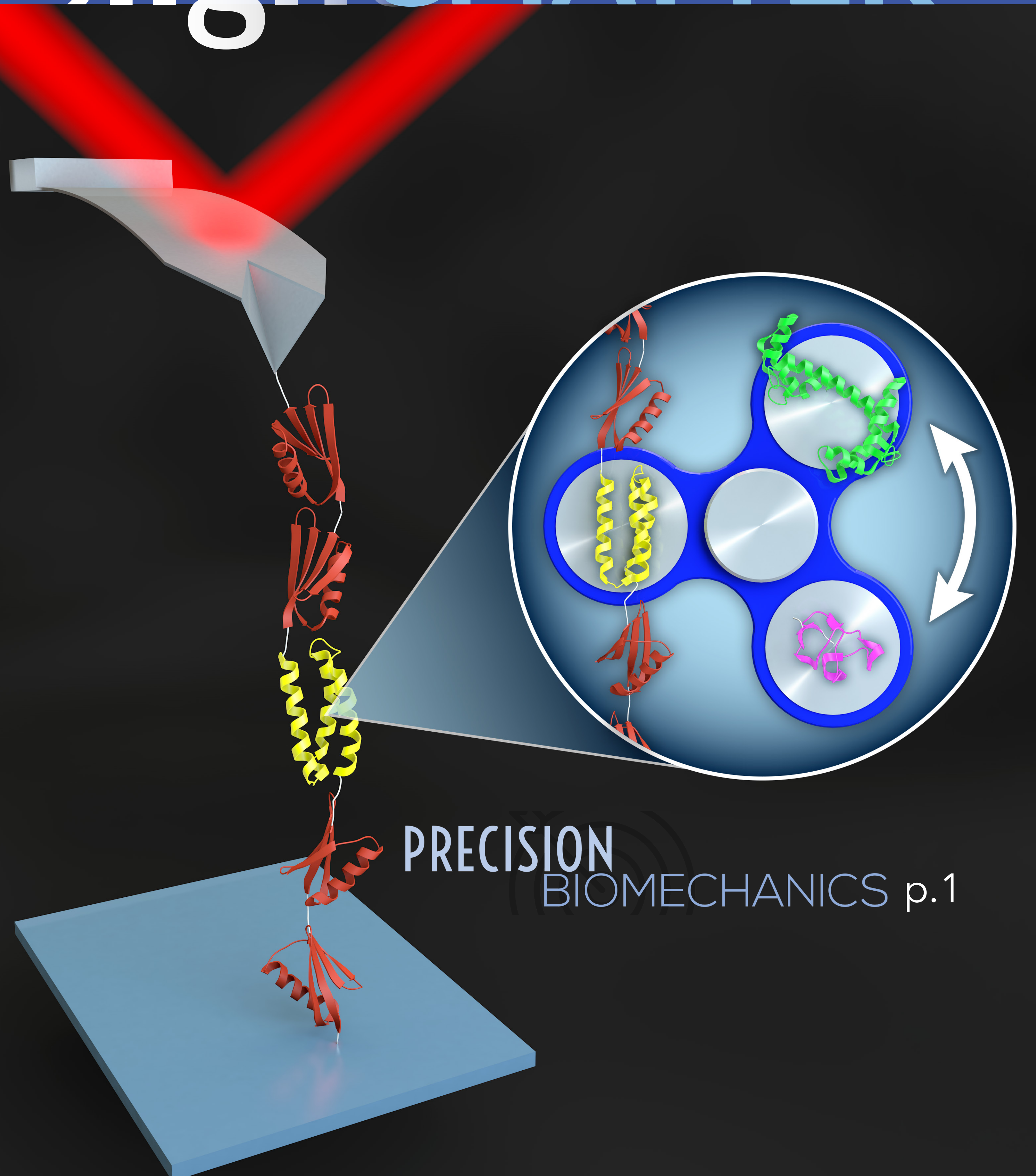
JILA
Fall 2017 | jila.colorado.edu

light & MATTER



PRECISION BIOMECHANICS p.1

A frosty view from JILA on a cold, fall morning. Credit: Kristin Conrad, JILA.

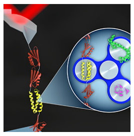
JILA Light & Matter is published quarterly by the Scientific Communications Office at JILA, a joint institute of the University of Colorado Boulder and the National Institute of Standards and Technology.

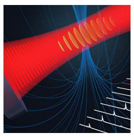
The editors do their best to track down recently published journal articles and great research photos and graphics. If you have an image or a recent paper that you'd like to see featured, contact us at: communications@jila.colorado.edu.

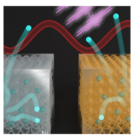
Please check out this issue of *JILA Light & Matter* online at https://jila.colorado.edu/publications/jila/light-matter.

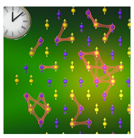
Kristin Conrad, Project Manager, Design & Production
Julie Phillips & Catherine Klauss, Science Writers
Steven Burrows, Art & Photography
Gwen Dickinson, Editor

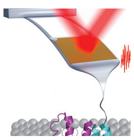
Stories

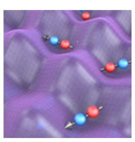












Features

Precision Biomechanics

The Perkins group has made dramatic advances in the use of Atomic Force Microscopes (AFMs) for studying large single biomolecules, such as proteins and nucleic acids (DNA, RNA), that are important for life. After improving AFM measurements of biomolecules by orders of magnitude for stability, sensitivity and time response, the Perkins group has now developed ways to make these precision biomechanical measurements up to 100 times faster than previously possible—obtaining useful information in hours to days rather than weeks to months.

The Perkins group uses its precision AFM technology to measure the tiny forces and structural states involved in the folding and unfolding of individual molecules of proteins and nucleic acids in their native wet, warm biological environments. How proteins fold and unfold normally—and sometimes misfold—are crucial questions to understanding normal physiology and many of the most widespread and devastating diseases such as cancers, neurodegenerative diseases, and some heart diseases. The Perkins group had already used their AFM technology to reveal new details in the biomechanics of key proteins. Now by enormously increasing the rate of acquiring these precision measurements, the group's latest AFM technology will provide bioscientists with a flood of new crucial information.

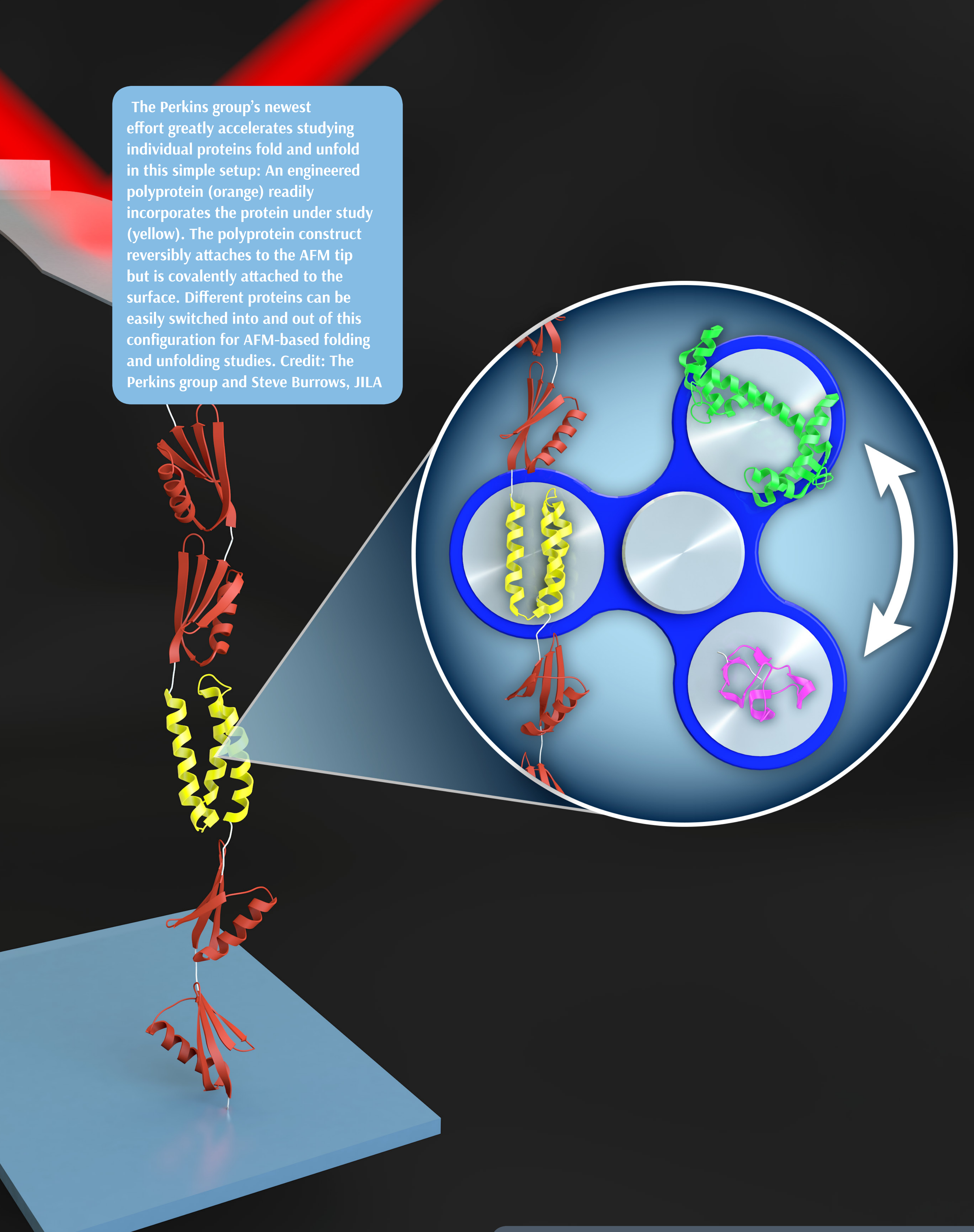
The group accomplished this game-changing feat by (1) developing a relatively easy and reproducible method to anchor a target biomolecule with special chemical groups to an otherwise non-stick cover slip and an AFM tip, and (2) creating a novel protein-stretching platform that allows the researchers to efficiently embed different proteins under study into a larger protein structure.

