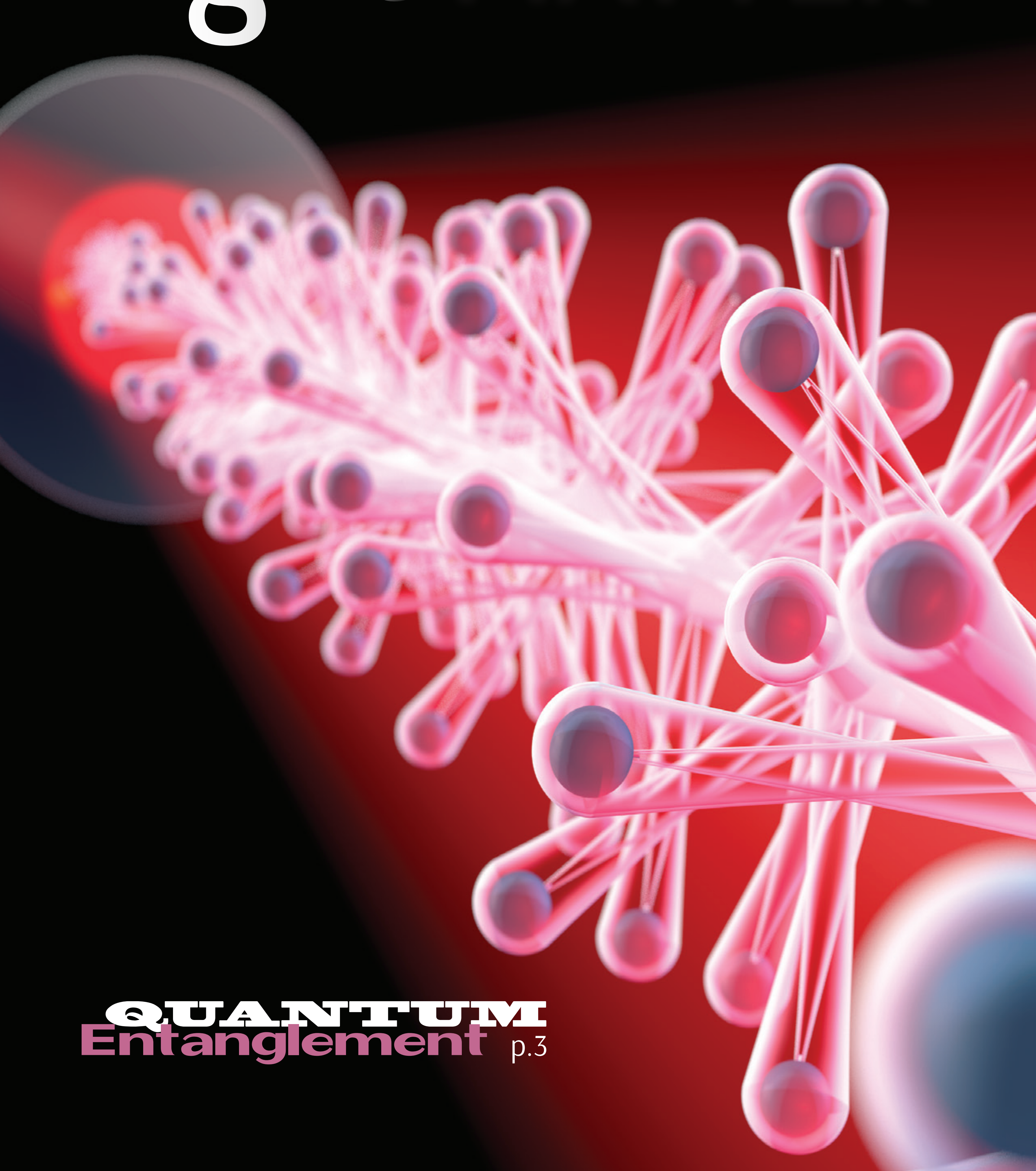
JILA light & MATTER

Winter 2015 | jila.colorado.edu



## QUANTUM Entanglement p.3

The 2nd Annual Poster Fest was held on October 3, 2014. JILA supports an eclectic and innovative research community. The Poster Fest provides an opportunity for JILA scientists to learn about the research of other JILAns and present information about their own work.

