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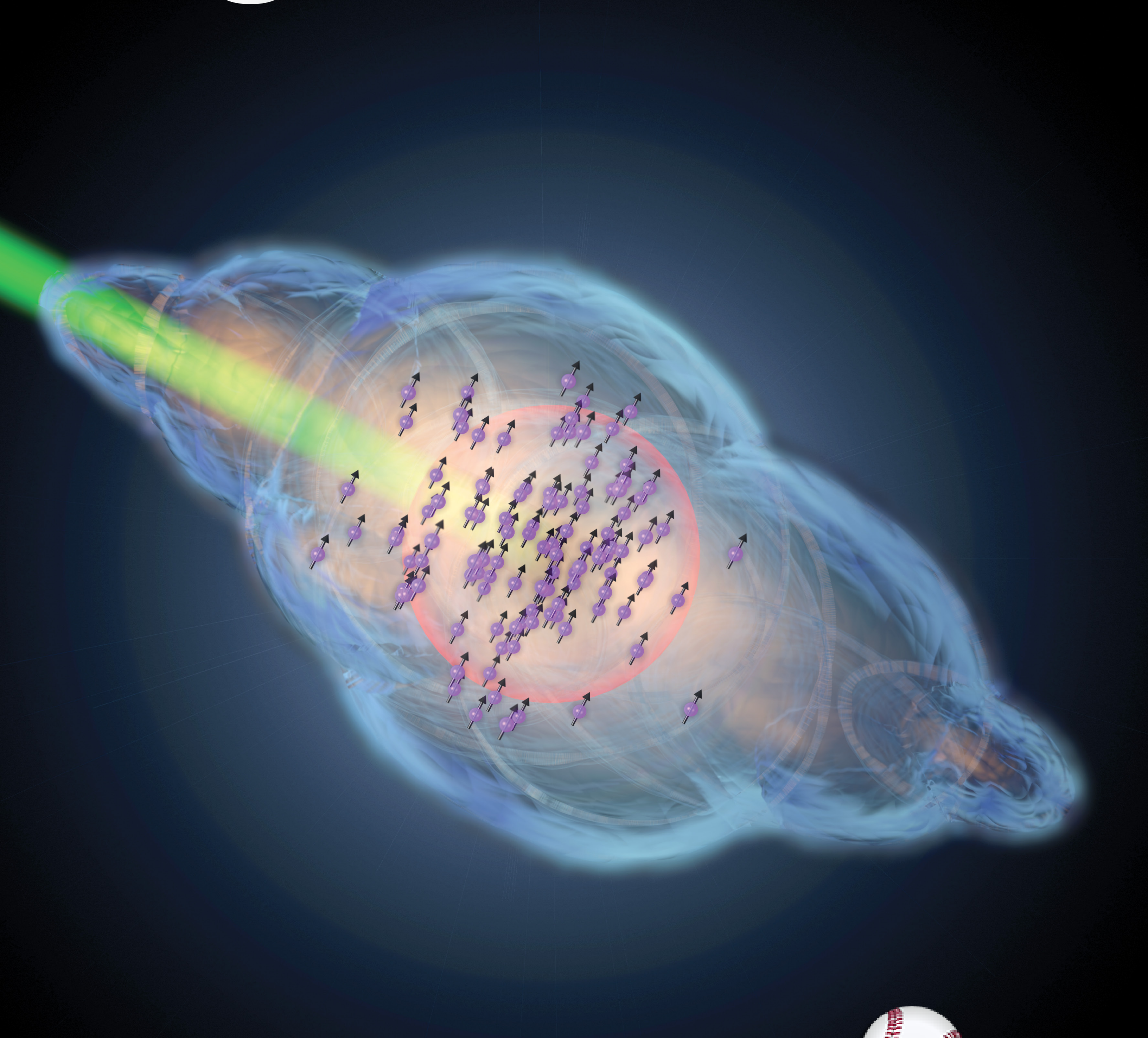
# JILA light & MATTER



Quantum Baseball p.1

JILA, from Farrand Field on the University of Colorado Boulder campus. Credit: Kristin Conrad, JILA

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**Kristin Conrad**, Project Manager, Design & Production
**Julie Phillips**, Science Writer
**Steven Burrows**, Art & Photography
**Gwen Dickinson**, Editor

# Stories



# Features

# Quantum Baseball

## Photons determine the game, and atoms go along for the ride

The Ye and Rey groups have discovered the strange rules of quantum baseball in which strontium (Sr) atoms are the players, and photons of light are the balls. The balls control the players by not only getting the atoms excited, but also working together. The players coordinate throwing and catching the balls. While this is going on, the balls can change the state of the players! Sometimes the balls even escape the quantum baseball game altogether and land on detectors in the laboratory. The rate at which these balls are detected provides information about the state of the players. This kind of communication between atoms and photons in three-dimensional (3D) quantum matter is going to have important application to a variety of quantum systems, including optical atomic clocks.

"Players communicate with each other by exchanging balls," said Ye. "Depending on the incidence of the balls with respect to a particular player lineup, all the players can start to act together and throw their balls in the same direction. "

And, Rey says, there is almost never just a single pass before a ball escapes. Rather, a ball is passed many times between the players. This process coordinates the movements of the players and provides information about their states. The closer players are to each other, the faster the balls get thrown between them. The fast pace of the quantum baseball game enhances the probability that balls escape.

Quantum baseball is essentially a novel form of interatomic communication in which photons simultaneously carry forces that influence the atomic responses and information about those atomic responses. All of this action is transmitted throughout a cloud of hundreds or thousands of atoms.

"Usually, atoms talk to each other by knocking into each other, in other words, via collisions," said Ye. "But a simple calculation shows that communication via collisions was not what we were observing with spectroscopy in our lab."

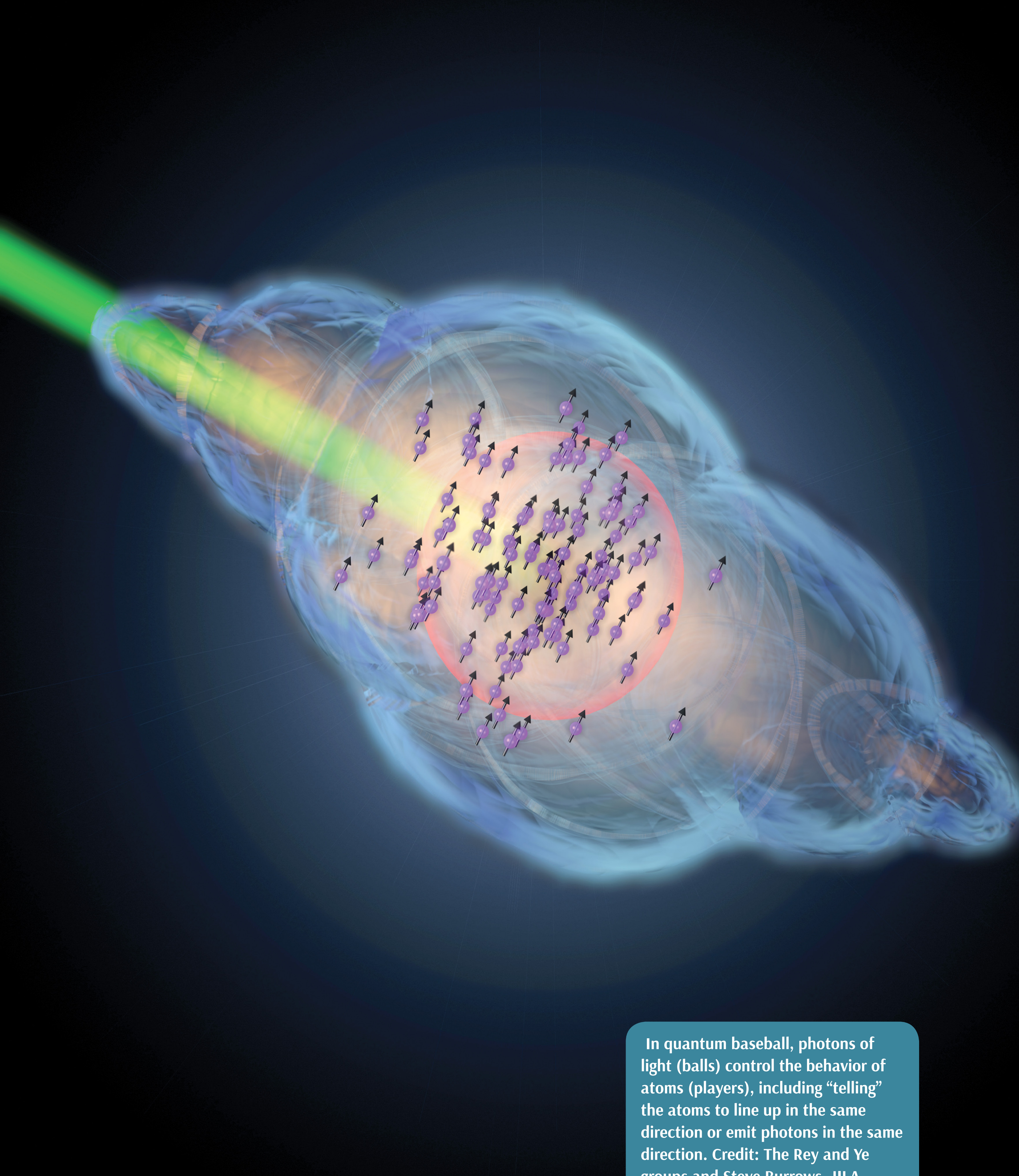
The Ye group's observation remained a mystery until French scientist Robin Kaiser visited JILA and championed the idea that collective communication in an atom cloud could result from the sharing of photons.