The researchers also engineered the attachment to the cover slip to be permanent, but the attachment between the biomolecule and the cantilever tip to be mechanically strong, but reversible. This configuration prevents buildup of unfolded protein on the AFM tip, making it possible to repeatedly use a single tip to study hundreds-to-thousands of proteins over relatively short time periods. With this system, it is now possible to fully characterize the folding and unfolding of a protein in one or two days.

"What Rob Walder developed over the course of years was a way to do this surface preparation rapidly, in fewer steps, and, most importantly, reliably," explained Fellow Tom Perkins. "What we've got now is the surface chemistry working on one end and the polyprotein-surface chemistry working on the AFM tips, so we can just rotate in the relevant proteins in the middle of these two and study what happens to the protein when we tug on it with the cantilever."

The new technique produces useful scientific data up to 100 times faster than older ways of doing similar research.

"We can now take publication quality data in a day or two that used to take us weeks to months," Perkins explained. "And, along the way, we've improved the quality of the data, and that's meant we've been able to do more complex experiments." (cont. page 3)



The Perkins group's newest effort greatly accelerates studying individual proteins fold and unfold in this simple setup: An engineered polyprotein (orange) readily incorporates the protein under study (yellow). The polyprotein construct reversibly attaches to the AFM tip but is covalently attached to the surface. Different proteins can be easily switched into and out of this configuration for AFM-based folding and unfolding studies. Credit: The Perkins group and Steve Burrows, JILA

(cont. from page 1) Two key innovations came together to produce the precision biomechanical studies now occurring in the Perkins Lab: First, the group teamed up with Prof. Marcelo Sousa's lab to make a protein-like backbone (called a polyprotein) that not only adhered strongly to the AFM tip, but also readily attached or detached to the protein or nucleic acid to be studied. Second, the researchers figured out the chemistry that allowed them to solidly anchor the biomolecule on a cover slip or other surface. This precisely engineered system has opened the door to many years of fruitful research.

"Now what we can do is drop in different types of proteins and get really high quality data," Perkins said. "It's a lovely situation to be in." ✺

R. Walder, M.-A. LeBlanc, W. J. Van Patten, D. Edwards, J. A. Greenberg, A. Adhikari, S. R. Okoniewski, R. M. A. Sullan, D. Rabuka, M. C. Souse, and T. T. Perkins, *Journal of the American Chemical Society*, **139,** 9867–9875 (2017).

Follow our research on social media!

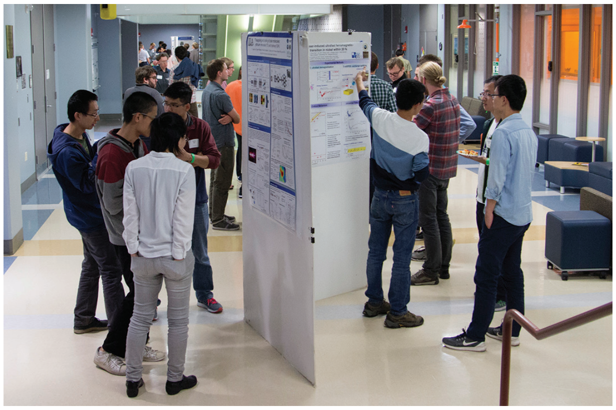
https://www.facebook.com/JILAscience

https://twitter.com/JILAScience

https://www.instagram.com/jilascience/

https://www.youtube.com/user/JILAscience

5^{th} Annual JILA Posterfest



The 5^{th} annual JILA posterfest was a smashing success, thanks to the outstanding posters, as well as the snacks.

The event, held this past Thursday, October 19, had 45 posters sharing the latest JILA research, from the very small (such as T. Thiele's, "*Toward Atomic Arrays Close to Nanoscopic Devices*") to the very large (such as A. Zderic's "*A Dynamical Instability in the Outer Solar System*").

JILA's posterfest was full of discussion. Many students, postdocs, and fellows used the opportunity to catch up on their neighbor's research. Events like these foster the collaborative and supportive research atmosphere that makes JILA a leading research institute. For more photos from the event, see the JILA Facebook page (https://www.facebook.com/JILAscience).

A huge thank you to our JILA Post Award Team (JPAT) hosts who made this a great event and to all the JILAns who particpated!

Tom Perkins Bestowed Governor's Award

At the CO-LABS' 2017 Governor's Awards for High Impact Research Thursday October 5, 2017, JILA Fellow Tom Perkins received a plaque commemorating his work described as *New Twists in the Molecules of Life*.

Tom Perkins, right, and his wife, Alden Perkins, stand together during the post-ceremony reception.

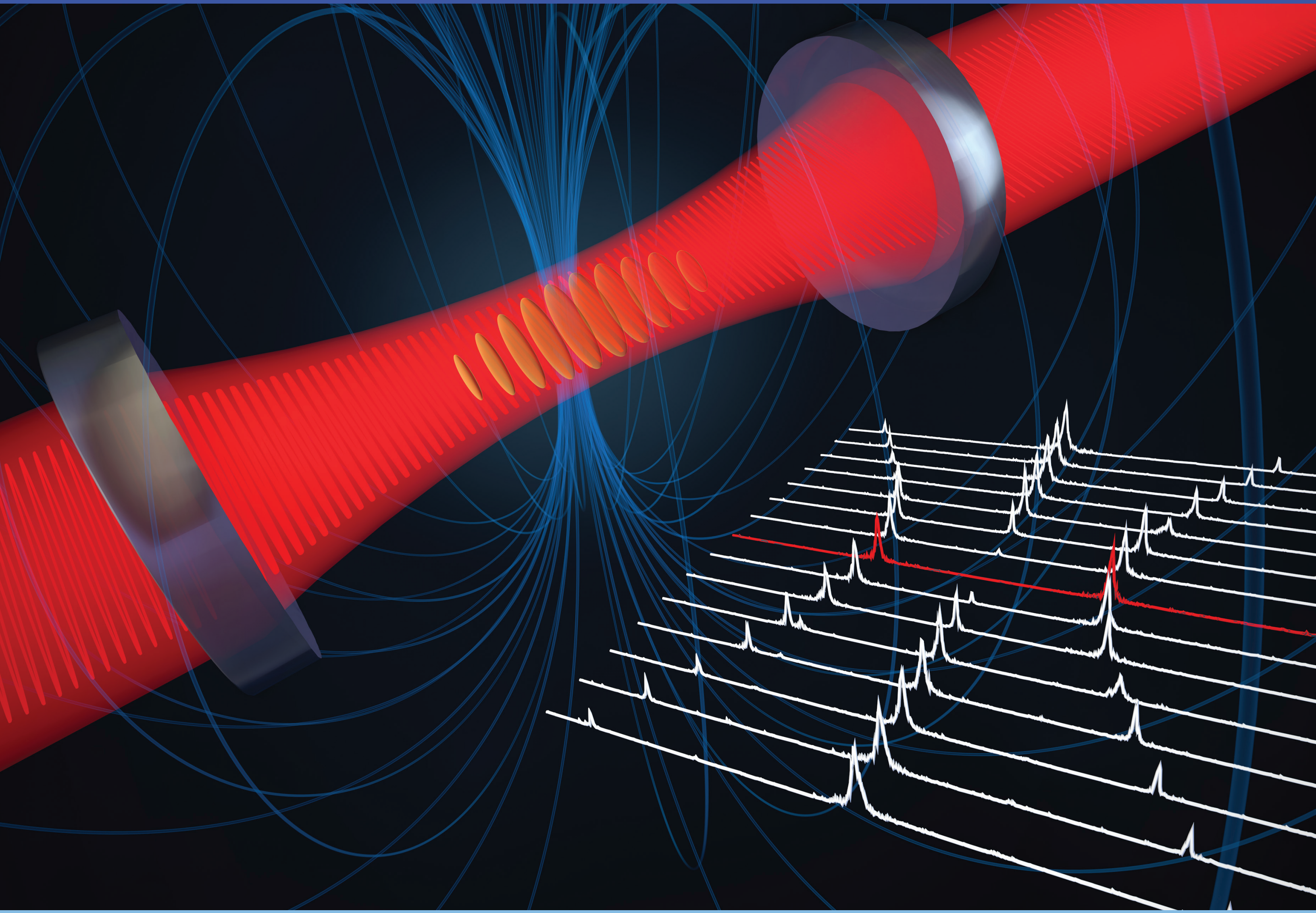
This year's ninth annual event honored Colorado's top scientists and engineers for projects that have had a significant impact on society. "The projects in this year's CO-LABS High-Impact Awards spotlight are what makes Colorado a leader in innovation," said Governor John Hickenlooper. "It's terrific to see research advance its partnerships with the private sector. I congratulate the scientific teams for their groundbreaking work and am excited to see the mark they will leave on our state and society as a whole."

