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QUANTUM LEGOLAND

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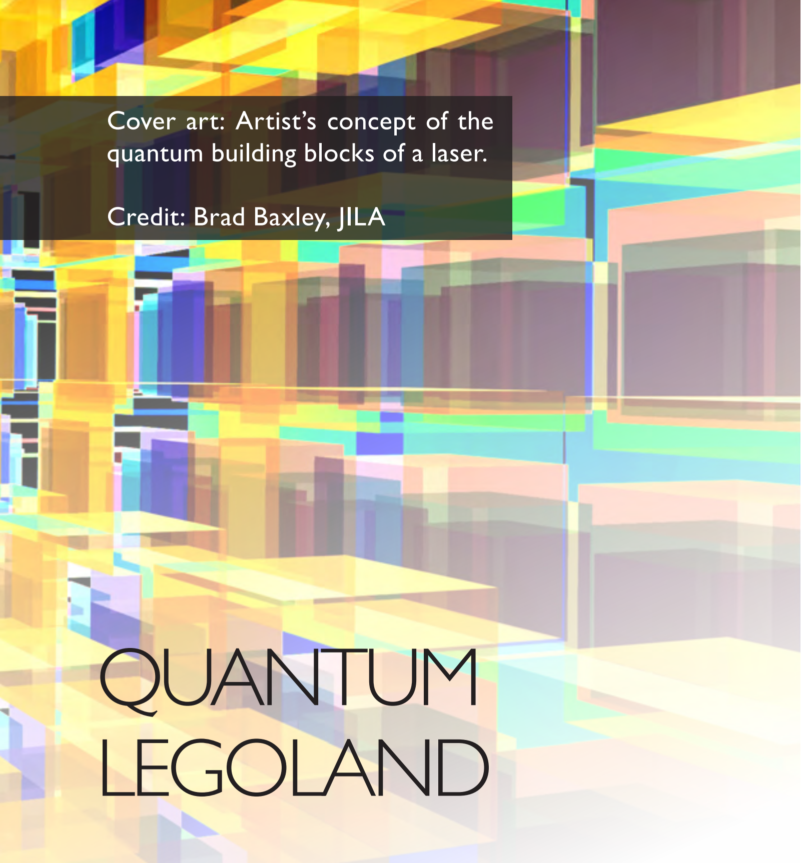


Cover art: Artist's concept of the quantum building blocks of a laser.

Credit: Brad Baxley, JILA

QUANTUM LEGOLAND

The quantum world is not quite as mysterious as we thought it was. It turns out that there are highways into understanding this strange universe. And, graduate students Minghui Xu and David Tieri with Fellow Murray Holland have just discovered one such superhighway that has been around since the 1950s. Traveling along this superhighway has made it possible to understand the quantum behavior of hundreds of atoms inside every laser used in JILA, including the superradiant laser in the Thompson lab that works entirely differently from all the others.

The weirdest thing is that this is the same superhighway traveled by the SU(4) group theory used to explain quark physics. Quarks are elementary particles that make up hadrons; hadrons are things like the protons and neutrons that sit inside every atomic nucleus. The lowest energy quarks are known as up, down, strange, and charm. And, as it turns out, up, down, strange, and charm quarks are analogs of the four basic "Lego building blocks" that also describe the quantum behavior of atoms in a laser.

So why is it so hard to figure out what's happening with hundreds of atoms inside a laser? The answer is easy. It's the fault of quantum mechanics and its mind-boggling complexity. A mere three hundred atoms, each with two possible states, have as many different combinations of quantum states as there are atoms in the entire Universe.

Fortunately, Fellow Murray Holland and graduate students Minghui Xu and David Tieri have just found a pathway through this complexity. This pathway exists because of something called invariance. Invariance is responsible for the familiar laws of conservation of energy and conservation of momentum that govern the classical world we are more familiar with. The two laws state that if no external forces are acting on a system, (1) the amount of energy remains constant over time and (2) an object will continue moving at the same speed forever. The fact that energy remains constant is due to the invariance of choosing the origin of time. The fact that an object just keeps going at the same speed is due to the invariance of choosing the origin of space.

As it turns out, the Holland group has just discovered an intricate invariance that governs the quantum physics of lasers. As "luck" would have it, only a relatively small number of possible quantum states are compatible with a particular value of the invariant quantity once it's determined by a laser system itself.

It's as if a laser can "choose" to be made of only one color such as red, blue, green, yellow, black, grey, or clear Legos. But, once decided, the laser obeys a conservation law that means that the color of the Lego blocks won't change in time. The constancy of the color represents the invariance. Once the invariance is in place, one can make any state of a laser from just four shapes of quantum Lego blocks, a square (up), a corner piece (down), a thin arch piece (strange) and a rectangle (charm).

Of course, like quarks, the laser analogs (Lego shapes) are actually quantum mechanical states. But, it's possible to construct quite complicated things from four elementary building blocks.

"We've got four types of blocks, and, out of them, we can make everything, Holland explains. "When you realize this, there is a clear path to an unbelievable reduction in complexity."

Holland and his students have just proved this assertion in a new *Physical Review A* paper. In the paper, they showed how "quark physics" mathematics could be used to solve the quantum master equations for both ordinary and superradiant lasers, feats once considered impossible.

The new theory opens the door to finding ways to build even more complicated structures out of the basic four quantum Legos. Plus, new building blocks, such as laser analogs of the much heavier top and bottom quarks, may be found.

"We already know there are some optical systems where the building blocks are slightly different," Holland says. "The questions are: How far can we push this new idea? Can we use our new theory to understand other important systems in quantum optics and ultracold gases?"

Perhaps an important question for the rest of us to ponder is: Without invariances, would we even have the world we know? — *Murray Holland and Julie Phillips*

Reference

Mingui Xu, D. A. Tieri, and M. J. Holland, *Physical Review A*, **87**, 062101 (2013).

TRAPPER MARMOT AND THE STONE COLD MOLECULES

The Ye group has opened a new gateway into the relatively unexplored terrain of ultracold chemistry. Research associate Matt Hummon, graduate students Mark Yeo and Alejandra Collopy, newly minted Ph.D. Ben Stuhl, Fellow Jun Ye, and visiting colleague Yong Xia of East China Normal University have built a magneto-optical trap (MOT) for yttrium oxide (YO) molecules. The two-dimensional MOT uses three lasers and carefully adjusted magnetic fields to partially confine, concentrate, and cool the YO molecules to transverse temperatures of ~2 mK. It is the first device of its kind to successfully laser cool and confine ordinary molecules found in nature.

Magneto-optical traps for atoms were invented during the 1980s. The atom traps made it relatively straightforward for scientists to make ultracold trapped atoms. In the process, the new traps led to revolutions in the fields of atomic and quantum physics. At JILA, they were used in the creation of the world's first Bose-Einstein condensate, the world's first ultracold Fermi gas, novel quantum sensors, and in dozens of other experiments with ultracold atoms.

Not surprisingly, researchers have been working for nearly 20 years to replicate the success of magneto-optical trapping with molecules. However, molecules are a lot more internally intricate than atoms, which typically have two energy levels that can be exploited simultaneously for cooling and trapping them. In contrast, laser cooling and trapping molecules (at ultracold temperatures) requires an apparatus that can address multiple energy levels at the same time.