Soon, theorists Ana Maria Rey, graduate student Bihui Zhu, and colleagues from Harvard discovered that the collective atom-photon interactions could be responsible for the enhanced emission rate measured by laboratory detectors. So graduate student Sarah Bromley and the Ye group's experimental team studied the quantum baseball-like behavior of photons and Sr atoms by using two lasers: a high-energy blue laser (that made the atoms very energetic and throw balls very fast) and a lower-energy red laser (that made the atoms less energetic and throw balls at a much slower rate).

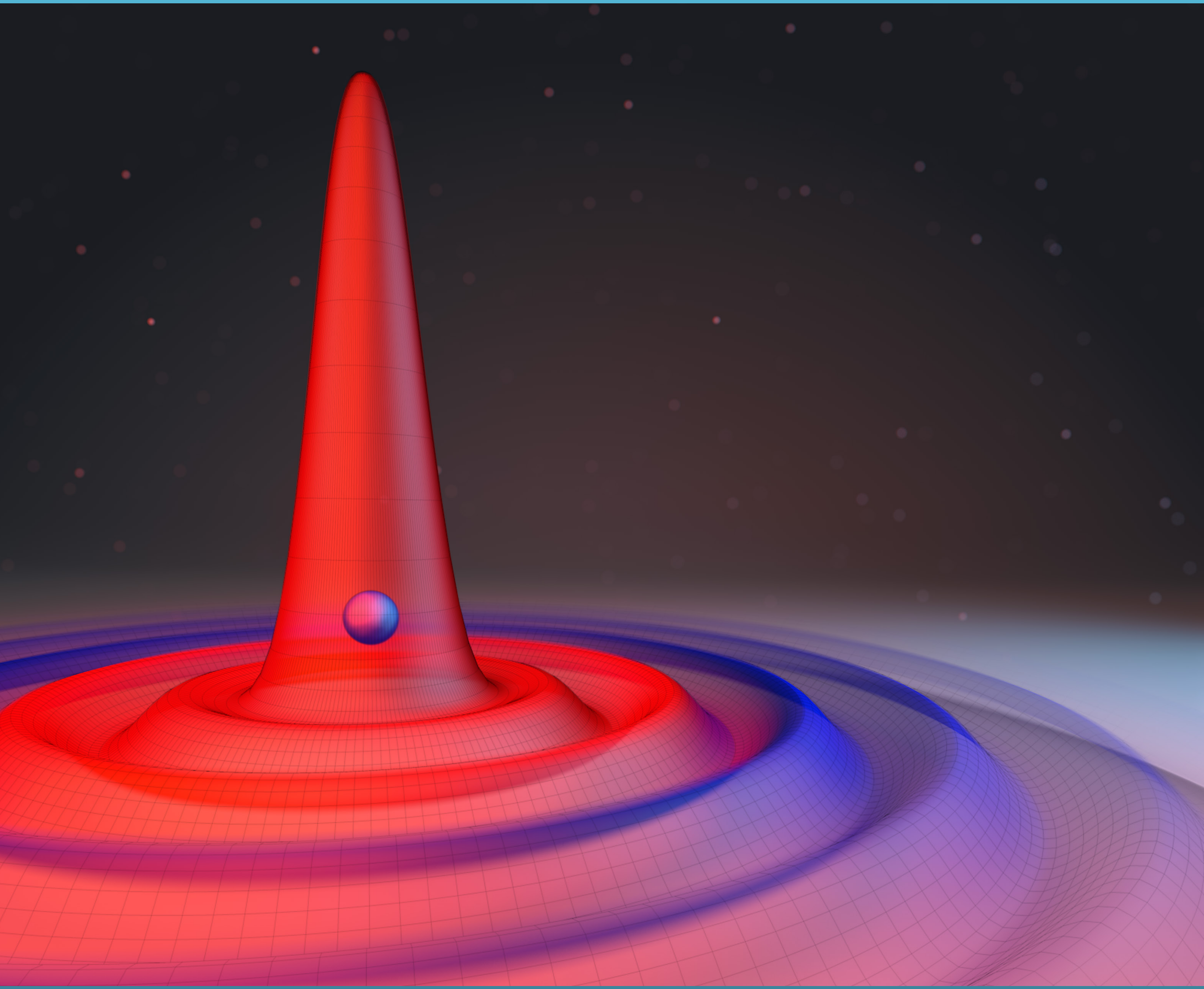
The red laser tracked the motion of the Sr atoms. In contrast, the blue laser "froze out" the motion of the atoms because the atom-photon (player-ball) exchange happens so fast. Together, the two lasers discovered the rules of quantum baseball in the microscopic quantum world.

The researchers responsible for this productive theory-experiment collaboration include graduate students Sarah Bromley, Bihui Zhu, and Tobias Bothwell, research associates Xibo Zhang and Johannes Schachenmayer, former graduate students Mike Bishof and Travis Nicholson, Fellows Ana Maria Rey and Jun Ye, Mikhail Lukin and Susanne Yelin of Harvard, as well as colleagues from the Université de Nice Sophia Antipolis (France) and the University of Connecticut.✺

S. L. Bromley, B. Zhu, M. Bishof, X. Zhang, T. Bothwell, J. Schachenmayer, T. L. Nicholson, R. Kaiser, S. F. Yelin, M. D. Lukin, A. M. Rey & Jun Ye, *Nature Communications* **7**, 11039 (2016).



In quantum baseball, photons of light (balls) control the behavior of atoms (players), including “telling” the atoms to line up in the same direction or emit photons in the same direction. Credit: The Rey and Ye groups and Steve Burrows, JILA



A single impurity (shown as a round ball) entering a Bose-Einstein condensate (BEC) creates excitations that give researchers information about both the impurity used as the probe and the condensate. Credit: The Jin and Cornell groups and Steve Burrows, JILA

# All Dressed Up and Ready to Probe

## An impurity may help JILA scientists better understand a strongly interacting BEC

Newly minted Ph.D. Ming-Guang Hu and his colleagues in the Jin and Cornell groups recently investigated immersing an impurity in a quantum bath consisting of a Bose-Einstein condensate, or BEC. The researchers expected the strong impurity-boson interactions to "dress" the impurity, i.e., cause it to get bigger and heavier. In the experiment, dressing the impurity resulted in it becoming a quasi particle called a Bose polaron.