In a decade long project, Perkins developed powerful new tools to measure and study individual biomolecules. He then partnered with the biotech industry to develop tools to improve the measurement and understanding of the structure and function of single proteins and nucleic acids, which play key roles in the biophysics and biochemistry of life. Amazingly, Perkins' new tools can probe these key biomolecules in real time and under real world conditions.

Starting with an ordinary atomic-force microscope (AFM), Perkins painstakingly modified the AFM cantilevers to make the world's most precise measurements of the structural components of individual proteins and nucleic acids. Today, he watches these large, complex molecules fold and unfold as they perform normal biological functions. His new AFM technology can completely analyze the folding and unfolding of a biomolecule in 2–3 days, a process that once took months of work.

The awards ceremony and reception were held at Denver Museum of Nature and Science. Perkins attended the ceremony last with his wife, Alden Perkins.

Three more awards celebrated innovative techniques in GPS, improvements of scanning electron microscopes, and the development of true-color imagery for geostationary satellites.



Experimental setup with strontium atoms in an optical cavity (top) that led to an unexpected peak in the data (below). The center peak in the data showed that for certain strengths of a magnetic field, the atoms and cavity become transparent to light. Credit: The Thompson group and Steve Burrows, JILA

Lassoing Colors with Atomic Cowpokes

How to use a magnetic field to enhance the frequency stability of a laser

Getting lasers to have a precise single frequency (color) can be trickier than herding cats. So it's no small accomplishment that the Thompson group has figured out how to use magnetic fields to create atomic cowpokes to wrangle a specific single color into place so that it doesn't wander hither and yon. The researchers do this with a magnetic field that causes strontium atoms in an optical cavity to stop absorbing light and become transparent to laser light at one specific color. What happens is that the magnetic field creates a transparent window that serves as a gate to let only light of a single frequency pass through.

Plus, the group showed how this transparency might be used to enhance the frequency stability of lasers. By matching a laser's frequency to that of the transparent window, the laser can be stabilized in a way that makes it insensitive to wanderlust. Wanderlust is caused by vibrations of the mirrors at both ends of the optical cavity, posing a serious challenge for making laser light as pure of a single color as possible. This new insight into laser stabilization could have a big impact on research and industry endeavors that require reasonably simple laser systems for precision measurement or the development of portable optical-timekeeping devices.

This breakthrough almost didn't happen.

"A long time ago we were exploring a totally different project, and we saw a feature we didn't understand," explained graduate student and ranch hand Matthew Norcia. "At first, we put it on the back burner. Then, we tried to tune it out and see if we could get rid of it."

This breakthrough almost didn't happen.

Eventually, the researchers decided to try and understand where the mysterious peak had come from and what it meant.

The surprising peak that the group originally decided to tune away has now yielded a lovely result. Understanding the peak has led to a promising new way to stabilize lasers to atoms and optical cavities.

"So what the cavity does, is let the light through when the laser is exactly at the correct frequency," explained undergraduate student Matthew Winchester. "It's kind of a passive system that just sits there, and you shine a light on it. If the laser is at the right frequency, it lets the light through."

Optical cavities normally do this as well, but if you change the distance between the mirrors, the transmitted color changes by a lot, kind of like a steer that can wander off anywhere and get lost. In this system, there are two special states of the atom that act like two cowhands that lasso the frequency and hold it in place. As the cavity length changes, the ropes may stretch a little, allowing the frequency to change by a little. But, by using a magnetic field, the researchers showed that the stretchiness of the ropes could be tuned in a way that changed the frequency by up to 20 times less than was normally possible without the atoms hogtying the frequency down. They also showed that it didn't matter if the atomic ropes were a little frayed by things such as Doppler broadening—the atoms still do a great job of tying down the frequency.

This is a big deal. With the atoms wrangling the frequencies into place, two labs in distant parts of the Universe could build their own versions of the system, and expect them to yield the same frequency—in much the same way as two atomic clocks based on the same kind of atom should always tick at the same rate.

A key feature of the new stabilization tool is that it is relatively simple to make in the lab and relatively immune to vibrations. These features suggest these atomic lassos may be useful for industrial and portable devices that work outside of the laboratory.

The cowhands responsible for discovering this new laser stabilization technique include undergraduate Matt Winchester, graduate students Matt Norcia, and Julia Cline as well as Fellow James K. Thompson. Their work appeared online on June 26, 2017, in *Physical Review Letters*. The same day, the breakthrough of inducing transparency with a magnetic field was featured online in an American Physical Society Viewpoint. ✺

M. N. Winchester, M. N. Norcia, J. R. K. Cline, and J. K. Thompson, *Physical Review Letters* **118**, 263601 (2017).

The Electron Stops When The Bands Play On

The Kapteyn-Murnane group has come up with a novel way to use fast bursts of extreme ultraviolet light to capture how strongly electrons interact with each other in materials.

This research is important for figuring out how quickly materials can change their state from insulating to conducting, or from magnetic to nonmagnetic. In the future such fast switching may lead to faster and more efficient nanoelectronics.

In this work, graduate student Cong Chen, research associate Zhensheng Tao, and their colleagues used sequences of attosecond (10^{-18}s) bursts of extreme ultraviolet light to compare how long it took an electron to be emitted from the same energy levels, or bands, in two different metals—copper (Cu) and nickel (Ni).

In the past, scientists thought that the photoelectric effect, in which a high-energy photon kicks out an electron from a material, was instantaneous. More recently, with the advent of shorter and shorter laser pulses, scientists have been able to investigate such super-fast processes directly. And, they have discovered many surprises.