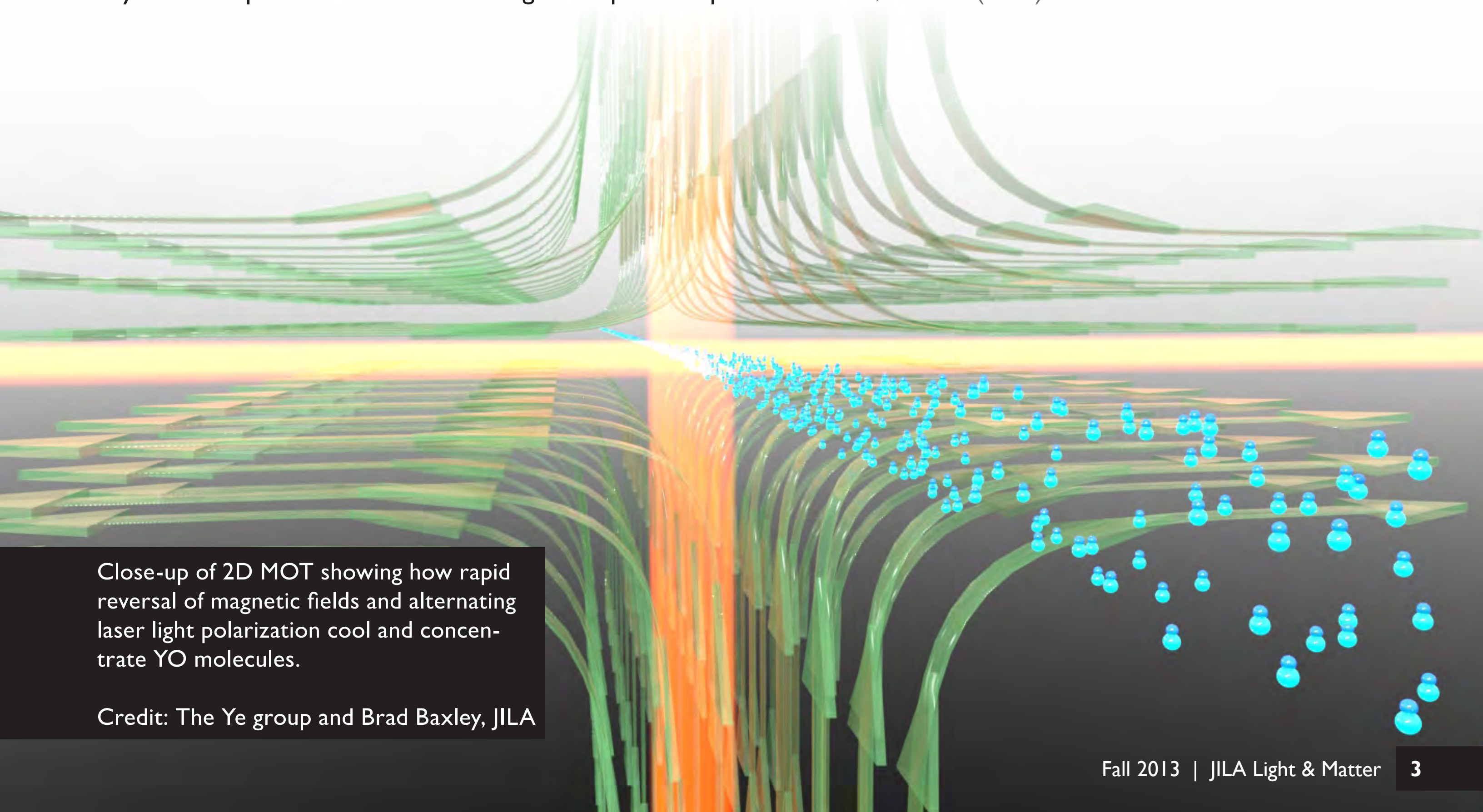
To meet this challenge, Hummon and his colleagues added two additional lasers to their MOT, alternated the polarization of the laser light interacting with the molecules, and rapidly reversed the direction of the magnetic field around the molecules. This combination allowed them to "talk to" multiple energy levels of the YO molecules at the same time and create a more concentrated gas of much colder molecules.

However, because the new device is a two-dimensional MOT, the cooler, denser molecules are still traveling with enough speed to escape from the trap. They are also moving too fast for ultracold chemistry experiments.

To make it possible to do chemistry experiments with ultracold YO molecules, the researchers are now working on stopping their stone cold molecules in their tracks. To accomplish this, they are redesigning their MOT to trap YO molecules in three dimensions. The three-dimensional MOT, whimsically named the Magnetically Alternating Remixed MOT, or MARMOT, is expected to produce colder and denser trapped YO molecules that move very, very slowly. Stay tuned.

Reference

Matthew T. Hummon, Mark Yeo, Benjamin K. Stuhl, Alejandra L. Collopy, Yong Xia, and Jun Ye, *Physical Review Letters* **110**, 143001 (2013).



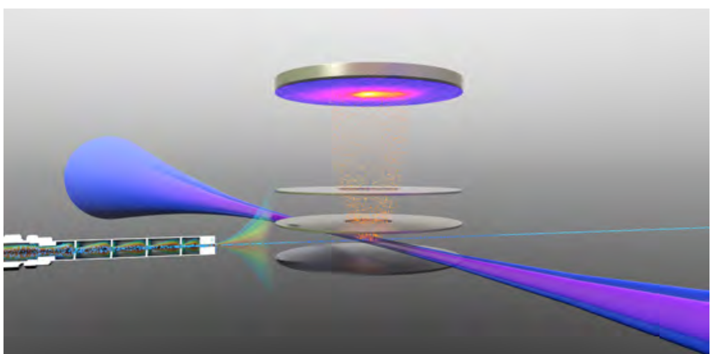
Close-up of 2D MOT showing how rapid reversal of magnetic fields and alternating laser light polarization cool and concentrate YO molecules.

Credit: The Ye group and Brad Baxley, JILA

NOT ALL WHO WANDER ARE LOST

-AFTER *J.R.R. TOLKIEN*

When research associate Wei Xiong and graduate student Dan Hickstein studied quantum dots by shining laser light on them in the gas phase, they got some surprising results. The tiny chunks of material responded differently to a series of two laser pulses—depending on their size. The scientists already knew that most of their quantum dots would end up with at least part of an electron wandering around outside of them for some period of time. However, Xiong and his colleagues showed that the electrons from the smallest quantum dots traveled the farthest away.



The experimental apparatus consisting of a velocity map imaging photoelectron spectrometer coupled to a nanoparticle aerosol source.

Credit: The Kapteyn/Murnane group and Brad Baxley, JILA

More importantly, the researchers found that it was much easier for a second laser pulse to knock electrons completely out of the smaller quantum dots than it was to pry the electrons loose from the larger dots. At first, this behavior seemed a little strange, but soon the researchers figured out what was going on.

When a laser pulse excites an electron inside a quantum dot, the electron will spend some of its time wandering around outside of quantum dot. However, the amount of time that the electron spends outside is much longer for the smaller quantum dots. In fact, electrons typically wander around outside the little guys roughly 10% of the time.

"That 10% is the important part," explained Xiong. "If you're an electron hanging partly outside a quantum dot, there are good reasons why it's easier to kick you all the way out. First, you cannot absorb photons (from laser light) as easily if you're inside a quantum dot. Second, even if you absorb a photon and try to escape, there's a chance you won't make it all the way out of the quantum dot."

In other words, the farther away an electron wanders from its quantum dot, the easier it is for a second light pulse to knock it all the way out of the ball park.

Xiong and Hickstein were assisted in this work by graduate students Jennifer Ellis and Chengyuan Ding; research associate Ellen Keister; Gordana Dukovic, assistant professor of chemistry and biochemistry, and her graduate student Kyle Schnitzenbaumer; Jose-Luis Jimenez, associate professor of chemistry and biochemistry and Fellow of the Cooperative Institute for Research in Environmental Sciences (CIRES), and his graduate student Brett Palm; as well as Fellows Margaret Murnane and Henry Kapteyn.

Xiong and his colleagues are interested in studying quantum dots and other nanostructures because they're half way between atoms and solids. Consequently, they behave differently than other materials. For instance, quantum dots can absorb light 100–1000 times better than most substances. However, efforts to use quantum dots to improve the efficiency of solar panels haven't paid off yet. It's been difficult to get electrons excited by sunlight to wander out of the quantum dots and into a wire.