"What we really did was study the behavior of the quantum bath when a potassium atom disturbed it," said Fellow Deborah Jin. Jin said the impurity created excitations in the BEC that helped the researchers understand how the quantum bath responded to the potassium-atom impurity.

She also explained that because the impurity was moving through a BEC, the researchers called it a Bose polaron. Similarly, an impurity moving through a quantum bath of fermions, or Fermi sea, would be called a Fermi polaron.

Jin said there is an interesting similarity between ultracold polarons and electrons moving through a crystal made of positively charged ions. For instance, scientists think of an electron moving through an ion crystal as a quasi particle. They observe that the farther an electron travels through an ion crystal, the larger and more massive the quasi particle appears. As the interactions get stronger, the distortions of the lattice get larger, and the quasi particle moves more slowly.

"The atom gases give you a new way to explore that same phenomena, but with a BEC and an impurity particle moving through it," Jin said. "It turns out that it doesn't matter what the quantum behavior of the impurity is because, in theory, you only have one particle, and it can be a fermion or a boson."

"Experiments like this one allow you to see some of the same behavior you might see from an electron moving through a crystal," Jin explained. "But our system isn't a crystal. It's continuous and has the ability to become strongly interacting under the right conditions."

Studies like this one where there is a single impurity moving through and interacting with a BEC are helping the Jin and Cornell groups plan for future investigations of a strongly interacting BEC in which all the bosons interact with each other.

"Experiments like this one allow you to see some of the same behavior you might see from an electron moving through a crystal," Jin explained. "But our system isn't a crystal. It's continuous and has the ability to become strongly interacting under the right conditions." Jin says this experiment has opened the door to a whole new area of exploration in ultracold physics.

This work appeared online as an *Editor's Suggestion* in *Physical Review Letters* on July 28, 2016, alongside a closely related article by another group. The JILA researchers responsible for this trailblazing work include Hu, graduate students Michael J. Van de Graaff, Dhruv Kedar, and John P. Corson, as well as Fellows Eric Cornell and Deborah Jin. ✺

Ming-Guang Hu, Michael J. Van de Graaff, Dhruv Kedar, John P. Corson, Eric A. Cornell, and Deborah S. Jin, *Physical Review Letters* **117**, 055301 (2016).

# Spot the Differences

There are 10 differences between the two photos of the JILA Instrument Shop's 2016 annual brat cookout. Either circle them on the photos or write them below. The first person to turn in a correct list to Kristin Conrad (S264) will win a $25 gift card.

1. ______________________________

2. ______________________________

3. ______________________________

4. ______________________________

5. ______________________________

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10. ______________________________


JILA Brat Cookout
Members and Guests Only


JILA Brat Cookout
Members and Pets Only

# Stalking the Wild Molecules

## Infrared frequency comb spectroscopy combined with buffer gas cooling enable the analysis of large molecules with crowded, messy spectra

The Ye group just solved a major problem for using molecular fingerprinting techniques to identify large, complex molecules: The researchers used an infrared (IR) frequency comb laser to identify four different large or complicated molecules. The IR laser-light absorption technique worked well for the first time with these larger molecules because the group combined it with buffer gas cooling, which precooled their samples to just a few degrees above absolute zero. This innovative combination is expected to provide insights into the physics of molecular structure and behavior. It will also improve trace gas detection techniques used in breath analysis, hazardous gas identification, atmospheric chemical analysis, and climate science studies.

> The Ye group just solved a major problem for using molecular fingerprinting techniques to identify large, complex molecules.

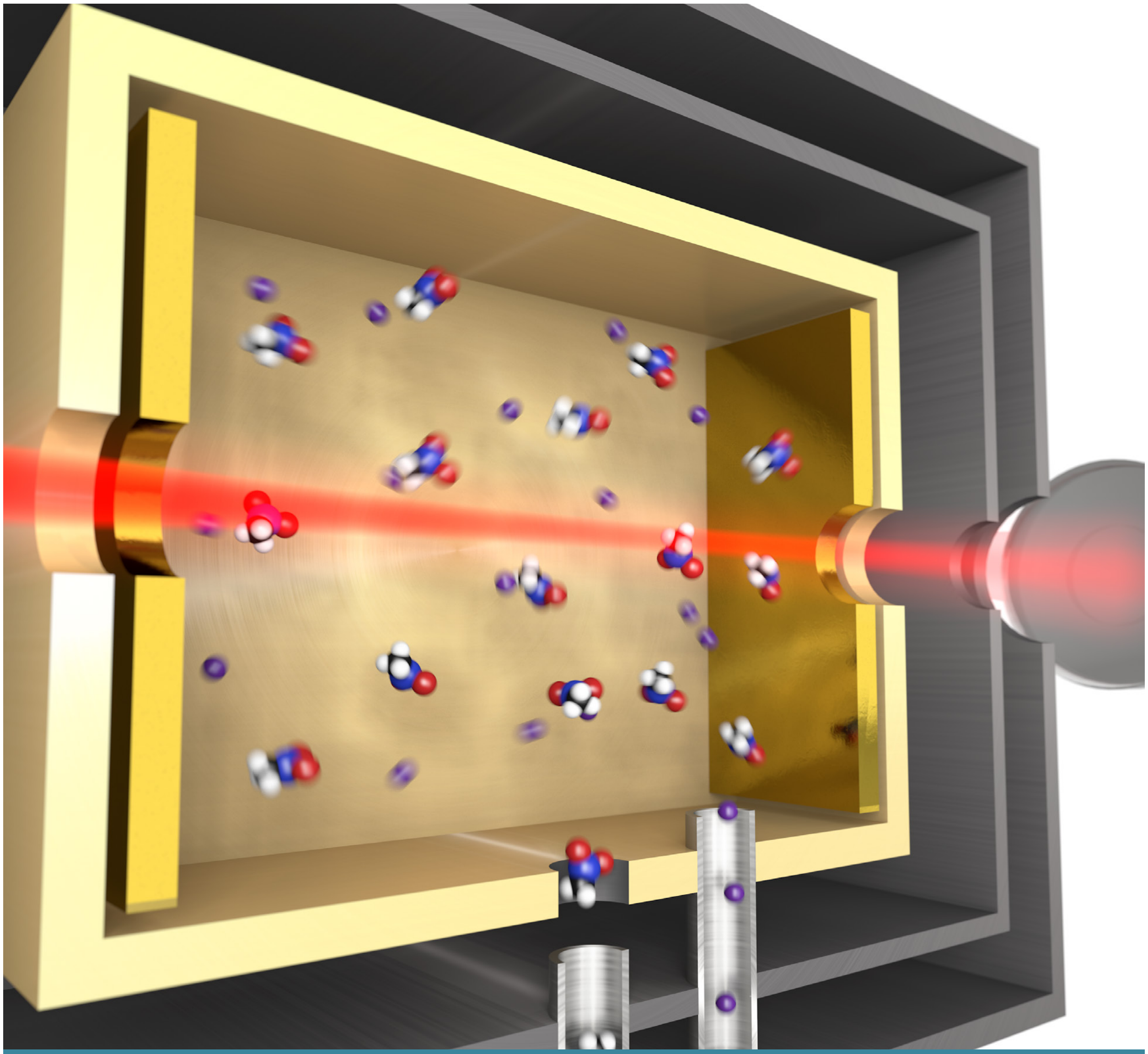
The reason even medium-sized molecules previously posed a problem in molecular fingerprinting is that all the atoms in molecules rotate and vibrate in complex patterns. And the more atoms there are moving wildly and communicating among themselves, the more spectral lines crowd into one spectrum. The spectrum becomes so congested it cannot be analyzed. This congestion occurs because even medium-sized organic molecules (containing carbon, hydrogen, and oxygen) typically have millions of rotational-vibrational states at room temperature. These states all show up in a single IR spectrum. And, the problem with congested spectra gets even worse as molecules get bigger and bigger.