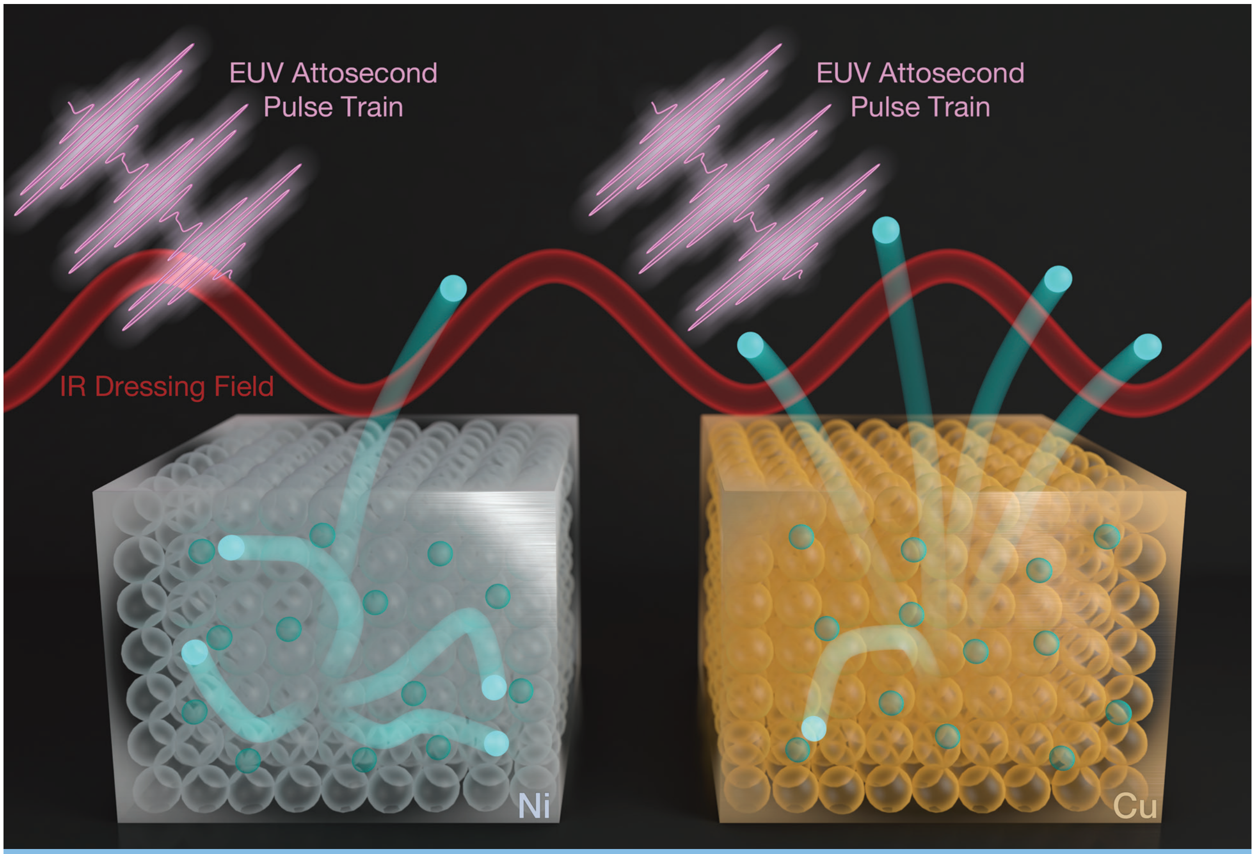
In Chen's and Tao's work, the researchers found that the photoelectron lifetime was 100 attoseconds longer in Cu than that in Ni—even though the two metals sit side by side in the periodic table and the photoelectrons were ejected from the same bands.

"This experiment enables a real time view of exactly how electrons are talking to each other in different materials," Margaret Murnane explained. "Nickel is more complicated in terms of how the electrons talk to each other than is copper. This experiment is the first measurement that can distinguish between the rearrangement of electrons, called screening, and the interaction of electrons, called scattering."

There is a key difference between the two materials, however. Nickel has more high-energy states that are normally empty. Thus, when an electron is kicked out of nickel, it has a significant probability of interacting with another electron on its way out. This interaction sends the photoelectron into one of nickel's empty states, and the photoelectron loses energy in the process. If this electron-electron scattering process occurs, it is difficult to measure the photoelectron. The result is a reduction of the photoelectron lifetime in nickel.

In contrast, when the laser light knocked out a photoelectron in copper, the researchers were able to "watch" it for 100 attoseconds. This ability to monitor electron behavior in real time should help scientists answer many important questions about materials where electron interactions are important.

"This experiment enables a real time view of exactly how electrons are talking to each other in different materials," Margaret Murnane explained. "Nickel is more complicated in terms of how the electrons talk to each other than is copper. This experiment is the first measurement that can distinguish between the rearrangement of electrons, called screening, and the interaction of electrons, called scattering."



In an experiment using ultrafast laser light, the Kapteryn/Murnane group was able to see how electrons talk to each other in different materials. Researchers observed photoelectrons coming out of copper (r) for 100 as, but most of the photoelectrons produced in nickel (l) were deflected into empty states where they couldn't be seen. Credit: The Kapteyn/Murnane group and Steve Burrows, JILA

Interestingly, the rearrangement of electrons is slower than 100 attoseconds, i.e., less than the photoelectron's lifetime. Also, since the researchers were able to directly measure electron scattering, they can use this information for the first time to disentangle which materials properties were dominated by electron screening or scattering. As a result, this experiment has opened the door to experimentally verifying the fundamental electron-electron interactions that theorists calculate. These seminal results were reported online in the *Proceedings of the National Academy of Sciences U.S.A.* on June 19, 2017.

The researchers responsible for this work include newly minted JILA Ph.D. Cong Chen, research associate Zhensheng Tao, JILA Ph.D. Adra Carr, former research associate Piotr Matyba, Fellows Margaret Murnane and Henry Kapteyn as well as colleagues from the University of Wisconsin-Madison, the University of Kaiserslautern (Germany), the National Institute of Standards and Technology, Kansas State University, and Uppsala University (Sweden). ✺

C. Chen, Z. Tao, A. Carr, P. Matyba, T. Szilvási, S. Emmerich, M. Piecuch, M. Keller, D. Zusin, S. Eich, M. Rollinger, W. You, S. Mathias, U. Thumm, M. Mavrikakis, M. Aeschlimann, P. M. Oppeneer, H. Kapteyn, M.Murnane, *Proceedings of the National Academy of Science U.S.A.* **114**, E5300-E5307 (2017).

IN THE NEWS

IN THE NEWS

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

Tom Perkins Named APS Fellow

Fellow Thomas Perkins has been named a 2017 Fellow of the American Physical Society. He was cited for innovations in precision measurement of dynamic biological systems at the smallest scales.

Perkins's fellowship was recommended by the APS Division of Biological Physics. He is the first JILA Fellow to receive an APS fellowship through this division.

The number of APS Fellows elected each year is limited to no more than one-half a percent of the membership. Only seven fellows could be elected through the biological physics division this year. Perkins' nomination is therefore a prestigious recognition of his outstanding contributions to physics.

Sarah Bromley wins Harry Lustig Award

JILA graduate student Sarah Bromley won the Harry Lustig Award from the American Physical Society Four Corners Meeting.

The Harry Lustig Award was established in 2015 to remember Lustig's academic achievements and strong commitment to support the work of physics students through APS. The award recognizes outstanding graduate-level research by individuals working in one of the four corner states (AZ, NM, CO, and Utah).

The three finalists invited to present their research this year were Sarah Bromley (CU/JILA), Andrew Missert (CU), and Chandramouli Nyshadham (BYU). Bromley's presentation, entitlted "Probing Many-Body Physics in an Optical Lattice Clock", detailed her research from the Ye lab at JILA. As the selected winner, Bromley will receive a $1000 stipend.

David Jacobson wins APS Thesis Award

JILA and NRC postdoc Dr. David Jacobson was awarded the American Physical Society's 2017 Award for Outstanding Doctoral Thesis Research in Biological Physics. The thesis prize is awarded for outstanding quality and achievement in any area of experimental, computational, engineering, or theoretical biological physics. While JILA has had great success with the APS Award for Outstanding Doctoral Thesis Research in Atomic, Molecular or Optical Physics, now named after Debbie Jin, this is the first time anyone associated with JILA has won an APS Outstanding Thesis Award from APS Biological Physics.

Jacobson was awarded the prize for pioneering studies of the electrostatic, elastic, and conformational behavior of single-stranded nucleic acids. For his thesis, done at the University of California, Santa Barbara under the supervision of Prof. Omar Saleh, Jacobson developed and experimentally tested a theory describing how charge repulsion affected the stiffness of the nucleic acids RNA and DNA.

The prize, consisting of a certificate and $1,500 split between two recipients, will be presented at the APS March Meeting Prize and Award Ceremony. Jacobson will give an invited talk during the APS March Meeting, held in Los Angeles, California, March 5 - 9, 2018.

Dennis Gardner wins 2017 Laser Science Dissertation Award

Former JILAn Dennis F. Gardner Jr. (Kapteyn-Murnane group) has been awarded the 2017 American Physical Society's Carl E. Anderson Division of Laser Science Dissertation Award for his doctoral work in extreme ultraviolet (EUV) imaging. Gardner received $1,000 and a certificate citing his contribution to laser science.

Gardner's thesis, entitled "Coherent diffractive imaging near the spatio-temporal limit with high harmonic sources" (2017), demonstrates the highest resolution-to-wavelength ratio ever achieved with coherent diffractive imaging. These advances to imaging are critical for advancing nanoelectronics, data storage, and nanoengineered systems.

Gardner is currently a Research Physicist at Sotera Defense Solutions, Inc. in Washington D.C.

Gardner graduated summa cum laude from the University of Colorado at Boulder with a Bachelor of Arts in physics before joining the Kapteyn-Murnane group at JILA in the summer of 2011. During his time at JILA, he was awarded a Ford Foundation Fellowship (2011) and a National Science Foundation Graduate Research Fellowship (2011). He also won the Optical Society's Emil Wolf Outstanding Paper Competition in 2015.