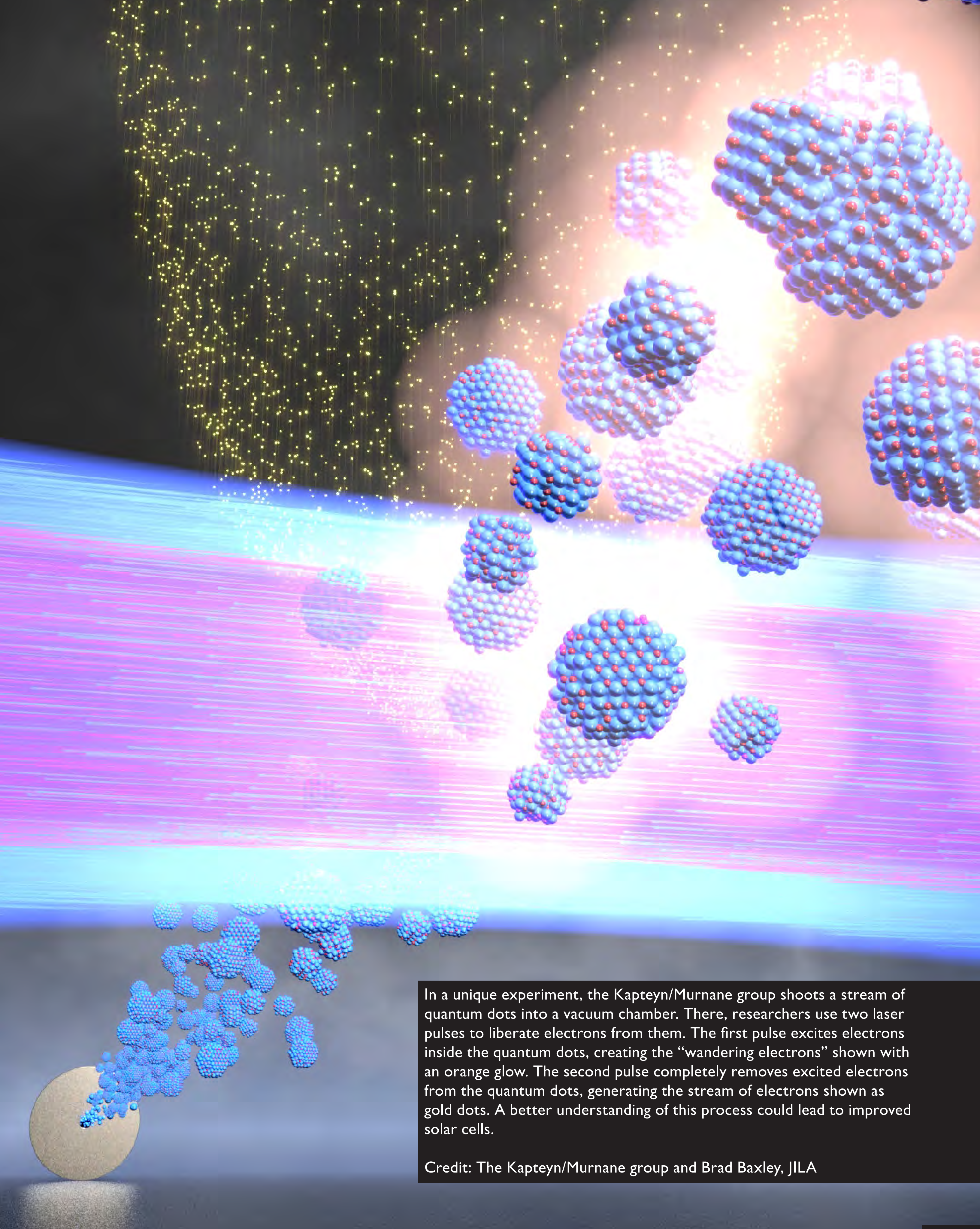
Here's where the basic research underway by Xiong and his colleagues may be able to help. They've just made the first direct measurements of the amount of time that the excited electrons spend outside of various sizes of quantum dots after being excited by laser light. They've also shown that these excited-wandering electrons are easier to remove from the quantum dots with a second pulse of laser light. They may even have made a significant step towards understanding how best to use quantum dots to harvest the Sun's energy.

This project was made possible via a collaboration of three groups, two at the University of Colorado and one in JILA. The experiment included two instruments from the Kapteyn/Murnane group, a special aerodynamic lens and source of nanoparticles from the Jimenez lab, and assistance with sample preparation and theoretical understanding of the quantum dots from the Dukovic group.

The next step for Xiong and his colleagues is to seek a better understanding of the basic physics of how electrons move from quantum dots to other nanomaterials. Initially, they plan to attach quantum dots to quantum rods, molecules, and other nanostructures to study more about the physics of electron transfer.

Reference

Wei Xiong, Daniel D. Hickstein, Kyle J. Schnitzenbaumer, Jennifer L. Ellis, Brett B. Palm, K. Ellen Keister, Chenyuan Ding, Luis Miaja-Avila, Gordana Dukovic, Jose L. Jimenez, Margaret M. Murnane, and Henry C. Kapteyn, *Nano Letters* **13**, 2924–2930 (2013).



In a unique experiment, the Kapteyn/Murnane group shoots a stream of quantum dots into a vacuum chamber. There, researchers use two laser pulses to liberate electrons from them. The first pulse excites electrons inside the quantum dots, creating the "wandering electrons" shown with an orange glow. The second pulse completely removes excited electrons from the quantum dots, generating the stream of electrons shown as gold dots. A better understanding of this process could lead to improved solar cells.

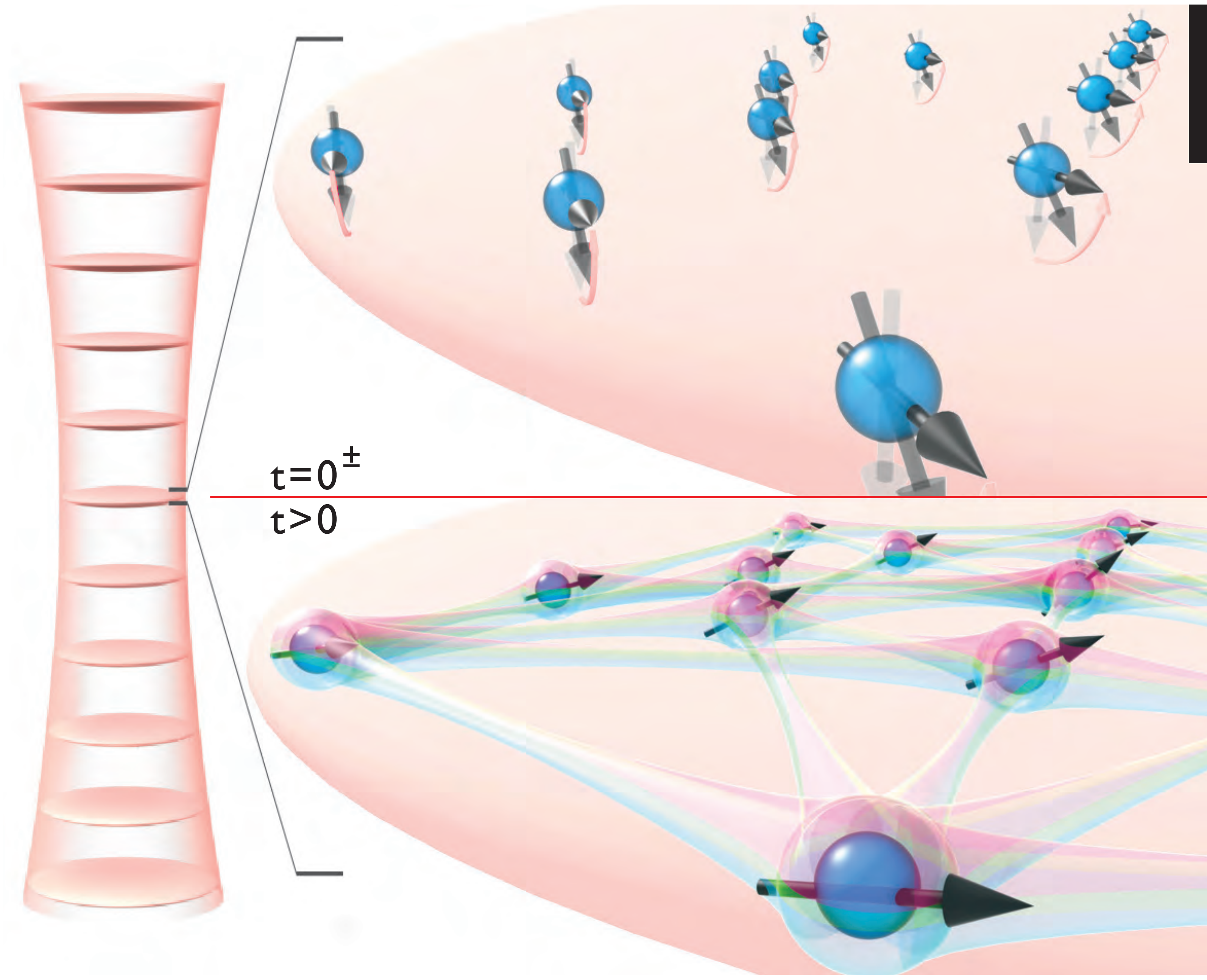
Credit: The Kapteyn/Murnane group and Brad Baxley, JILA