The researchers who solved the problem of analyzing large, complex wild molecules include research associates Ben Spaun and Oliver Heckl, graduate students Bryan Changala and Bryce Bjork, Fellow Jun Ye and their colleagues Dave Patterson and John Doyle from Harvard University.

Spaun and his team were well positioned to make this breakthrough. The Ye group figured prominently in the development of the original laser frequency comb, or ruler of light; the group also developed the first mid-IR laser frequency comb. The mid-IR comb consists of thousands of evenly spaced spectral lines that can be used to detect, measure, and identify unknown substances with exquisite accuracy—as long as the spectrum isn't too congested.

In this breakthrough experiment, researchers first cooled molecules of nitromethane (7 atoms), naphthalene (18 atoms), adamantine (26 atoms), or hexamethylenetetramine (22 atoms). Then the researchers placed the molecules in a hollow chamber with comb light bouncing back and forth through the molecules. The molecules absorbed the comb light at the specific frequencies at which the molecules rotate and vibrate. These absorption patterns, which are unique for each different molecule, are the molecular fingerprints that made their identification possible.

Identifying these large, complex molecules also required the use of an innovative cooling technique known as buffer-gas cooling, which was developed by Patterson and Doyle. This technique used a small commercial liquid helium refrigerator cooled to 4 K (just 4 degrees above absolute zero).



Infrared-laser comb spectroscopy can now identify large, complex molecules if the molecules are first cooled to ultralow temperatures with a buffer-gas cooling technique developed at Harvard. Credit: The Ye group and Steve Burrows, JILA

First, the researchers flowed helium atoms into the refrigerator. These atoms collided with the walls of the refrigerator, which cooled them to 4 K.

Second, the researchers introduced some of their "hot" test molecules to the refrigerator. The test molecules collided with the helium atoms, which transferred heat from the test molecules into the walls of the refrigerator. Once the test molecules got very cold, their vibrations and rotations calmed way down. The molecules now moved very slowly through the hollow chamber where the comb light was bouncing back and forth between two mirrors.

The wild molecules were tamed, and the molecular fingerprinting process worked like a charm!

Ben Spaun, P. Bryan Changala, David Patterson, Bryce J. Bjork, Oliver H. Heckl, John M. Doyle and Jun Ye, *Nature* **533**, 517–520 (2016).

# The Great Escape

The Kapteyn/Murnane group has measured how long it takes an electron born into an excited state inside a piece of nickel to escape from its birthplace. The electron's escape is related to the structure of the metal. The escape is the fastest material process that has been measured before in the laboratory—on a time scale of a few hundred attoseconds, or $10^{-18}$ s. This groundbreaking experiment was reported online in *Science* on June 2, 2016.

To document the electron's great escape from nickel, the group used a high-harmonic generation-based measurement scheme that promises to open the door to measurements of many processes that occur inside atoms, molecules, liquids, and solids. These processes occur too fast to be measured with ordinary techniques in the laboratory.

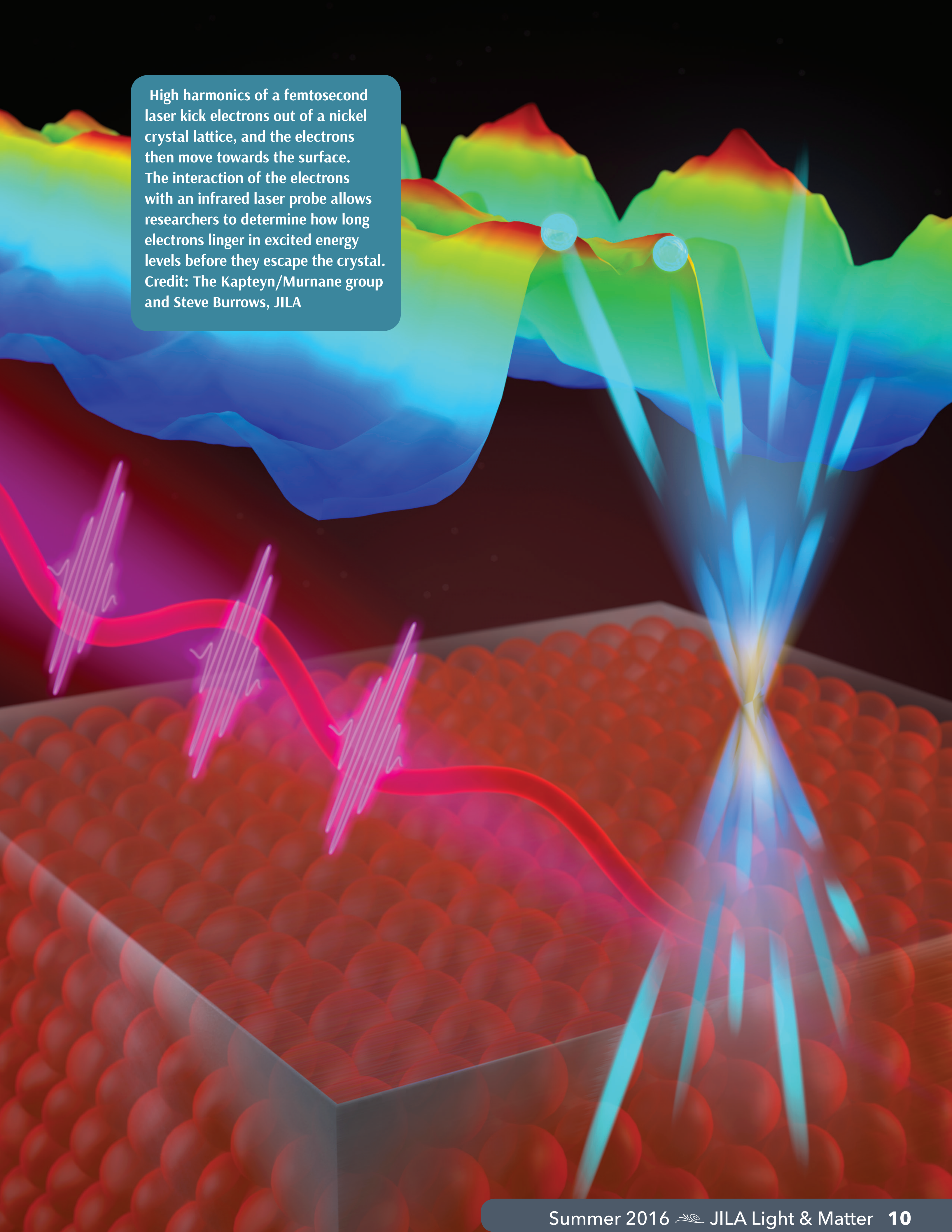
To make the electron-escape measurement, the researchers aimed a sequence of high harmonics of femtosecond laser light at a sample of nickel. The different colors (i.e., photon energies) of the harmonics kicked electrons out from different energy levels in the crystal structure of the nickel, sending them towards the surface. Some electrons escape almost instantaneously. But other electrons–if their energy coincides with a high-energy nickel state–are temporarily grabbed by the high-energy state and linger there for a few hundred attoseconds.

The challenge was how to measure this linger time, or lifetime. Here the researchers took advantage of the weirdness of quantum mechanics. The researchers shined a laser beam onto the sample at the same time as the high harmonics, making it possible for the electrons to absorb different numbers of harmonics and laser photons and still end up in the same final state. This process gave rise to interferences between the different quantum paths taken by the electrons. The researchers analyzed how these quantum interferences changed as the time delay between the laser and high harmonic pulses was changed. The analysis showed that it was possible to determine exactly how long the high-energy nickel band temporarily grabbed onto some electrons before the electrons finally were able to escape for good!