*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 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

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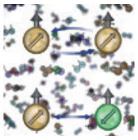
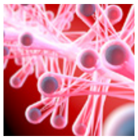
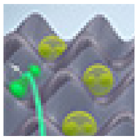
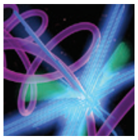
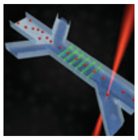
# Stories

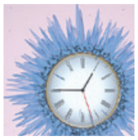












# Features

# *Atoms, Atoms, Frozen Tight in the Crystals of the Light, What Immortal Hand or Eye Could Frame Thy Fearful Symmetry?*

–after William Blake

Symmetries described by SU(N) group theory made it possible for physicists in the 1950s to explain how quarks combine to make protons and neutrons and JILA theorists in 2013 to model the behavior of atoms inside a laser. Now, the Ye group has observed a manifestation of SU(N≤10) symmetry in the magnetic behavior of strontium-87 ($^{87}$Sr) atoms trapped in crystals of light created by intersecting laser beams inside a quantum simulator (originally developed as an optical atomic clock).

This first-ever spectroscopic observation of SU(N) orbital magnetism in $^{87}$Sr atoms cooled to micro-Kelvin temperatures was reported online in *Science Express* on August 21, 2014.

Several advances made this observation possible: (1) seminal theory work by the Rey group predicted the magnetic behavior of $^{87}$Sr atoms at cold and ultracold temperatures, (2) exquisite measurement precision available from an ultrastable laser developed for the $^{87}$Sr-lattice optical atomic clock, (3) the ability to freeze out the motional states of the atoms, but preserve the flow of information, at relatively "high" μK temperatures, (4) the use of $^{87}$Sr atoms, whose 10 nuclear spin states are decoupled from their interparticle interactions, and (5) the experimental control of the number of $^{87}$Sr atoms in the ground and excited electronic states used as orbitals.

This groundbreaking work opens the door to: (1) precision studies of collisions between nearly identical $^{87}$Sr atoms that differ only in the states of their nuclear spins, (2) a deeper understanding of the role of atomic orbitals in collisions and chemical reactions, and (3) investigations of quantum magnetism and exotic materials. For instance, theorists have predicted that a chiral spin liquid will form if $^{87}$Sr atoms are prepared in all 10 nuclear spin states and cooled down in a two-dimensional lattice (crystal of light). This exotic substance has no apparent order even at ultralow temperatures approaching absolute zero!

> This first-ever spectroscopic observation of SU(N) orbital magnetism in $^{87}$Sr atoms cooled to micro-Kelvin temperatures was reported online in *Science Express* on August 21, 2014.

The researchers responsible for launching this new, exciting work include research associate Xibo Zhang, graduate students Mike Bishof and Sarah Bromley, research associate Christina Krauss and Professor Peter Zoller of the University of Innsbruck (Austria), Professor Marianna Safronova of the University of Delaware, and Fellows Ana Maria Rey and Jun Ye.

For a more whimsical description of the science in this highlight, please see *Alice's Adventures in Quantum Land: Lost inside a strontium-lattice watch,* at https://jila.colorado.edu/book/alices-adventures-quantumland/01. ✺