THE MAGNIFICENT QUANTUM LABORATORY

Because quantum mechanics is crucial to understanding the behavior of everything in the Universe, one can understand key elements of the behavior of a neutron star by investigating the behavior of an atomic system in the laboratory. This is the promise of the new quantum simulator in the Ye labs. It is a fully controllable quantum system that is being used as a laboratory to study the behavior of other less controllable and more poorly understood quantum systems.

Most people would imagine such a quantum simulator as being very different from a clean and deceptively simple experiment like the Ye group's strontium (Sr) lattice optical atomic clock, which includes an exquisite precision measurement capability. But, they would be wrong. The precision measurement capability of the Sr-lattice clock offers researchers a unique ability to probe systems for long times. This ability is necessary for the study of quantum behavior in atomic systems, whose interactions (and energy) are tinier than other quantum systems such as liquids, solids, or neutron stars.

So, once newly minted Ph.D. Mike Martin and his colleagues had developed one of the world's most accurate and precise atomic clocks, all they needed to transform the clock into a quantum simulator was a lot of patience and a powerful collaboration with the Rey theory group. The first use of the new simulator to probe collective atomic interactions was reported recently in *Science*.



The interactions studied by Martin and his colleagues can be used to model a magnetic spin system. A better understanding of the quantum behavior of magnetic spins will not only lead to a better understanding of magnetism in general, but also of superconductivity. It will also lead to a deeper appreciation of the mysteriously interconnected quantum world and its relationship to the world we know.

Even though the researchers discovered how to use the Sr-lattice clock as a quantum simulator, their initial goals were to make a better clock and to improve advanced tools used to measure the clock's accuracy and precision. To accomplish these goals, Martin built one of the world's best, lowest-noise clock lasers. Pulses from this laser interacted with Sr atoms inside a stack of 100 "pancakes" of approximately 20 atoms each, causing the atoms to cycle between two energy levels. The energy-level changes are the ticks of the clock.

Inside the Ye group's new quantum simulator, the electron spins of strontium atoms evolve over time and may become entangled (lower left). Once the particles are entangled, if something changes in one of them, all linked partners respond.

Credit: Ye group and Brad Baxley, JILA

However, the Ye group already knew that with the new, quiet laser with its enhanced precision, atomic interactions would still appear to play a dominant role in causing the tiny variations in the ticks of the clock. As Martin and others probed the causes of these variations, they sought help from the Rey theory group to eliminate them. New theory helped the experimentalists eliminate the variations in the clock ticks due to atomic interactions.

In the process, Martin and his colleagues realized that since their precision measurement tools had allowed them to observe quantum interactions inside the clock, the clock would be a superb laboratory for exploring spin behavior in the quantum world. Spins interact with each other in a complex manner that is nearly impossible to model with classical physics. Plus, such interactions are so low in energy, they can only be detected in the laboratory with the very best precision-measurement tools.

"Precision measurement and control allow us to remove irrelevant classical noise and ensure that quantum phenomena stand out in the quantum laboratory," Ye explained. "And, what happens in the laboratory is helping us to expand the frontiers of measurement science, because we can use our deeper understanding of the quantum system to design better tools."

Precision measurement makes it possible to observe the evolution of a quantum spin system. The clock laser can place all the atoms in the simulator in a "superposition," in which all the spins point up and down at the same time. Over time, the collective superposition of all these atoms will evolve.

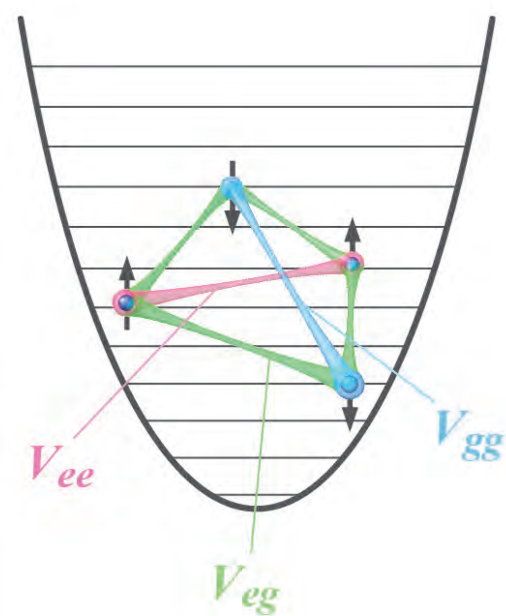
In watching the evolution of spin states, the researchers have concluded that the atoms must be "talking" to each other inside the pancakes, or perhaps even "hooking up" in a spooky quantum process known as entanglement. Once particles are entangled, if something changes in one of them, all linked partners respond. The experimental signatures for these effects include the progressive distortion of the clock transition spectrum as spin interactions increase, a shift of the atomic transition frequency due to spin interactions, distinctive changes in behavior when spins lose their coherence, and a modification in the quantum spin-noise distribution.

The Rey group is working with the Ye group to explain observations and guide future experiments. The theorists are developing mathematical models to describe the behavior of Sr atoms in the clock. They have already shown that Sr atoms can simulate some aspects of the behavior of electrons in magnetic materials. They are now working to see whether the similarities hold for more complex situations.

Preliminary work suggests that an atomic clock simulator may behave similarly to real spins in magnetic materials. If so, the simulator may lead to better modeling and understanding of quantum magnetism, exotic materials, and superconductivity (which occurs in materials that can conduct electricity without resistance).

Reference

M. J. Martin, M. Bishof, M. D. Swallows, X. Zhang, C. Benko, J. von Stecher, A. V. Gorshkov, A. M. Rey, and Jun Ye, *Science* **341**, 632-636 (2013).



Relationships between entangled atoms.

Credit: Ye group and Brad Baxley, JILA

A FAMILY TRIP TO PARIS FOR THE L'ORÉAL-UNESCO AWARD

For Fellows John Bohn and Deborah Jin, physics often involves the entire family, including 10-year-old daughter Jackie Bohn, a fifth grader at Mesa Elementary School. Jackie was born in 2002, just weeks after her mother's lab succeeded in making the world's first condensate of diatomic molecules of ^{40}K from an ultracold degenerate Fermi gas of atoms. She went to her first scientific conference (a Gordon Research Conference) when she was eight months old and just learning to walk. When Jackie was five, her mother collaborated with Fellow Jun Ye to makes the world's first ultracold molecules, an accomplishment cited in this year's L'Oréal-UNESCO For Women in Science award. Jackie still goes to conferences sometimes, but what happened this year was the most fun of all.