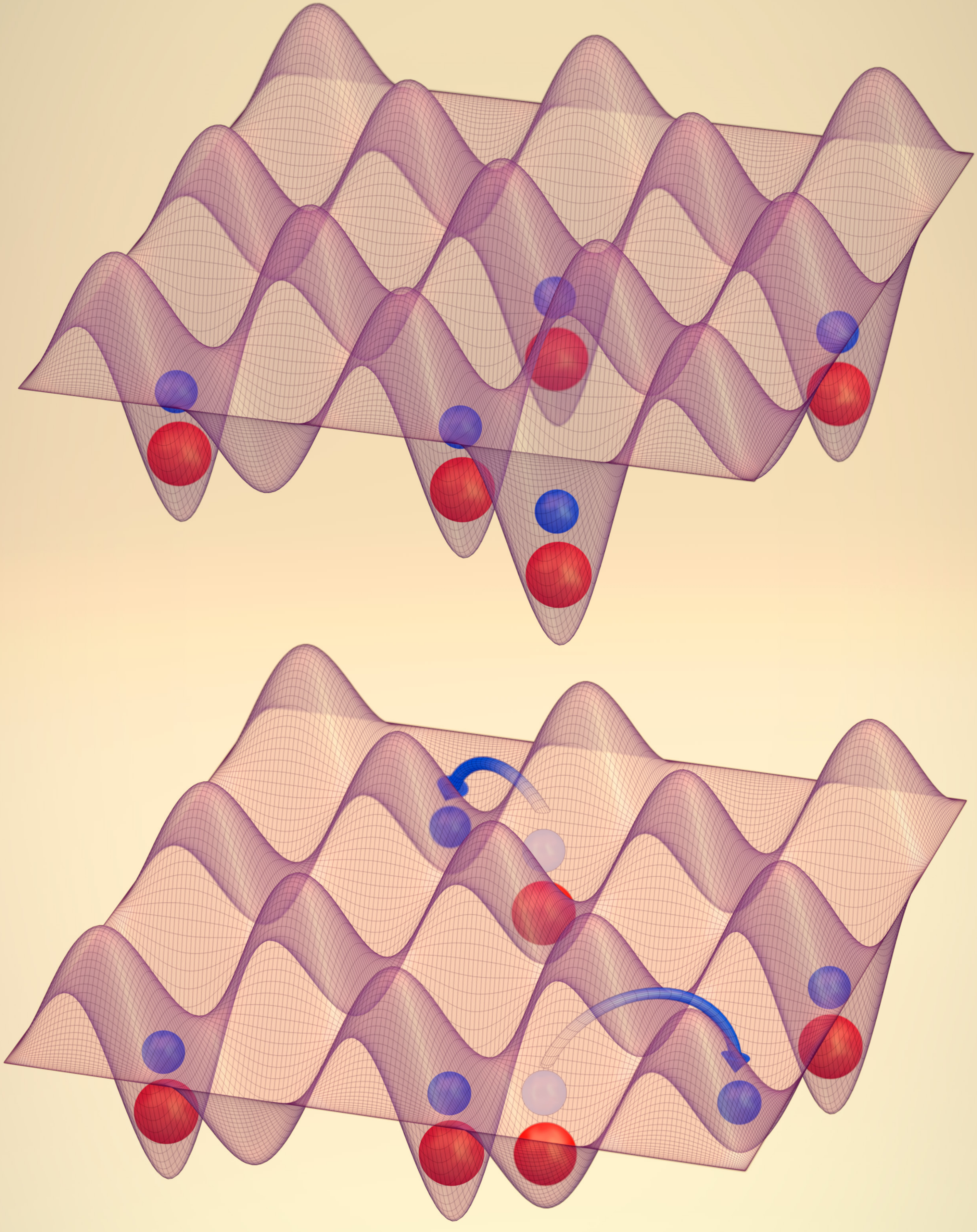
This study added new insights to our understanding of how light ejects electrons from solids in a process called the photoelectric effect. Historically, explaining the photoelectric effect played a major role in the development of quantum mechanics. Over a century later, the group has captured the photoelectric effect in real time to study how electrons bounce off each other (a process called scattering) or rearrange to repel electric fields from a metal (a process called screening). Because electrons are so small and move so quickly, both screening and scattering occur in tens to hundreds of attoseconds. This study demonstrated that scientists are able to directly investigate both processes, which formerly were very challenging to understand and probe.

The researchers responsible for uncovering this great escape include research associate Zhensheng Tao, graduate student Cong Chen, Fellows Henry Kapteyn and Margaret Murnane, and colleagues from NIST and the University of Wisconsin-Madison. ✺

Zhensheng Tao, Cong Chen, Tibor Szilvási, Mark Keller, Manos Mavrikakis, Henry Kapteyn, Margaret Murnane, *Science* **353**, 62–67 (2016).



High harmonics of a femtosecond laser kick electrons out of a nickel crystal lattice, and the electrons then move towards the surface. The interaction of the electrons with an infrared laser probe allows researchers to determine how long electrons linger in excited energy levels before they escape the crystal. Credit: The Kapteyn/Murnane group and Steve Burrows, JILA



The Jin-Ye group's new method of creating just pairs of potassium (K) and rubidium (Rb) atoms (known as doublons) and nothing else inside a crystal of light (optical lattice) paves the way for upcoming JILA experiments in intermolecular communication, ultracold chemistry, and quantum simulation. Credit: The Rey, Jin, and Ye groups and Steve Burrows, JILA

# The Ultramodern Molecule Factory: I. Doublons

The old JILA molecule factory (built in 2002) produced the world's first ultracold polar molecules [potassium-rubidium (KRb)] in 2008. The old factory has been used since then for ultracold chemistry investigations and studies of the quantum behavior of ultracold molecules and the atoms that form them. The Jin-Ye group, which runs the molecule factory, is now wrapping up operations in the old factory with experiments designed to improve operations in the ultramodern factory, which is close to completion.

Recently, graduate student Jacob Covey and both experimentalist and theorist colleagues came up with an ingenious way to ensure that every energy well in the crystal of light (optical lattice) inside a molecule factory is either (1) empty or (2) contains exactly one K and one Rb atom, both in their motional ground states, which is ideal for KRb molecule formation. The group also studied the conditions that kept the K atoms on top of the Rb atoms in the energy wells and the conditions that allowed the K atoms to just hop away.

Then, the researchers made the atom pairs form molecules in relatively deep energy wells with a special trick of using a magnetic field to induce a Feshbach resonance. After using the Feshbach resonance to form the molecules, the researchers removed all the stray atoms from the experiment. Finally, they used the Feshbach resonance to turn the molecules back into atoms, leaving pairs of K and Rb atoms (called doublons) *and nothing else* in the crystal of light.

Once the group made the doublons, they characterized them and figured out how to avoid a tiny resonance that caused many unwanted KRb molecules to form in an excited state. Then they studied conditions that allowed one or both atoms to hop out of the energy wells so they could prevent these hops. This new information will allow the group to increase the fraction of lattice sites occupied by doublons inside a three-dimensional crystal of light. Increasing the filling fraction will open the door to studies of long-range intermolecular communications, ultracold chemistry, and quantum behaviors!

The researchers responsible for refining the production of ultracold KRb molecules for the ultramodern molecule factory include graduate students Jacob Covey and Matthew Miecnikowski, newly minted Ph.D. Steven Moses, research associates Martin Gärttner, Arghavan Safavi-Naini, and Johannes Schachenmayer, former research associate Zhengkun Fu, Fellows Ana Maria Rey, Deborah Jin, and Jun Ye as well as Paul Julienne of the Joint Quantum Institute.