The Carl E. Anderson Division of Laser Science Dissertation Award was established by the American Physical Society (APS) in 2013 to recognize novel applications of light-matter interactions in doctoral research, and to encourage effective written and oral presentations. Four finalists were selected to present their dissertation work at the Laser Science Conference.

Ralph Jimenez Awarded Department of Commerce Gold Medal

Ralph Jimenez was awarded a Department of Commerce Gold Medal on September 26, 2017, at DOC headquarters in Washington, D.C. Jimenez was part of a National Institute of Standards and Technology (NIST) team that recently developed and produced X-ray movies of molecules. The team developed the research tools to make stop-action X-ray measurements of light interacting with molecules on near instantaneous time scales.

Jimenez and his team used an innovative table-top system that produced results with 10 times better resolution than what is available at large X-ray synchrotron facilities costing hundreds of millions of dollars. The team also collected X-rays with its new system with 10-to-100 times better efficiency. The new system is expected to make it possible to perform rapid turn-around measurements of materials for photonics, energy storage, and industrial catalysis.

The team's goal was to create the world's first laboratory-scale tool capable of measuring ultrafast motions of atoms and electrons during light-driven chemical reactions. The team's new understanding of this dynamic behavior is expected to spur the design of molecules for a variety of research and industrial applicatons.

The remarkable new system replicates capabilities found at multimillion-dollar user facilities at a fraction of the cost. Its novel laser-driven source creates ultrashort X-ray pulses safely and reliably. This powerful new tool is significantly more accessible and affordable than large national facilities. It is compact and fits on two laboratory benches. Astonishingly, it can distinguish events within six trillionths of a second, a feat that is ten times better than synchrotrons.

This new capability is already transforming the nation's X-ray metrology infrastructure. Congratulations to Dr. Jimenez and his team!

Ana Maria Rey Named NIST Fellow

Ana Maria Rey has been appointed a NIST Fellow as of August 21, 2017, by the Acting Director of NIST. JILA is a research and training partnership between the University of Colorado and NIST, and Ana Maria is one of the several JILA Fellows who are NIST employees. Ana Maria was named a NIST Fellow in recognition of her world-leading program in quantum theory, her pioneering work in quantum many-body physics, and her continuing powerful collaborations with experimentalists at JILA, at NIST, and across the world.

NIST Fellow is the highest scientific position at NIST. It is limited to no more than 40 of the more than 1,800 scientific employees across the organization who demonstrate unique scientific leadership and innovation. The NIST Director also relies on the NIST Fellows to provide advice and guidance about current and future research directions for the organization. Ana Maria joins Eric Cornell, David Nesbitt, Jun Ye, and Judah Levine as JILA Fellows who are also NIST Fellows.

"It's a great honor for me," Ana Maria said. "NIST has been part of my life, my research, and my career since I did my PhD thesis work with Charles Clark of NIST. I chose to become a theoretical physicist because I heard (NIST Nobel Laureate) Bill Phillips giving a talk at NIST."

"Becoming a NIST Fellow is the latest of many well-deserved honors for Ana Maria in her enormously productive scientific career," said Tom O'Brian, Ana Maria's NIST supervisor at JILA. "Ana Maria has a huge impact on JILA, NIST, and the international scientific community. She and her group have the unique ability to fully collaborate with experimentalists. They have developed new theory that directly advances experiments such as the world's best atomic clocks, world-leading programs in ultracold molecules, and world-record entanglement of ions for quantum simulation—among many other accomplishments. Ana Maria is also an exceptional mentor and teacher, preparing her graduate students and postdoctoral researchers for highly productive careers of their own. JILA and NIST are extremely fortunate to have Ana Maria's leadership."

Leah Dodson Wins 2017 Miller Prize

Leah Dodson won the Miller Prize at the 72nd International Symposium on Molecular Spectroscopy, held June 19–23 in Urbana, Illinois. Dodson is an NRC postdoc whose official advisor is Jun Ye, but who primarily works on molecular spectroscopy in the Mathias Weber lab. Her award-winning talk was entitled "Oxalate Formation in Titanium-Carbon Dioxide Anionic Clusters Studied by Infrared Photodissociation Spectroscopy."

"Leah gave a nice polished presentation with good organization and clarity," said Ben McCall, Chair of the International Symposium on Molecular Spectroscopy, in a letter to Weber announcing the award. "She clearly outlined the rationale, the experiment, and the results. She was engaged, excited about her project, and good at thinking on the spot."

Dodson's project was the investigation of catalysts in model systems. Specifically, she studied the possible use of titanium dioxide (TiO_2) as a catalyst to break carbon-oxygen (C–O) bonds in carbon dioxide (CO_2) produced in a factory. Breaking C–O bonds in CO_2 is a key step in turning this greenhouse gas back into usable fuel—and keeping it out of the atmosphere. Dodson's experiment worked surprisingly well. In the experiment, TiO_2 anions effectively broke CO_2 molecules, forming metal carbonyl in the process. This experiment was the basis for her symposium talk, which resulted in the Miller Prize.

Bryce Bjork Awarded 2017 Rao Prize

Bryce Bjork's talk entitled "Direct Measurement of OD+CO→ cis-DOCO, trans-DOCO, and D+CO_2 Branching Kinetics using Time-Resolved Frequency Comb Spectroscopy" was selected by a panel of judges at the International Symposium on Molecular Spectroscopy as one of three winners of the 2017 Rao Prize. The prize will be presented to Bjork at the June 2018 Symposium.

In addition, Bjork was asked to serve as a judge in the 2018 Rao Prize competition.

"There were many superb talks, but yours was exceptional," said Gary Douberly, Chair of the 2017 Rao Prize Committee, in a recent letter to Bjork informing him of his selection. "We hope that this prize represents the beginning of what we expect will be a distinguished career in science."

Rao Prize winners and their co-authors are invited to submit articles based on their talks to the *Journal of Molecular Spectroscopy*. When published, the article will appear in the journal with a caption linking the paper with the symposium talk that won the Rao Prize.

"The prize is given to graduate students," said Jun Ye, Bjork's advisor at JILA. "But, it usually signifies the beginning point of a young spectacular scientific career in the field of molecular spectroscopy."

Ana Maria Rey Wins 2017 Alexander Cruickshank Award

Ana Maria Rey has been named the winner of the 2017 Alexander Cruickshank Award in Atomic Physics by the Gordon Research Conferences. The award recognizes international leadership and impact in the organization's main areas of biological, chemical, and physical sciences. It was presented to Rey by the Atomic Physics Gordon Research Conference "From Quantum Control to Tests of Fundamental Physics," held on June 11–16 in Salve Regina University, Newport, Rhode Island. Rey was nominated by Conference Chair Mariana Safronova.

The big surprise for Rey came at the conference when Safronova announced Rey had won the award. Safronova highlighted the number of people who had received the award in atomic physics, including Nobel Physics Laureates and other internationally prominent scientists.

"She said it was her honor to give me the award," Rey recalled, who realized at that moment just how selective the honor was.

Past winners in the physics category have included Nobel Laureates Eric Cornell of JILA and Dave Wineland of NIST Boulder. Other past winners with ties to JILA include Immanuel Bloch (Ludwig-Maximilians University and Max Planck Institute of Quantum Optics), Mikhail Lukin (Max Planck Institute of Quantum Optics and Harvard University), and 1997 Nobel Laureate Claude Cohen-Tannoudji (University of Paris).

NPR's Eric Westervelt Talks with Carl Wieman about His New Book

NPR's education reporter Eric Westervelt is excited about Nobel Laureate Carl Wieman's passion for transforming how undergraduate science courses are taught. On June 7, 2017, Westervelt talked with Wieman about his new book *Improving How Universities Teach Science: Lessons from the Science Education Initiative*, which was published by Harvard University Press in May of 2017.

Wieman's message is that universities should do away with lectures in undergraduate science courses and replace them with active learning methods. Instruction based on active learning substantially improves understanding and retention of complicated material. Plus, students attend more classes and get more out of their classroom experiences. Armed with data to prove that he's right about the effectiveness of active learning methods, Wieman is determined to convince universities across the nation to give up on the lecture method of teaching science to undergraduates.

The lecture system "grew up haphazardly," Wieman explained during the interview. "Really it grew before the printing press was invented, and the structures–like the lecture–were how to transmit information to people who didn't have books."

Wieman said his research showed that lectures actually circumvent the way the brain processes and learns new information. During a lecture, information just flows by and students typically retain only about 10% of what they hear. And, to make matters worse, many students these days are busy with cell phone apps as the information flies by. Another problem is that universities often value faculty research accomplishments far more than teaching skills.

Westervelt first spoke with Wieman on NPR about improving science teaching in universities on April 14, 2016. That program was entitled "A Nobel Laureate's Education Plea: Revolutionize Teaching," In that interview, Westervelt said that Wieman believed that, "the college lecture is the educational equivalent of bloodletting, one long overdue for revision."