In March 2013, Jackie accompanied her parents to Paris where her mother received one of five L'Oréal-UNESCO For Women in Science awards in a formal ceremony on March 28 at the Sorbonne University in Paris. Jin was honored as the 2013 Laureate for North America for her having been the "first to cool down molecules so much that she can observe chemical reactions in slow motion, which may further understanding of molecular processes which are important for medicine or new energy sources."

"That was the big thing we went to in Paris," Jackie recalled. "She had to give a two-minute speech on fermions and other 'ons.' It was fun to see my Mom do that." Jackie said that she and her Dad had to sit way in the back of the auditorium during the ceremony. But they did get to wear fancy headphones like they have at the United Nations that broadcast translations of the award proceedings into English.

"The Sorbonne was an elaborate and ornate auditorium," Bohn said. "All along the walls were statues of these famous French intellectuals. And, right there between statues of (mathematician and physicist) Blaise Pascal and Cardinal Richelieu (the world's first prime minister) were these two giant banners with pictures of Debbie on them, so we took a picture of all of them."

The L'Oréal-UNESCO awards ceremony lasted about an hour and was followed by a reception. Jackie especially liked the reception because they had strawberries dipped in red sugar and Uncle Craig (Jin) was there.

Jackie and her Dad attended Jin's and the other Laureates' scientific talks at the French Academy of Sciences. The whole family also got to come along on a walk up and down the Champs-Élysées that featured a photo exhibition of larger-than-life pictures of the five Laureates and the 15 L'Oréal-UNESCO Fellows who were each given a year of support for their postdoctoral research at locations around the world.

Despite being a gloomy grey day, the Champs-Élysées walk was a highlight of the trip, in part because Jin's family was able to join her.

"Picture all the Laureates on the Champs-Élysées and a random guy," quipped Bohn, who posed with Jackie and his wife in front of Jin's picture in JILA's Cold Molecule Lab.

"When I looked at the pictures of John and Jackie with me, I realized we still have to help women believe it's possible to be a world-class scientist and still have a family," Jin reflected. "During the walk down the Champs-Élysées, I wondered how the others felt when Jackie gave me all those big hugs." She added that only one other Laureate had a child, an infant who had remained at home while her mother journeyed to Paris.

The five-day L'Oréal-UNESCO program was more than just a walk down the Champs-Élysées and an elegant awards ceremony, however. L'Oréal put a lot of money into an evening and three days of activities to promote women in science. These events, which were not open to families, provided opportunities for the Laureates to interact with the L'Oréal-UNESCO Fellows, who have completed graduate work in a different country from where

they are doing their postdoctoral research. The postdoctoral fellowships will likely have far more impact in the long run than the five big awards that garner the most publicity, says Jin.

"The postdoctorals were nice and interesting," Jin said. "There were so many from Africa, the Arab nations, and Latin America. Most of their research was not in physics; instead it was more immediately relevant. For instance, one woman was doing research in food security, which meant figuring out how to secure food for people in her country, which has a rather short growing season, for an entire year. It puts our life in perspective."

Both Jin and Jackie plan to continue their contact with Allison Louthan, a postdoc in ecology at the University of Colorado, Boulder, who is doing field work in Kenya. Jin invited Louthan to speak to her group this fall when she returned to Boulder. This is the kind of ongoing relationship L'Oréal-UNESCO wants to encourage with its private activities that include special dinners, round-table discussions, press interviews, as well as visits to the L'Oréal laboratories and the Paris Observatory.

The L'Oréal-UNESCO For Women in Science awards and fellowships are not well known in the United States, but they are a huge deal in Paris, Jin says. She's delighted that Nobel Laureate Bill Phillips nominated her for the award, which meant a great deal to her and to her family.

"Paris is a pretty nice place to visit," she admits. "We got to stay across the street from where Ernest Hemingway hung out in the 1920s, visit the Luxembourg Gardens, browse neat shops, and eat in local cafés. We had a lovely time."

While Jin was busy with private activities, Bohn and Jackie explored Paris together, visiting the Eiffel tower to make watercolor paintings. The next day the entire family climbed 700 steps up to the second floor. "It's not your average second floor," acknowledged Jin of the feat.

Even with a few extra days in Paris to be tourists, the time soon arrived for the Jin-Bohn family to depart for Boulder. But, there was one more surprise awaiting them: different pictures of Jin hung all over the Charles De Gaulle airport.

"Her big picture in the airport was right by our gate when we were leaving," Jackie said. "That was the only place we saw where they used the picture that had the graduate students in it. There we were, standing in line, and the people were looking at Mom because Dad pointed her out to them. Then they gawked at her."

Jackie was asked who told the most jokes in the family. Without hesitation, she pointed at her Dad, who was trying hard to look innocent. While this was happening, Jin leaned over and, pointing at Jackie, said softly, "You know, she's just as important as any award in science could ever be."

ALIEN ATMOSPHERIC CHEMISTRY

Astrophysicist Jeff Linsky and his colleagues from CU's Center for Astrophysics and Space Astronomy have come up with a neat strategy for helping to determine whether an exoplanet's atmosphere contains evidence of Earth-like life. The first step is to see whether an exoplanet's atmosphere contains oxygen (O_2), ozone (O_3), or other molecules that could have been produced by Earth-like organisms such as the plants that produce O_2. Next, Linsky and his collaborators propose analyzing spectral lines from the host star's light to determine if the same molecules could exist in the atmosphere without life.

Producing O_2 without life, for instance, requires hydrogen Lyman-alpha radiation from the planet's host star. Lyman-alpha radiation is the brightest ultraviolet (UV) spectral line. It can produce oxygen molecules (O_2) in an exoplanet's atmosphere via the photodissociation of water (H_2O) and carbon dioxide (CO_2).