This achievement will give the ultramodern molecule factory the capability of hosting experiments to explore the fundamental physics of not only the KRb molecules, but also of the individual K and Rb atoms. Plus, the new factory should be able to experimentally test theories that explain the interactions of bosons like the Rb atoms with fermions like the K atoms in an optical lattice. (Bosons are particles that don't mind piling up in the same energy state, whereas only two fermions with opposite spin can occupy the same energy state.) The physics will likely be quite interesting when KRb molecules densely populate the crystal of light, as no one yet knows the microscopic details of how many quantum particles all talk to each other at the same time. ✺

Jacob P. Covey, Steven A. Moses, Martin Gärttner, Arghavan Safavi-Naini, Matthew T. Miecnikowski, Zhengkun Fu, Johannes Schachenmayer, Paul S. Julienne, Ana Maria Rey, Deborah S. Jin & Jun Ye, *Nature Communications* **7**, 11279 (2016).

# IN THE NEWS

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

## President Obama Taps Dr. W. Carl Lineberger for Second Term on the National Science Board

President Barack Obama announced on May 20, 2016, his intent to appoint Dr. W. Carl Lineberger to a second term on the National Science Board. The National Science Board serves as an advisory board to the President and Congress on issues involving science and engineering. Lineberger's duties will include helping to establish the policies of the National Science Foundation. He is currently completing a five-year term on the National Science Board that began in August 2011.

Lineberger is the E. U. Condon Distinguished Professor of Chemistry and Fellow of JILA, a joint institute of the University of Colorado Boulder and the National Institute of Standards and Technology. He is a member of the National Academy of Sciences and the American Academy of Arts and Sciences and currently serves on the National Research Council's Committee on Responsible Science and Laboratory Assessments Board, as well as the Ethics Advisory Committee of the National Academy of Engineering.

He has chaired or co-chaired the National Science Foundation Advisory Committees on Mathematical and Physical Sciences, and Science and Technology Centers, the Department of Energy Basic Energy Sciences Advisory Committee, and the National Research Council Commission on Physical Sciences, Mathematics and Applications. Lineberger recently received the 2015 National Academy of Sciences Award in Chemical Sciences.

"I am truly honored and delighted to be afforded this continued opportunity to work with superb colleagues in shared efforts to enhance the National Science Foundation's role as the nation's preeminent fundamental research-funding institution," said Lineberger.

Lineberger earned B.S., M.S., and Ph.D. degrees from the Georgia Institute of Technology. His former graduate students and postdoctoral associates hold major research-related positions throughout the world.

## Jennifer Ellis Wins OSA Award

Jennifer Ellis won an Optical Society of America (OSA) award in recognition of her excellent oral contribution at the International Conference on Ultrafast Phenomena, held July 17–22, 2016 in Santa Fe, New Mexico. Ellis, who is a graduate student with the Kapteyn/Murnane group, spoke about her work on Femtosecond Dynamics of Solvated Electrons in Nanodroplets Probed with Extreme Ultraviolet Beams. She told how her group used EUV light to conduct time-resolved photoemission measurements of isolated nanodroplets in vacuum. With this technique, her group was able to observe what happens when nanodroplets absorb EUV photons. Ellis and her colleagues were able to watch the creation and relaxation of electrons surrounded by solvent molecules–– inside the nanodroplets! Congratulations Jennifer!

## Former JILAn Adam Kaufman Wins 2016 DAMOP Thesis Prize

Adam Kaufman has been awarded the 2016 DAMOP Thesis Prize for his outstanding thesis research on assembling neutral atoms in optical tweezers, work conducted in the Regal group at JILA. As part of this work, Kaufman and his coworkers developed an experiment that allowed the team to use laser cooling to assemble arrays of ground-state neutral atoms in optical tweezers. First, the team demonstrated three-dimensional ground-state cooling of a single atom in an optical tweezer. Next, they conducted a two-particle interference experiment. In this experiment, the researchers observed the atomic analog of the Hong-Ou-Mandel effect. The original Hong-Ou-Mandel effect was a two-photon interference effect that was identified when two identical single-photon waves entered a 50:50 beam splitter, one in each input port. When both photons were identical they snuffed each other out. However, as they became more distinguishable, it became more likely they could be detected. Kaufman and his team observed similar behavior with two atoms trapped in optical tweezers.

In another experiment, Kaufman and his colleagues were able to use their experiment to engineer spin entanglement. This experiment has opened the door to the use of optical tweezers for studies of quantum information.

Kaufman is currently a postdoctoral researcher in the Markus Greiner group at Harvard University. There he investigates many-body systems of bosons in a quantum gas microscope. Kaufman received his undergraduate degree from Amherst College in 2009. At Amherst, he participated in a Bose-Einstein condensate experiment in the David Hall group. Next, Kaufman pursued graduate studies at the University of Colorado Boulder and JILA, working with the Cindy Regal group. His work at JILA was supported by a National Defense Science & Engineering Graduate Fellowship.

Congratulations Adam! JILA is proud of your noteworthy accomplishment.

## Maithreyi Gopalakrishnan: Outstanding Graduate for Service

Former JILAn Maithreyi Gopalakrishnan is one of two 2016 Outstanding Graduates for Service in the University of Colorado Boulder's College of Engineering and Applied Science. Gopalakrishnan graduated from CU on May 7, 2016, with Bachelor's and Master's degrees in engineering physics. As part of her 5-year program of study, she spent two years working with the magnetics group in the Kapteyn/Murnane labs.

"For my Master's, I looked at ultrafast demagnetization dynamics in three different ferromagnetic materials: iron, cobalt, and nickel," Gopalakrishnan said.

In her spare time, Gopalakrishnan started a new company, Surya Conversions. Surya Conversions has plans to develop, manufacture, and sell hybrid electric conversion kits for rickshaws and other small vehicles in India and developing countries. Her idea for the company came after multiple family trips back to India.

"I noticed that the pollution was getting worse each time I visited," she said. "So I really wanted to do something about this because it was so sad to see the country where I was born and where my whole family lives to be so affected by pollution. I want to help solve this problem."

Gopalakrishnan says it's actually a two-pronged problem: the pollution plus the poverty of the rickshaw drivers, who can barely afford to pay for their children's education.

The solution to both problems could be the new hybrid electric conversion kit for rickshaws. The kit is expected to cut a rickshaw's emissions by 33 percent each day. A payment plan developed by Surya Conversions will allow the rickshaw drivers to pay off their kits in one year, with their payments offset by savings on gasoline. After the first year, drivers' incomes should increase 33% because of ongoing fuel savings.

Today, Surya Conversions has five team members: Irfan Nadiadi, Samuel Winston, Matthew Minkler, Kimberlee Ott, and Gopalakrishan. The company currently works out of the Idea Forge on the southeast side of the CU Boulder campus.

"We do our mechanical engineering work there as well as having our meetings there," Gopalakrishnan said. "We figured, why rent office space when we're still a really small company. We don't have any profit yet, so we decided to use the resources here.

"We plan to have a subsidiary company in India to do manufacturing because it doesn't make sense to make the kits here and ship them to India."

For more information about Gopalakrishnan's efforts to solve global problems with entrepreneurism, see *Class of 2016: Solving global problems through entrepreneurism* (http://goo.gl/f9P2vm).