Carl Wieman began his research on undergraduate science education on while a Professor of Physics at the University of Colorado Boulder and a Fellow of JILA. Wieman joined the University of British Columbia in 2007 and moved to Stanford University in 2013, where he is Professor of Physics and Professor of the Graduate School of Education. Wieman is a Fellow Adjoint of JILA.

Eric Coughlin Wins 2016 IAU Thesis Prize

Eric Coughlin has been named winner of the 2016 Ph.D. Thesis Prize from the High Energy Phenomena and Fundamental Physics Division of the International Astronomical Union. He will receive the prize at the next IAU General Assembly. Coughlin is also winner of the 2017 Dissertation Prize from the High Energy Astrophysics Division of the American Astronomical Society. The IAU Thesis Prize consists of a grant to attend the IAU General Assembly in Vienna, in August 2018. There he will have the opportunity to present his thesis work in one of the General Assembly sessions.

Coughlin, who is currently a NASA Einstein Fellow at the University of California, Berkeley, received his Ph.D. in 2016 from the University of Colorado Boulder. His thesis advisor was JILA Fellow Mitch Begelman.

The Ties that Bind

JILA and NIST scientists are hot on the trail of understanding quantum correlations (or entanglement) among groups of quantum particles such as atoms or ions. Such particles are the building blocks of larger and larger chunks of matter that make up the everyday world. Interestingly, correlated atoms and ions exhibit exotic behaviors and accomplish tasks that are impossible for noninteracting particles. Therefore, understanding how entanglement is generated in those systems is not only central to comprehending our world, but also advancing technology.

The development of a new experimental method to measure quantum correlations between particles was the focus of a recent collaboration between Ana Maria Rey's theory group at JILA and NIST experimentalist John Bollinger's group. The two groups worked together on an experimental study of quantum correlations in a trapped-ion magnet consisting of ~100 beryllium (Be^+) ions. The Rey group's theory predicted that the experimenters could measure the build up of entanglement caused by the interactions between the ions by illuminating the ions with lasers that allow the ions to interact going forwards and then backwards in time. These steps were followed with an examination of how much the ions resembled the state they were in before their time-traveling adventure.

So what exactly happened in this experiment?

Imagine that the ions were like magnetic cars racing on a very icy route. The result would be lots of accidents. Because the cars were magnetic, a multi-car collision would result in several cars getting stuck together, forming larger clusters of wrecked cars. The icy route in this analogy is like the vibrations of the ion crystals in the experiment. These vibrations mediate interactions between the ions.

In actuality, the ions in the experiment were set up as if each car were driving in its own lane on the icy road. The ions (cars) moved forward for some time, then backwards for the same amount of time. In the absence of icy conditions (i.e., without interactions), the cars would return to their initial position after going forwards and backwards. However, if the road were icy, two, three, or more ions (cars) might collide and form larger clusters. In the experiment, the system did not return back to its initial state. In fact, it became very different. Clusters of ions became correlated. Furthermore, as the ions became correlated, information about their individual properties got lost or scrambled.

Curiously, the researchers only identified groups of eight correlated ions in their measurements, rather than a hundred-ion pileup. The reason is that entanglement between ions is quite fragile. Entanglement can be destroyed by quantum processes collectively called decoherence. Decoherence is induced by laser beams—the same laser beams that excited the vibrations in the crystal in the first place and made the ions interact. It's as if the decoherence "demagnetized" the cars (ions). When collisions happened between demagnetized cars, the cars (ions) could still change the direction of their motion, but they couldn't stick together. If they couldn't stick together, they weren't able to form big clusters. But in the experiment with the Be^+ ions—even with decoherence—the researchers still observed the build-up of eight-body correlations.

"The most interesting aspect of this story was that the quantities that we were measuring were something unique," Rey said. "Then we heard a talk about black holes and their connection to quantum chaos. The idea was that black holes are the objects which erase, or scramble, information at the fastest rate allowed by nature.

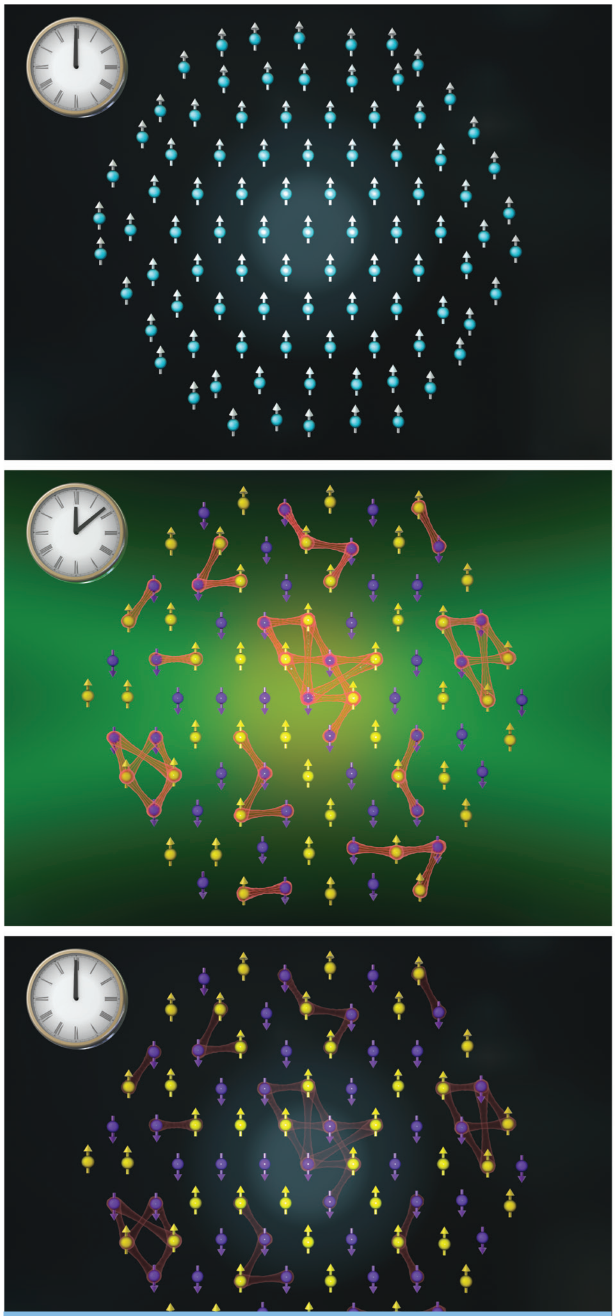
"Information is rapidly scrambled by a black hole because it's a hot, crazy system. The high-energy community was proposing a way to quantify how fast information is scrambled in a black hole by measuring a very complicated correlator. But this correlator was exactly what we were measuring in our experiment."

One difference is that in contrast to black holes, Be_+ ions lose information slowly enough for the researchers to watch the process as ions become correlated. It's also important to realize that the trapped-ions experiment showed for the first time that laboratory measurements of these correlations are possible and can provide unique information about the build up of entanglement.