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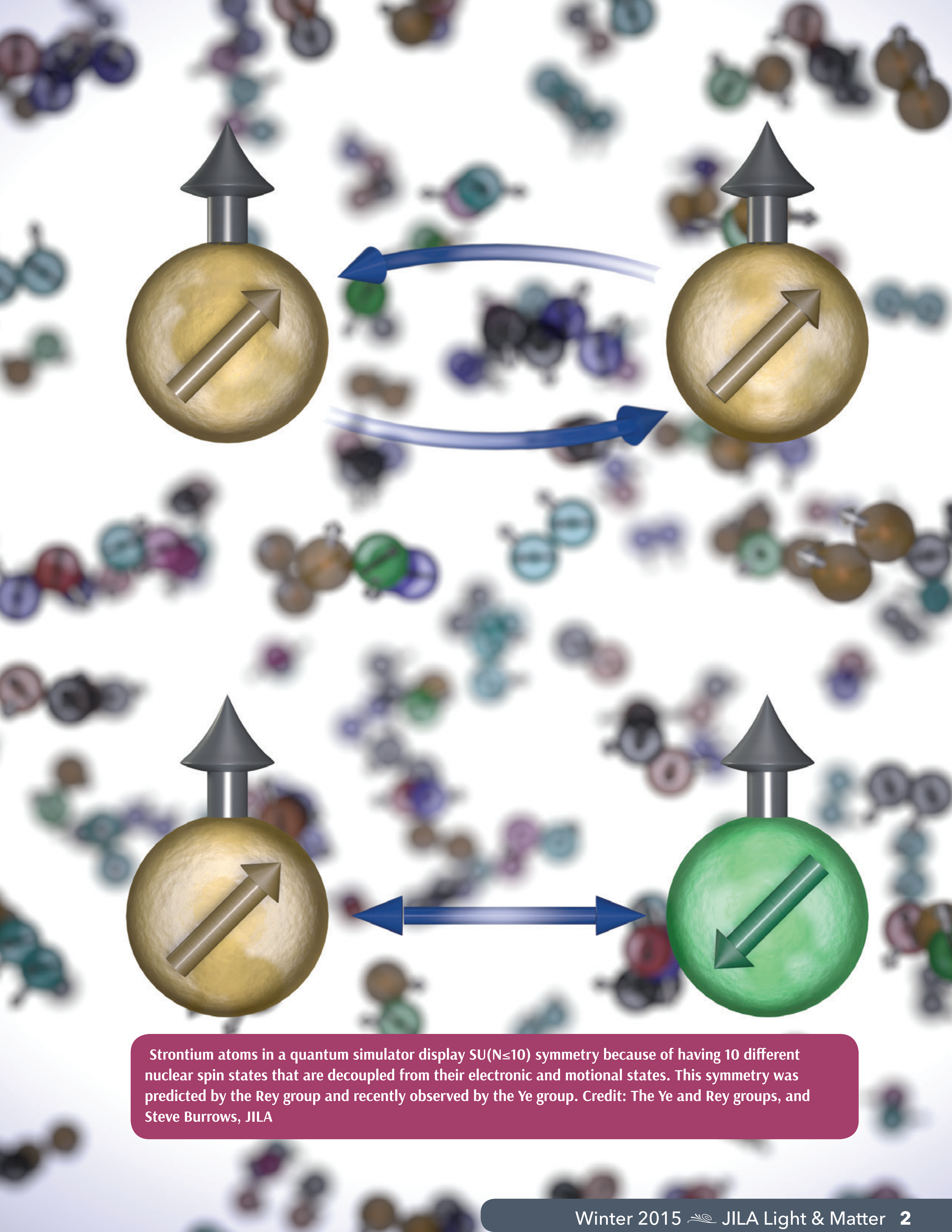
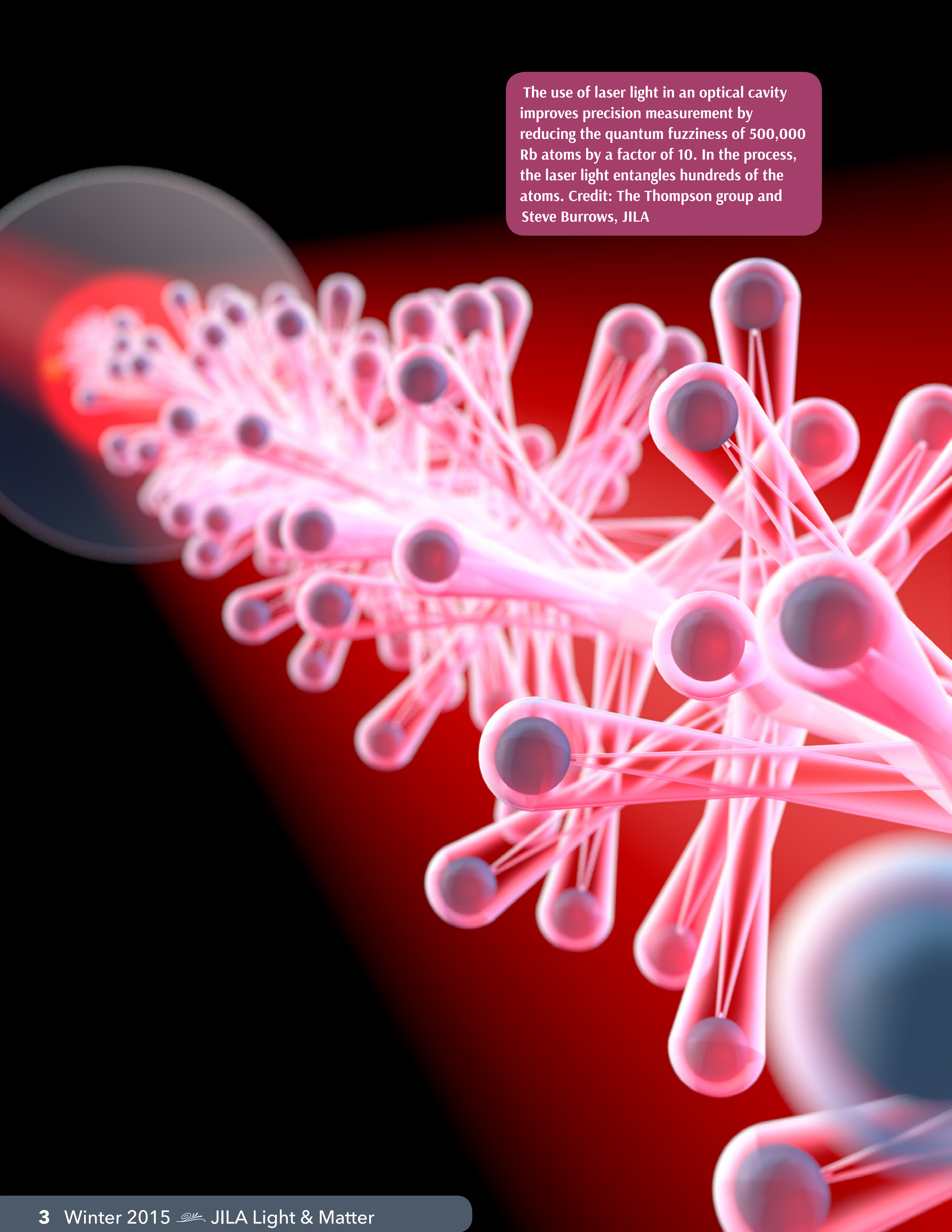
X. Zhang, M. Bishof, S. L. Bromley, C. V. Kraus, M. S. Safronova, P. Zoller, A. M. Rey, J. Ye, *Science* **345**, 1467–1473 (2014).