# A Wrinkle in Time

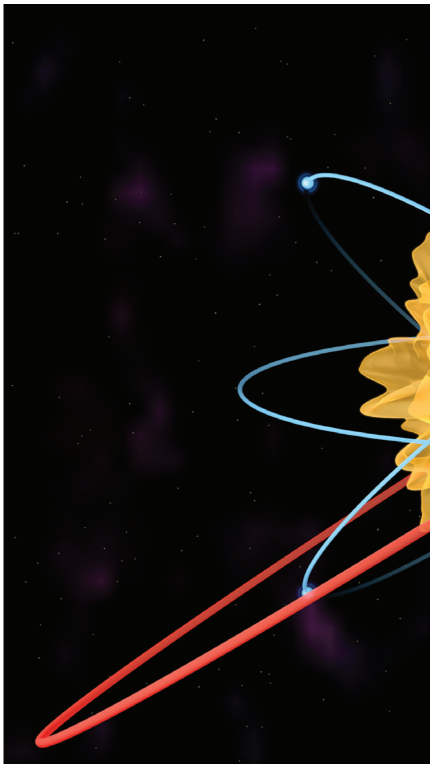
Fellow Judah Levine recently presented a discussion of our understanding of time from antiquity to the present day in an insightful paper published in the April 2016 issue of the *European Physical Journal H*.

Levine recounted that for at least 7000 years, the measurement of time has been linked to the rotation of the Earth, the lunar cycle, the path of the Earth around the Sun, and other observable astronomical phenomena. That the length of a day varies throughout the year didn't faze the ancients. Our forebears simply adjusted the length of time on their primitive timekeeping devices to accommodate changes in daylight accompanying annual seasonal variations.

The earliest water and sand clocks appeared in Egypt, India, China, and Babylonia before 1500 BC. In general, these devices measured relatively short time intervals that were defined in terms of astronomical periods. The Egyptians also divided the day into 24 hours of 60 minutes each, with each minute comprising 60 seconds—a strategy still in use today.

In contrast to time, ancient civilizations weren't concerned with absolute frequency. Frequency was the province of musicians rather than astronomers. Musical scales depended more on frequency ratios and differences than on absolute frequency values. In addition, there was no need for maintaining community standards of time or time interval because both of these quantities were defined in terms of readily observable astronomical phenomena.

However, this simple astronomically based time-measurement strategy hasn't satisfied the requirements for precision timekeeping for more than half a century. Problems arose because of the close connection between time interval and frequency. Any variation in the astronomical standard for time interval introduced a variation in its corresponding frequency. For example, the length of the solar day has been increasing for some time because the Earth's rotation is slowing down. The long-term steady increase in the length of the day is accompanied by an irregular frequency variation that is hard to predict.

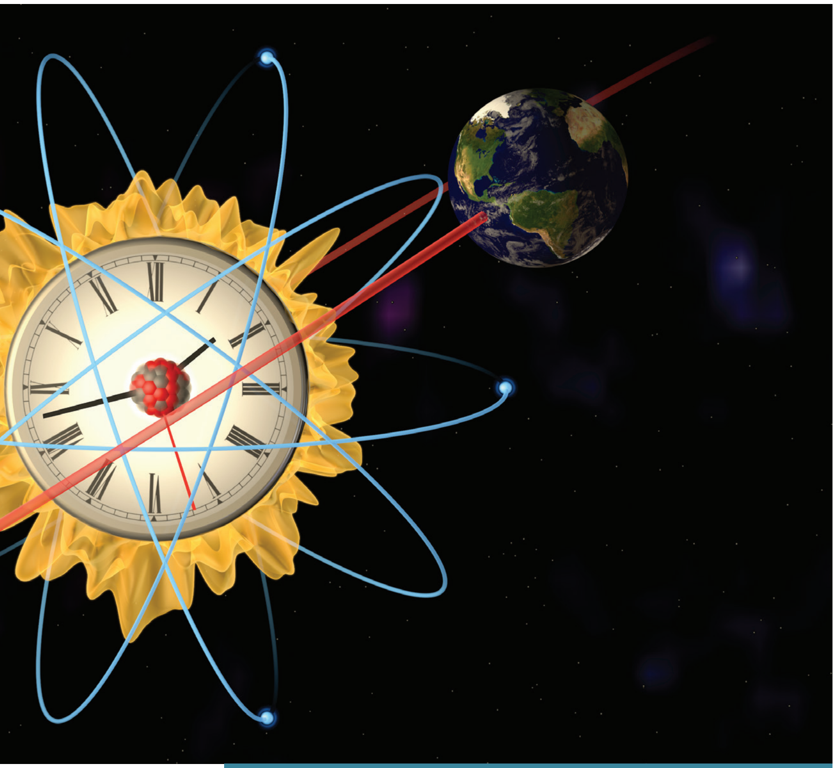


There were attempts to remove this variation by changing the definition of time interval from the apparent solar day to the mean solar day, then to the tropical year, and then to a specific year (1900). However, none of these changes was successful in providing a stable standard for time interval and frequency. Each of these changes did succeed in moving the definitions of time and time interval further away from everyday experience.

Fluctuations in the definition of frequency (caused by variations in the astronomical standard for time interval) began causing major problems in the 1920s when accurate frequencies became important. New radio stations had difficulty maintaining their assigned frequencies, for example. The problem resulted in the separation of the standard of frequency—maintained at National Bureau of Standards (NBS) by various electronic circuits and components—and the definitions of time and time interval, which were defined and observed astronomically.

The invention of the first cesium (Cs) atomic clock at the National Physical Laboratory in the United Kingdom in 1955 offered the world an opportunity to unify the standards of time interval and frequency while removing the astronomically induced variations in them. The definitions of both time interval and frequency would both be tied to counting the number of oscillation cycles in the frequency associated with the hyperfine transition in the ground state of Cs 133.

The link between the astronomically defined second and the Cs transition frequency was measured in a joint experiment between the National Physical Laboratory (NPL) in the United Kingdom and the United States Naval Observatory (USNO). The result of this experiment was that 9192631770 cycles of the hyperfine transition frequency of Cs were equivalent to one astronomical second. The hyperfine frequency of the cesium transition became the standard, and the second became a quantity derived from it. Since ancient times, it had been just the opposite—astronomical time and time interval had always been the fundamental standards.



The rotation of the Earth is slowing, and atomic clock time is getting further ahead of astronomical time, which is based on the Earth's rotation. Currently, the addition of leap seconds to atomic clock time helps keep the two in sync. For more than 20 years, international forums have debated whether to move to purely atomic-clock-based timekeeping, but nothing has happened thus far to resolve the issue. Credit: The Levine Group and Steve Burrows, JILA

However, the value chosen for the number of cycles of the Cs frequency that would correspond to one second was too small. Thus, the length of the day defined in terms of the Cs frequency was shorter than the length of the day defined by astronomy. And, because the Earth is slowing down, it is impossible to define the second based on the hyperfine transition in Cs in a way that will exactly match an astronomically observed second for all time.

Nevertheless, applications that depend on standard frequencies, ranging from telecommunications to financial transactions to power distribution, are fundamental to a modern society. Unless the world community decides to return to 19th century technologies, it's no longer possible to define frequency as a quantity derived from a varying astronomical time.

To further complicate matters, the Earth's rotation continues to slow down, and our days are slowly getting longer. The slowing of Earth's rotation means that atomic clocks are getting further and further ahead of astronomical time. Timekeepers have addressed this problem since 1972 by adding a leap second to atomic clock time—26 times thus far, not counting the 10 seconds that were inserted when the scale was defined. More recently, the interval between leap seconds has gotten longer because the slow-down of the Earth is slowing down. *(Continued, page 17)*

For more than 20 years, the international timekeeping community and high-ranking national officials have debated whether to keep the leap second and the link between atomic clock time and astronomical time or simply move to atomic clock time for precision timekeeping. If the linkage between atomic time and astronomical time were to be broken by eliminating leap seconds, then atomic time would advance relative to solar time. At present, the rate of advance is about one minute per century.

"We have a controversy to resolve," said Judah Levine, JILA's resident timekeeping expert. "The hardest question is: Who is going to resolve the controversy?"

Levine said that the next round of international discussions of what to do with the leap second won't take place until the next World Radio Conference in 2023 unless the Bureau of Weights and Measures in Paris takes up the question next year. Up until now, however, participants in the controversy have been inclined to "kick the can down the road" to some date in the future rather than agreeing on how to resolve the issue.