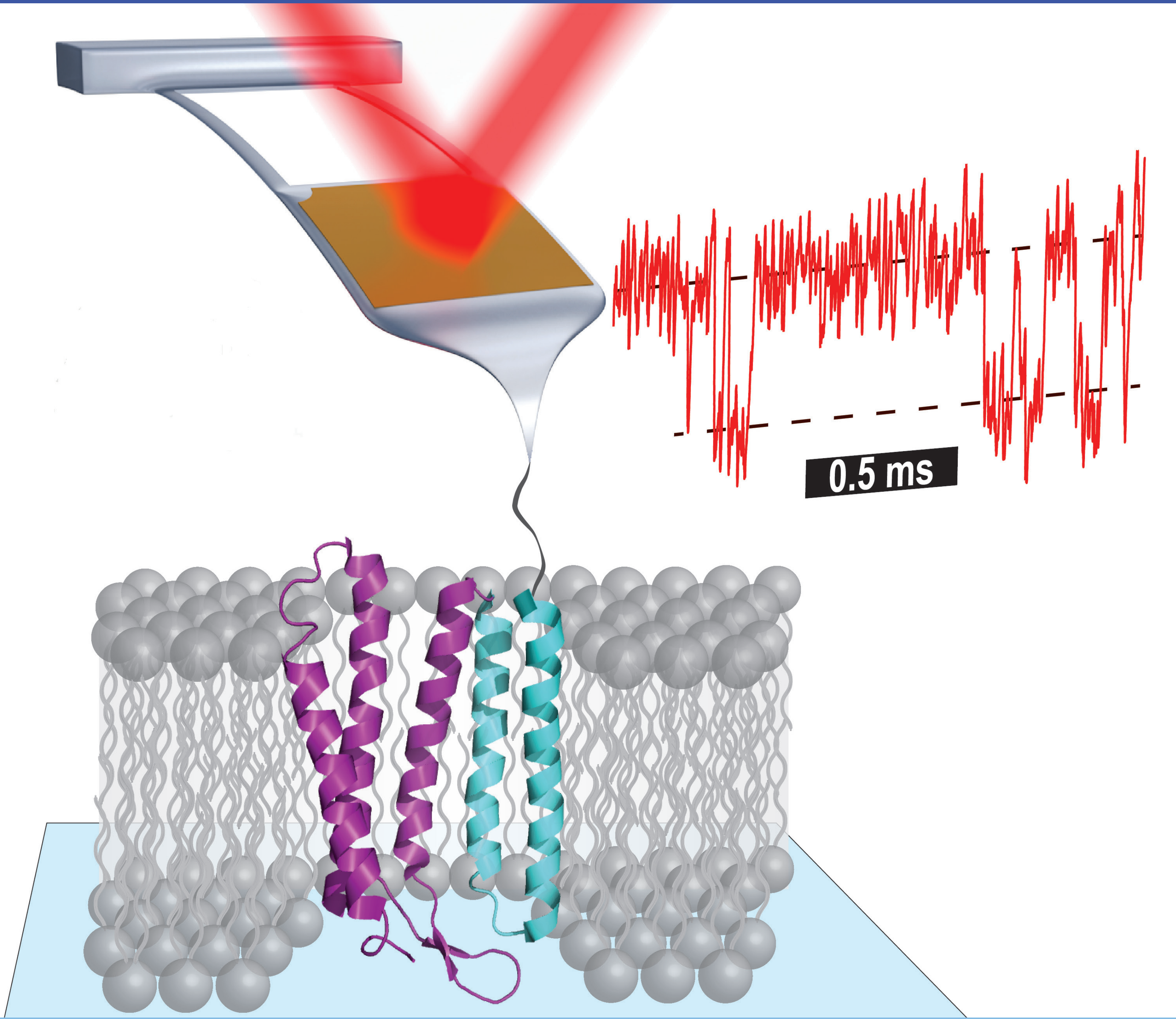
"In fact, entanglement may be the common language that explains the behavior of very different systems in nature, including ions and black holes," Rey said.

The researchers responsible for this provocative new theory-experiment collaboration include former research associate Martin Gärttner (currently at the University of Heidelberg), research associate Arghavan Safavi-Naini, former senior research associate Michael Wall, NIST scientists Justin Bohnet and John J. Bollinger as well as Fellow Ana Maria Rey. ✺

M. Gärttner, J. G. Bohnet, A. Safavi-Naini, M. L. Wall, J. J. Bollinger, A. M. Rey, *Nature Physics* **13**, 781–786 (2017).



In an experiment to better understand quantum correlations, lasers caused interactions between 100 Be^+ ions by going forwards and then backwards in time. Without correlations, this procedure would have returned the ions to their initial state. Instead, something exciting happened: Clusters of up to eight ions became correlated! Credit: The Rey group and Steve Burrows, JILA



A tiny modified gold-coated AFM cantilever detects protein folding and unfolding in the membrane protein bacteriorhodopsin in a lipid bilayer (grey). Right: A trace of cantilever motion reveals folding and unfolding of protein segments as short as 2–3 amino acids long. Credit: The Perkins group and Steve Burrows, JILA

Vision Quest

Exquisitely sensitive experiment yields new view of membrane protein unfolding

The Perkins group continues to extend the performance of its unique Atomic Force Microscope (AFM) technology, revealing for the first time a dozen new short-lived intermediate states in the folding and unfolding of a membrane protein that controls the exchange of chemicals and ions into and out of living cells. Measuring the energetics and dynamics of membrane proteins is crucial to understanding normal physiology and disease, and the Perkins group's observation of multiple new folding/unfolding states shines new light on these cellular "gatekeepers."

The Perkins group used its recent 100-fold improvement in time resolution in AFM technology to probe the folding and unfolding of the protein bacteriorhodopsin, a key example of a membrane protein. Like all membrane proteins, bacteriorhodopsin exists in a thin membrane made of two layers of fat molecules called lipids. The group's goal was to better understand the membrane proteins, which make up about 30% of the proteins expressed by an organism's genome. In living organisms, these membrane proteins thread through the fat layers in cell membranes, with one side facing the outside of the cell and the other the inside. This configuration allows the membrane proteins to control the exchange of chemicals into and out of the living cell. It also allows drugs to bind to the proteins on the cell's exterior and cause structural changes that can alter the functioning of biomolecules inside the cell. For this reason, membrane proteins are targets of about 50% of current and future drug therapies.

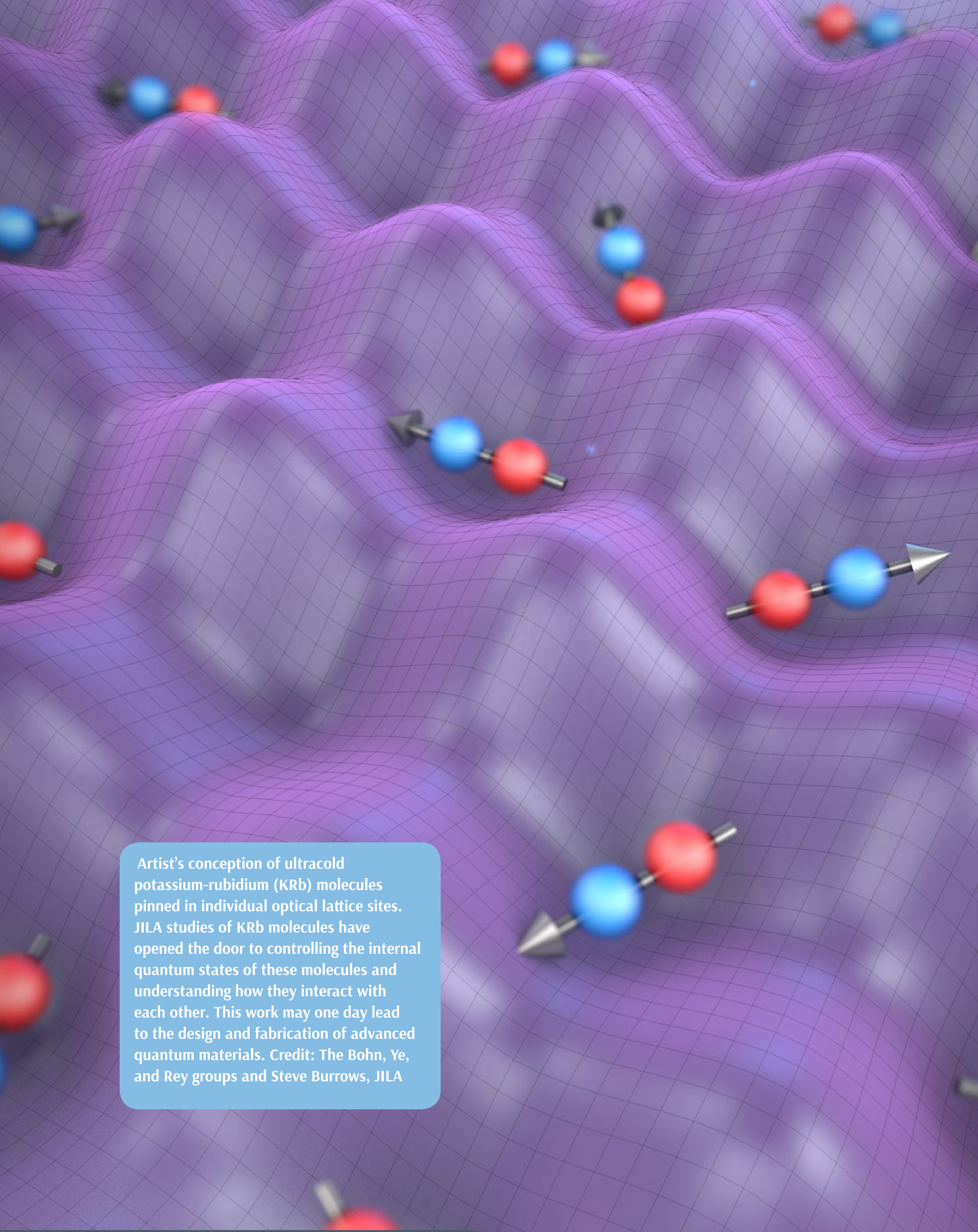
Because membrane proteins are so important, the Perkins group wanted to understand membrane behavior inside their natural environment, i.e., a lipid bilayer. For nearly 20 years, researchers have been studying the behavior of these proteins with AFM. Bacteriorhodopsin, like many membrane proteins, contains seven helical structures that span the width of the lipid bilayer that separates the outside of the cell from the inside. And, in the last 15 years, researchers have seen just two structural variations, called intermediates, when unfolding a particular pair of these helices.