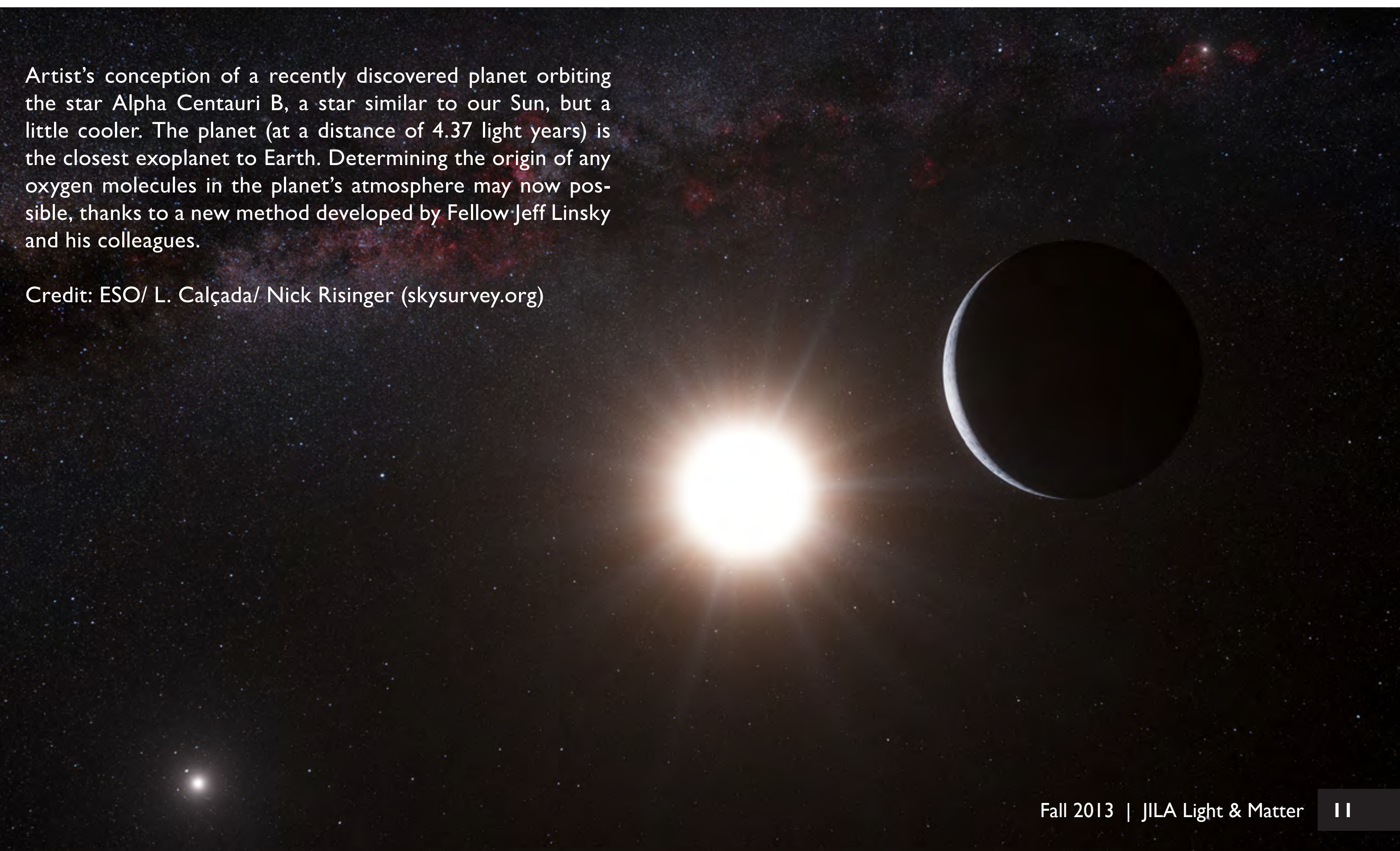
The hard part of knowing whether photodissociation is occurring is figuring out the brightness of the Lyman-alpha radiation emanating from a star. It's hard to do because hydrogen in the interstellar medium absorbs most of the Lyman-alpha radiation. This absorption makes it impossible for space-based observatories to measure how much of the high-energy UV light is reaching an exoplanet's atmosphere.

To reconstruct the intrinsic Lyman-alpha radiation from a star, Linsky and his colleagues correlate the amount of Lyman-alpha radiation with other spectral lines in the optical, UV, and x-ray regions of the star's spectrum. The lines include ionized carbon, oxygen, magnesium, and calcium radiated by a star at roughly the same temperature as Lyman-alpha radiation. The radiation from the atoms isn't absorbed by interstellar hydrogen and can be accurately measured by spectrometers aboard the Hubble Space Telescope and other observatories. The correlation method can be used to come up with reasonable estimates of Lyman-alpha radiation.

This new technique works with any relatively cool star like the Sun. In the future, when space-based observatories are able to measure O_2 in the atmospheres of exoplanets, this new method will allow astrophysicists to determine whether photodissociation is responsible for part, or all, of the O_2 in an exoplanet atmosphere.

Reference

Jeffrey L. Linsky, Kevin France, and Tom Ayres, *The Astrophysical Journal* **766**, 69 (2013).



Artist's conception of a recently discovered planet orbiting the star Alpha Centauri B, a star similar to our Sun, but a little cooler. The planet (at a distance of 4.37 light years) is the closest exoplanet to Earth. Determining the origin of any oxygen molecules in the planet's atmosphere may now possible, thanks to a new method developed by Fellow Jeff Linsky and his colleagues.

Credit: ESO/ L. Calçada/ Nick Risinger (skysurvey.org)

THE TRANSPORTER

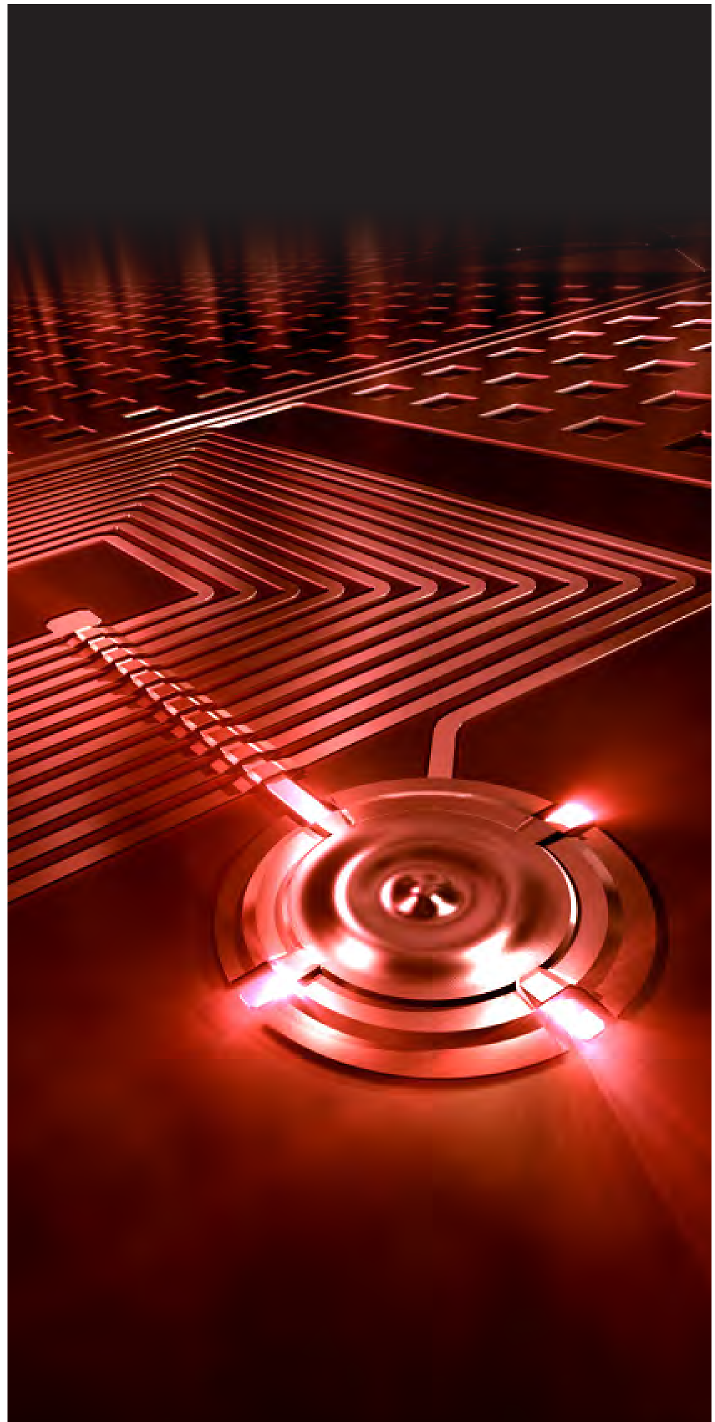
The Lehnert group has come up with a clever way to transport and store quantum information. Research associate Tauno Palomaki, former graduate student Jennifer Harlow, NIST colleagues Jon Teufel and Ray Simmonds, and Fellow Konrad Lehnert have encoded a quantum state onto an electric circuit and figured out how to transport the information from the circuit into a tiny mechanical drum, where is stored. Palomaki and his colleagues can retrieve the information by reconverting it into an electrical signal.

This transportation scheme should make it possible to use tiny drums for memory storage in quantum computers. It also opens the door to using the drums as intermediaries in systems that convert quantum information from one physical system, such as a microwave field, into another physical system, such as a laser light field.