"I can't tell you what's going to happen," Levine said. "Time is political, and it always has been. For now leap seconds are going to stay." In other words, for the time being, official time will continue to be linked to astronomical phenomena as it has been for thousands of years.

In the meantime, researchers at JILA, NIST, and national laboratories around the world are investigating even more accurate frequency standards, including strontium (in the Ye labs at JILA), ytterbium, and calcium. Atomic clock time is only going to get even more precise at the same time astronomical time gets more imprecise with the slowing of Earth's rotation.

**Water clocks are thought to be some of the earliest timepieces. Amenhotep I, an Egyptian pharaoh, was buried with one around 1500 BC. Although water clocks were not the most accurate timekeeper, they enabled people to tell time without relying on the Sun. Credit: Kristin Conrad, JILA**

Although it requires the addition of leap seconds to work for modern timekeeping applications, astronomical time has the advantage of being as familiar to people as the Sun and the Moon, the seasons, and Earth's journey through the stars. Not surprisingly, astronomers like it. The British like it because it allows them to assert a close connection between Greenwich Mean Time (GMT) and official international time; and, so far national laboratories around the world have adjusted to more than half a century of complex timekeeping requirements imposed by linking precision timekeeping to astronomical time.

Even so, leap seconds cause problems for many users. Real-time applications, such as satellite navigation, use a time scale that does not include leap seconds. Private time scales are likely to proliferate in the future as more real-time applications require a smooth time scale lacking the discontinuities that result from adding leap seconds.

Of course, Levine would like to see international agreement to implement ultraprecise timekeeping based on the next generation of atomic clocks—but he's not sure he'll be around long enough to see a global consensus develop around this sensible idea.✺

Judah Levine, *The European Physical Journal H* **41**, 1–67 (2016).

# How Did They Get Here?

**Jun Ye** was born in Shanghai, China, in 1967. His father was a naval officer who later pursued a career in business. His mother was an environmental scientist and city official who controlled funding for environmental protection. While his parents were busy with their careers, Ye grew up in Shaoxing, a city about 200 km south of Shanghai. He was raised by his father's mother, E-Gui Jin, who placed such a high value on education that he would dedicate his Ph.D. thesis to her in 1997.

Ye says his generation had many more educational opportunities after Mao Zedong died in 1976. Ye and his contemporaries were too young to be affected by the Cultural Revolution, which had incited widespread destruction of much China's traditional cultural heritage. Ye also reaped the benefits of a strong revival of China's national educational system in the late 1970s.

His own interest in science began as a freshman in high school when he began reading profiles of leading physicists in Chinese journals. After reading about the life of Erwin Schrödinger, he remembers thinking "what an interesting life he had lived." At about the same time, he had to make a difficult decision between an educational path emphasizing science and technology and another emphasizing literature. Soon after deciding upon the science and technology path, he was selected to represent his high school in a national physics competition. "I did reasonably well, especially on the experimental part where I was told to figure out problems with a non-functioning Wheatstone Bridge circuit," he recalls. "And, I discovered that physics was exciting for me. I decided that I would go to college and study physics."

Ye earned a Bachelor's degree in physics at Shanghai Jiao-Tong University in 1989. His courses were mostly in theory until his undergraduate thesis, which was based on work performed in an optics laboratory. This work led to Ye's first publication in the journal *Applied Optics* (in 1990). At Jiao-Tong, Ye was an excellent student. He expected to travel a smooth path to graduate school and a career as a physicist in China.

The student uprising and turmoil of the spring 1989 changed his plan. "We were very idealistic at the time, and who wouldn't be at a young age" he says. "We wanted an open society immediately. And, perhaps we were a bit too impatient."

Disappointed, in late 1989 Ye came to the United States to work on quantum optics theory with Marlan Scully at the University of New Mexico (UNM). He also started an experimental career with John McInerney on semiconductor lasers. One summer he had the opportunity to work with Howard Bryant on high-energy beam collisions involving negative ions at Los Alamos National Laboratory. By the time Scully announced he was moving to Texas, Ye had earned a Master's degree in physics from UNM (1991). He also knew he wanted to pursue a hardcore experimental career in AMO physics. He began looking around and discovered an experimental genius at JILA named Jan Hall. "I told Jan, 'I want to be your student,'" Ye recalls.

"Jan said, 'You must be very brave.'" Hall accepted Ye (in 1992) as the last graduate student to enter his research group. For his thesis, Ye worked on high-resolution and high-sensitivity molecular spectroscopy. He profited from Hall's technical wizardry every step of the way.

"The molecule work was very difficult," Ye recalls. "At room temperature, molecules fly around all over the place. You can see why I decided later on to study cold molecules, which stay put long enough to enable precision study." Ye's graduate work was a resounding success and laid the foundation for his career as an experimental physicist. He earned his Ph. D. from the University of Colorado in 1997.

His next stop was as a Millikan postdoctoral fellow in experimental quantum optics in Jeff Kimble's lab at CalTech. Kimble's lab was another formative experience. There, Ye was given the assignment of developing a single atom trap in a tiny optical cavity, some space in the lab, and a million dollars to spend.

Ye returned to JILA in 1999 as an Associate Fellow. His thesis advisor and mentor Hall donated most of his laboratory space to him. That year was a starting point for the rapid development of optical frequency combs based on ultrafast lasers, and Ye got to work closely with both Steve Cundiff and Jan Hall. It was a great experience for the JILA scientists to marry two once-separated fields of precision single-frequency lasers and ultrafast optical science.

Ye also began working on a new optical atomic clock based on neutral strontium atoms and started another program on cold molecules. In 2001, he became a Fellow of JILA. Today, he directs a large group of young scientists from all over the world. The group recently began using a second Sr-lattice clock to explore the frontier of light-matter interactions at the quantum level.

Currently the Ye group does research in three key areas: (1) the physics of strontium (Sr) atoms, including the development and enhancement of a neutral Sr optical atomic clock and Sr-based quantum simulations for novel quantum many-body systems; (2) research on the behavior and chemistry of cold and ultracold molecules, including a collaboration with Deborah Jin on using ground-state potassium-rubidium (KRb) molecules as a quantum simulator and a study of collisions of ammonia and other molecules at milliKelvin temperatures; and (3) precision spectroscopy, including the precision measurement of fundamental constants and the expansion of optical frequency comb technology into higher- and lower-frequency regions of the electromagnetic spectrum.

Ye has earned many awards for his scientific accomplishments, including the 1999 OSA Adolph Lomb Medal, a 2002 Technology Review Magazine's TR100 Young Innovator, a 2003 Presidential Early Career Award in Science and Engineering, the 2005 Arthur S. Flemming Award, the 2006 NIST Samuel W. Stratton Award, the 2006 William F. Meggers Award from the Optical Society of America, the 2007 I.I. Rabi Prize from the American Physical Society, the 2007 Friedrich Wilhelm Bessel Research Award from the Alexander von Humboldt Foundation, the 2007 Carl Zeiss Award, two Department of Commerce Gold Medals (in 2001 and 2011), the 2009 European Time and Frequency Forum Award, and a 2011 Frew Fellowship. Ye was named a Gordon and Betty Moore Distinguished Scholar by CalTech in 2008 and elected Director at Large of the Optical Society of America in 2011. He is a Fellow of the National Institute of Standards and Technology, the American Physical Society, and the Optical Society of America as well as a member of the National Academy of Sciences. In 2015, President Obama selected Ye to receive a 2015 Presidential Rank Award.

Ye is married to Ying Zhang, whom he knew as a child when her family were neighbors of his grandmother in Shanghai. The couple has two daughters. The Ye family enjoys music, hiking, and visiting libraries, churches, and museums in the United States, Europe, and China.

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 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; Astrophysics & 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.

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