But now, thanks to the Perkins' group's tremendous improvements in AFM instrumentation, the JILA team, led by research associate Hao Yu and graduate student Matt Siewny, saw at least 14 intermediates. Some intermediates along the unfolding pathway differed by only 2 amino-acid subunits, or half a helical turn. The group's ability to see these intermediates occurred as a result of using its modified 9-μm-long AFM cantilevers. This innovation led to a 100-fold improvement in time resolution and a 10-fold improvement in temporal resolution in the group's membrane-protein studies.

Not only are the membrane proteins folding on smaller structural scales than previously measured, but they are also unfolding and refolding on time scales much faster than could be resolved before now. The unfolding pathway of bacteriorhodopsin is incredibly more complicated than anyone had previously experimentally determined. However, molecular-dynamics theorists had previously predicted such complexity. It turns out that there is now good agreement between the group's new experimental data and long-standing computational predictions of how a system like this should behave!

These exciting new results were reported online in *Science* on March 3, 2017. The researchers responsible for the results include research associates Hao Yu and Devin Edwards, graduate student Matthew Siewny, Fellow Tom Perkins, and Aric Sanders of NIST. ✺

H. Yu, M. G. W. Siewny, D. T. Edwards, A. W. Sanders, and T. T. Perkins, *Science* **355**, 945-950 (2017).



Artist's conception of ultracold potassium-rubidium (KRb) molecules pinned in individual optical lattice sites. JILA studies of KRb molecules have opened the door to controlling the internal quantum states of these molecules and understanding how they interact with each other. This work may one day lead to the design and fabrication of advanced quantum materials. Credit: The Bohn, Ye, and Rey groups and Steve Burrows, JILA

Quantum Adventures with Cold Molecules

Researchers at JILA and around the world are starting a grand adventure of precisely controlling the internal and external quantum states of ultracold molecules after years of intense experimental and theoretical study. Such control of small molecules, which are the most complex quantum systems that can currently be completely understood from the principles of quantum mechanics, will allow researchers to probe the quantum interactions of individual molecules with other molecules, investigate what happens to molecules during collisions, and study how molecules behave in chemical reactions. Armed with such fundamental insights into the workings of molecules, researchers anticipate developing tools not only to control reaction chemistry, but also to design and manufacture advanced quantum materials.

"We have now reached the stage where we have the capability to start controlling molecules," Rey said. "Now we want to understand how they react and how they interact. And, this understanding is orienting us on a path to learning more about chemical reactions from start to finish."

With these goals in mind, Fellows John Bohn, Ana Maria Rey, and Jun Ye collaborated on a review article discussing how progress over the last dozen or so years in cold-molecule research by a large scientific community has laid the groundwork for the exquisite control of molecules and their interaction processes. The article, entitled "Cold Molecules: Progress in Quantum Engineering of Chemistry and Quantum Matter," appeared online in *Science* on September 8, 2017.

"We can control the initial state of molecules and how they approach each other, monitor intermediate states, and analyze the end products," explained Ye. "Being able to control these three steps in a state by state fashion gives you resolution limited only by quantum mechanics for the study of a molecular reaction process." Ye said that it's also possible to use ultracold (quantum) molecules to simulate quantum magnetism and study fundamental reaction processes in the quantum regime.

"We have now reached the stage where we have the capability to start controlling molecules," Rey added. "Now we want to understand how they react and how they interact. And, this understanding is orienting us on a path to learning more about chemical reactions from start to finish."

Bohn summed it up this way: "The gist of all this is that now we're starting to get a handle on anything you may want to know about a chemical reaction."

J. L. Bohn, A. M. Rey, and J. Ye, *Science* **357**, 1002-1010 (2017).

Spotlight on James Thompson

James K. Thompson was born to John and Noreen Thompson in Fort Worth, Texas and moved to Orlando, Florida when he was seven years old. His father was a Baptist minister who had abandoned his study of mathematics, and his mother was an elementary school teacher. Together they fostered the sense that education and curiosity about the world were critical to being a complete and happy person.

James' interest in math was fueled at the age of nine by learning to program video games on his first computer, a Commodore 64, which was his all-time favorite Christmas present. A second powerful influence on his eventual career choice was that James had notoriously bad summer jobs. While scrubbing roadside curbs using acid during a hot Florida summer, James thought "they really ought to hire someone to do this," only to immediately realize that they had, and it was him! He decided then and there that he would work his tail off to make sure that he would not end up doing such jobs for a living.

In junior high school, James wanted to be an engineer. But, in high school he realized that what he really meant was physicist—the people who ask the universe why. It was also in high school that James met an intelligent and beautiful girl that he somehow convinced to marry him some seven years later. His wife Deborah Whitehead is a professor in the Department of Religious Studies at the University of Colorado, and together they have three children. Raising them has taught him the invaluable skill of taking naps on the JILA elevators—a skill that he does not have to use as often now that they are getting older

James attended Florida State University, earning a B.A. and M.S in physics in 1995 and 1997, respectively. He performed laser spectroscopy on fast beams of highly charged ions generated using a particle accelerator. The results were used to test relativistic many-body calculations relevant for determining the fine structure constant from precise measurements in helium.

James received his Ph.D. in physics in 2004 from the Massachusetts Institute of Technology (MIT), where he worked with Dave Pritchard. In his thesis work, he made the world's most precise mass comparisons by learning how to detect and precisely control the relative motion of two single ions confined for weeks to months in a Penning trap consisting of magnetic and electric fields. His work led to the most precise direct test to date of Einstein's relationship $E=mc^2$ and a novel method for non-destructively monitoring the quantum state of a single molecular ion. He received the 2004 American Physical

Society's DAMOP thesis award for this research.

James did his postdoctoral research with Vladan Vuletic in the MIT-Harvard Center for Ultracold Atoms. There he focused on the interface between ultracold atoms and quantum optics, developing efficient quantum memory and photon generation techniques.

James was appointed an Associate Fellow of JILA in 2006 and a Fellow of JILA in 2013. During his time at JILA, he has studied techniques for applying collective effects for improving precision measurements. His students have learned to nondestructively measure and cancel out the quantum fluctuations in the collective spin state of an ensemble of atoms. By learning how to minimize the effect of quantum noise, Thompson hopes to advance the precise measurements required for atomic clocks and searches for permanent electric-dipole moments in atoms and molecules. The Thompson lab's entangled atoms currently hold the world's record for reducing the fuzziness inherent to using quantum objects to make measurements.

James has also developed a superradiant laser that can operate even with less than one photon on average inside the cavity. Instead of storing the laser's information inside of the light field, his group demonstrated that the information is almost entirely stored inside of the atoms, and that stimulation is driven by the collective emission of the atoms in a process known as superradiance. This optical analog of a hydrogen maser may pave the way for ultranarrow frequency lasers that may advance optical interferometry at solar-system scale distances and the most advanced optical clocks by several orders of magnitude. Thompson was awarded a Department of Commerce Bronze Medal in 2013 for his work on the proof-of-principle superradiant laser.

When not doing physics experiments, James enjoys playing with his girls, reading, and the occasional pick-up game of basketball.

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

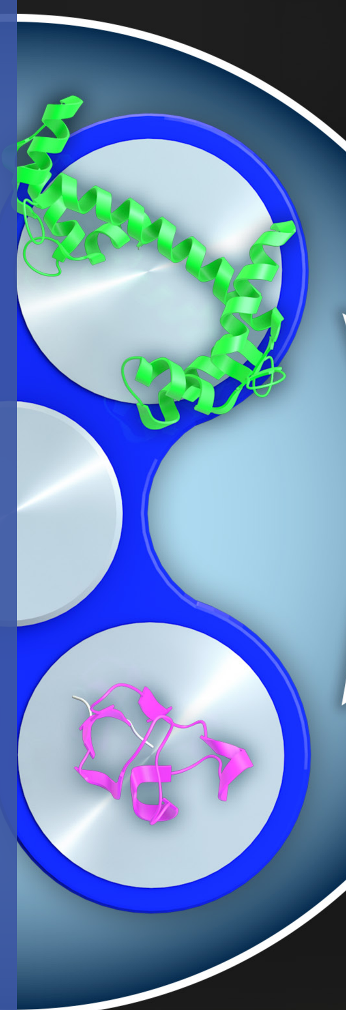
University of Colorado **Boulder**

NIST 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 in 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 CU members hold faculty appointments in the Departments of Physics; Astrophysical & Planetary Science; 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:
jila.colorado.edu