One interesting aspect of this new scheme is that voltage oscillations describing the quantum state in an electrical signal can be transformed into mechanical energy (vibrations) in the drum. This information transformation is very handy because the drum can store information for much longer than the electrical signal. And, the researchers can reconvert the drum vibrations into an electrical signal whenever they want to for as long as the drum keeps vibrating.

The setup for accomplishing this information shape shifting is shown in the figure. A microwave field, which runs diagonally across the top, passes through the square-shaped circuit into the drum at the lower right of center. The vibrating metal drum is itself part of the electrical circuit transporting the information that makes the drum pulsate.

This nifty information transporter was described in a recent article in *Nature*. One possible future use for it may be in quantum information processing. The transporter can store quantum information in the mechanical energy of the tiny vibrating drum a hundred times longer than it can be stored in other forms of energy. Once this quantum storage capacity is developed, it could prove invaluable for the design of quantum computers, for example.



Artist's concept of the Lehnert group's information transporter. The transporter moves quantum information back and forth between an electronic circuit and a tiny vibrating drum.

Credit: Jack Bertram, Motion Forge, Inc. for the National Institute of Standards and Technology.

One day the transporter may also play a role in transferring quantum information from a microwave light field to a laser light field. Right now, these two forms of electromagnetic radiation cannot communicate with one another on the quantum level. Once the Lehnert and Cindy Regal groups succeed in building a new transporter that connects a vibrating mechanical drum with a laser light field, it may be possible to build a supertransporter to send quantum information back and forth from a microwave field (the realm of electronic devices) to a visible light field. Such an information supertransporter could open the door to quantum systems engineering on a grand scale.

Reference

T. A. Palomaki, J. W. Harlow, J. D. Teufel, R. W. Simmonds, and K. W. Lehnert, *Nature* **495**, 210–214 (2013).

LIFE IN THE FAST LANE

Many people are familiar with the beautiful harmonies created when two sound waves interfere with each other, producing a periodic and repeating pattern that is music to our ears. In a similar fashion, two interfering x-ray waves may soon make it possible to create the fastest possible strobe light ever made. This strobe light will blink fast enough to allow researchers to study the nuclei of atoms and other incredibly tiny structures. The new strobe light is actually very fast coherent laser-like radiation created by the interference of high-energy x-ray waves.

The theory predicting this advance was developed by research associate Carlos Hernández-García; senior research associates Agnieszka Jaroń-Becker and Tenio Popmintchev; Fellows Andreas Becker, Margaret Murnane, and Henry Kapteyn; and their colleagues from the Universidad de Salamanca and El Centro de Láseres Pulsados, both in Salamanca, Spain.

The theory says that a mid-infrared laser would be able to accelerate an electron away from its parent atom, then crash the electron back into the atom, not once, but many times. Every time the electron crashed back into the parent atom, it could emit coherent bursts of x-rays, in a process known as high-harmonic generation. Moreover, each half-cycle of the mid-infrared laser field could accelerate a different part of the electron cloud. The interference of different x-ray bursts would then produce pulses of coherent radiation hundreds of zeptoseconds (10^{-19} s) long. For comparison, the shortest laser pulse lengths that can be produced right now are about a thousand times wider: 100 attoseconds, or 10^{-16} s.

"We already knew how to generate high harmonics of a laser that span into the x-ray regime. But, now we're proposing to manipulate these x-rays to design light pulses at the shortest time scales," explains Fellow Andreas Becker.

High-harmonic generation is already used in the Kapteyn/Murnane labs to make wide swaths of coherent ultraviolet-to-soft x-ray radiation from near-infrared coherent laser light. Now Hernández-García and his colleagues have figured out how to use a mid-infrared laser to control the behavior of an electron during high-harmonic generation so that two (or more) x-ray bursts interfere to produce the fastest strobe light ever, i.e., coherent-zeptosecond laser-like radiation.

There are two key ingredients to bringing the new theoretical vision into reality: (1) Extending current mid-infrared lasers towards even longer wavelengths, a process that could take 5–10 years; and then (2) using the longer-wavelength laser field to make it possible for electron waves emitted at different times to recombine at the same time and produce the desired interference of x-ray bursts.

The good news is that Fellows Kapteyn and Murnane agree that producing shorter and shorter wavelength coherent radiation in the laboratory is an important goal. Achieving this goal may enable new and better medical imaging in the not-too-distant future. As soon as the mid-infrared-laser technology is developed, the creation of coherent-zeptosecond laser radiation will be just a matter of precisely controlling the interference of x-ray bursts, according to Becker.

The new laser theory was reported online July 18 in *Physical Review Letters* and highlighted in *Nature* and on the American Physical Society website.

Reference

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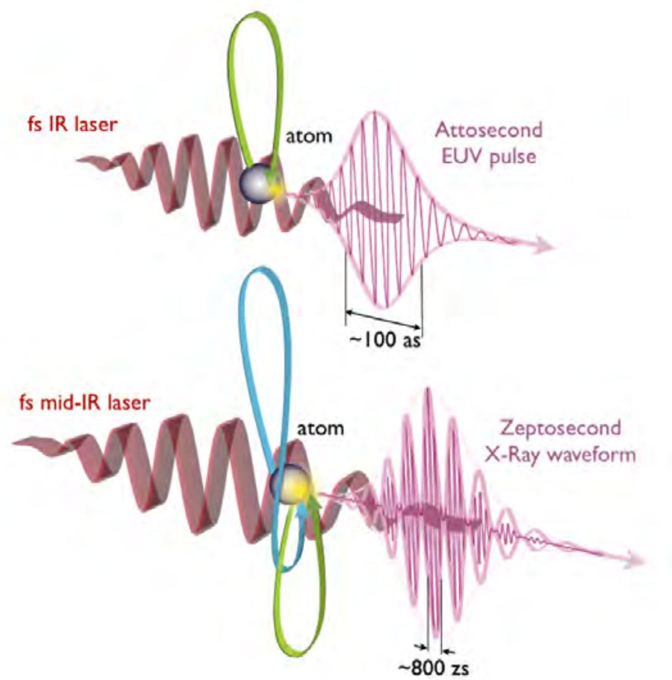

Top: In standard high-harmonic generation, a femtosecond laser removes an electron from an atom, then drives it back to the parent ion. The electron recombines with the ion, releasing its energy in the form of an attosecond pulse with a wavelength in the extreme ultraviolent region of the spectrum. Bottom: In zeptosecond pulse generation, two electronic wave packets generate x-ray bursts that interfere and create a waveform with amplitude beats hundreds of zeptoseconds long—a thousand times shorter than is possible today.

Credit: Carlos Hernández-García and Tenio Popmintchev, JILA

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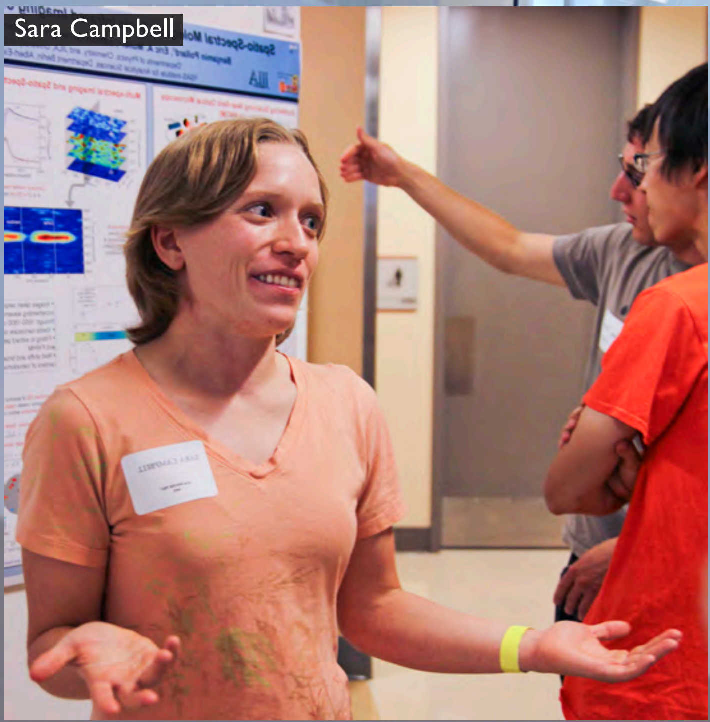
Photo credit: Brad Baxley, JILA


Susanna Kohler (center), Maryly Dole (right)

Dan Hickstein (left), Agnieszka Jaroń-Becker (right)


Sara Campbell


Johannes Schachenmayer (left), Andrew Spott (right)


Scott Parkins (left), Adam Kaufman (center), Brian Lester, (right)


Hao Wu (left), David Reens (center), Andrew Keller (right)


Kaden Hazzard (left), Sheng-Jie Huang (right)


Steven Moses (left), Karl Mayer (right)

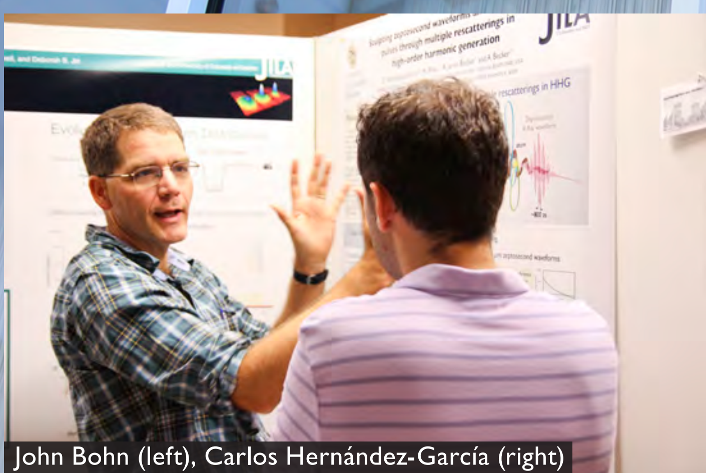

Takeshi Suzuki (left), Bosheng Zhang (center), Tenio Popmintchev (right)

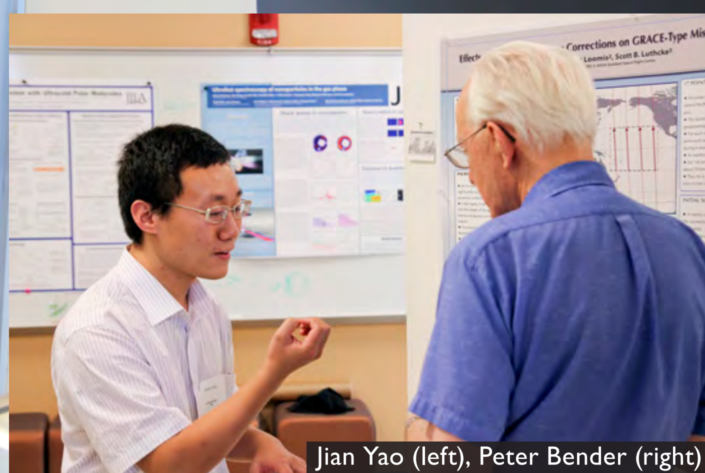

Tauno Palomaki (left), Joshua Weiner (right)


Hern Paik (left), Eric Muller (center), Kathy Hoogeboom-Pot (right)


François Labaye (left), Mehmet Ali Anil (center), Eric Martin (right)


Robert Peterson (left), Ben Pollard (center), Matt Grau (right)


John Bohn (left), Carlos Hernández-García (right)


Jian Yao (left), Peter Bender (right)

Kudos to...

Graduate student **Justin Bohnet** for winning an Outstanding Presentation award at the Boulder Laboratories 10th annual Poster Symposium in July 2013. His poster was entitled "A Steady-State Superradiant Raman Laser."

Research associate **Franklin Dollar** for winning the 2013 John Dawson Thesis Prize for his thesis entitled "High intensity, high contrast laser solid interactions with short pulses." Dollar received a medal, $500, and financial support to attend the conference where he received the prize.

Newly minted Ph. D. **Michael Foss-Feig** for winning the American Physical Society's DAMOP Award for outstanding doctoral thesis research in atomic, molecular, and optical physics. His thesis, entitled "Quantum simulation of many-body physics with neutral atoms, molecules, and ions," was completed under the direction of Ana M. Rey.

Research associate **Bryce Gadway** for winning an Outstanding Presentation award at the Boulder Laboratories 10th annual Poster Symposium in July 2013. His presentation was entitled "Realizing a Lattice Spin System with Ultracold Polar Molecules."

Research associate **Carlos Hernández-García** for winning a 4th Award for Young Researchers from the 12th International Symposium on Ultrafast Intense Laser Science. The award recognized Hernández-García's work on high-harmonic and zeptosecond pulse generation with the Becker and Kapteyn/Murnane groups in JILA and colleagues in Spain.

Dr. Katharine B. Gebbie for more than 40 years of service to JILA and NIST. Gebbie, who was honored with two symposia held in May 2013, made outstanding contributions as a scientist, leader, and mentor. Her tenure at NIST helped keep the institute at the cutting edge of science and technology; produced four Nobel prizes, a National Medal of Science winner, and a L'Oréal-UNESCO award for Women in Science; and enabled world-class achievements in measurement science.

Graduate student **Kathy Hoogeboom-Pot** for being selected as the winner of a Judge's Choice Award in the 2013 IGERT Video and Poster Competition. Hoogeboom-Pot attended an awards ceremony in the National Science Foundation.

Deborah Jin for being appointed as a member of the Secretary of Energy Advisory Board (SEAB). SEAB is an independent advisory committee to the United States Energy Secretary, Dr. Ernest Moniz.

Graduate student **Susanna Kohler** for winning the 2013 Richard N. Thomas Award.

Judah Levine for being presented the I. I. Rabi Award at the joint symposium of the IEEE-International Frequency Control Symposium (IFCS), the IEEE-International Ultrasonics Symposium (IUS), the IEEE-International Symposium on the Applications of Ferroelectric (ISAF) and the Piezoresponse Force Microscopy and Nanoscale Phenomena in Polar Materials (PFM), and the European Frequency and Time Forum (EFTF). Levine was cited for his outstanding contributions to the fields of precise timekeeping and time transfer.

David Nesbitt for winning the 2013 Pacesetter Award in the science category from the Boulder Daily Camera. The award honored Nesbitt's nearly 20 years of participating in and directing the CU Wizards program.

Graduate student **Travis Nicholson** for winning the competition for Best Student Paper (on the Ye group's ultracold strontium clock project) at the joint symposium of the IEEE-International Frequency Control Symposium (IFCS), the IEEE-International Ultrasonics Symposium (IUS), the IEEE-International Symposium on the Applications of Ferroelectric (ISAF) and the Piezoresponse Force Microscopy and Nanoscale Phenomena in Polar Materials (PFM), and the European Frequency and Time Forum (EFTF).

Ana Maria Rey for winning a 2013 MacArthur Foundation Fellowship, or "genius grant," for her ground-breaking theoretical work on ultracold atoms. The award includes a $625,000 unrestricted grant.

Ana Maria Rey for winning the 2014 Maria Goeppert Mayer award from the American Physical Society that recognizes outstanding achievement by a woman physicist in the early years of her career. The award consists of $2,500 plus a $4000 travel allowance.

Ana Maria Rey for winning the "Great Minds in STEM" Most Promising Scientist Award.

James Thompson for being awarded a 2013 Department of Commerce Bronze Medal for his pioneering work on superradiant lasers.

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