Strontium atoms in a quantum simulator display SU(N≤10) symmetry because of having 10 different nuclear spin states that are decoupled from their electronic and motional states. This symmetry was predicted by the Rey group and recently observed by the Ye group. Credit: The Ye and Rey groups, and Steve Burrows, JILA



The use of laser light in an optical cavity improves precision measurement by reducing the quantum fuzziness of 500,000 Rb atoms by a factor of 10. In the process, the laser light entangles hundreds of the atoms. Credit: The Thompson group and Steve Burrows, JILA

# Quantum Entanglement

## Coming Soon to a Precision Measurement Near You

The spooky quantum property of entanglement is set to become a powerful tool in precision measurement, thanks to researchers in the Thompson group. Entanglement means that the quantum states of something physical—two atoms, two hundred atoms, or two million atoms—interact and retain a connection, even over long distances.

Even without exploiting entanglement, atoms are already used as exquisite sensors of time, gravity, rotations, and magnetic fields because the rules of quantum mechanics allow them to be prepared in identical states. However, this matching comes at a price. Even individual identical atoms are fundamentally fuzzy because of how things work in the quantum world. It's as though the hands of your clock were blurry, making it difficult to precisely tell the time. What's worse, no amount of squinting makes this quantum blurriness go away.

What the Thompson group has done is to figure out how to create the right kind of "eyes" to measure the quantum fuzziness in 500,000 rubidium (Rb) atoms and reduce it by a factor of 10. This exciting result was the largest directly observed measurement enhancement due to entanglement ever reported for atoms. It appeared online in *Nature Photonics* on July 13, 2014. The research team responsible for this work included recently minted Ph.D. Justin Bohnet, graduate students Kevin Cox, Matt Norcia, and Josh Weiner, recent JILA grad Zilong Chen, and Fellow James K. Thompson.

One way to think about this experiment is that a measurement "squeezes" the quantum noise. Squeezing means that the researchers were able to design the measurement technique to preferentially force quantum noise out of the width of their quantum clock hand and into its length instead. A narrower clock hand allows one to read the clock more precisely. At the same time, more noise in the length has no bearing on a measurement of time.

The reason squeezing works is because the Thompson group's measurement of quantum fuzziness entangles the atoms. In a large entangled state, the fuzziness of each individual atom is partially cancelled by the fuzziness of other atoms. As a result, the overall fuzziness of all the entangled atoms is reduced. So, if precision measurement specialists entangle independent atoms, there are clever ways to make them work together. And when they work together, they can become a clock with higher precision than would be possible if all the atoms were separately trying to measure the exact time (as well as length, or another physical quantity).

The Thompson group was able to make an entangled collection of atoms by allowing all the atoms to interact with the same laser light many times by bouncing the light back and forth between mirrors prior to measuring the orientation of the clock arrows, or atomic spins. The information carried by the laser light told the researchers about the quantum state of all of the atoms, but without telling them the quantum state of any single atom. That's because very little light with information about the state of individual atoms comes out sideways from the laser cavity. The strategy of just measuring the state of all the atoms allowed every atom to remain in a quantum superposition of both pointing up and down simultaneously.

Keeping the atoms in this state was the key to generating entanglement.

In the quantum world, measurements are usually associated with destroying entanglement. But, now the Thompson group has shown that the right type of measurement can actually produce large amounts of entanglement.

"This was the first time anyone has actually gone in and directly observed a factor of 10 improvement over the original quantum fuzziness of atoms," said Thompson. "This is a lot of entanglement. And, it is what we actually see without correcting for any imperfections in the experiment. We also think that we can build even better eyes in the future to generate even more entanglement."

Thompson predicts that this new work means that entangled states will soon be coming to a precision measurement near you. ✺

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Justin G. Bohnet, Kevin C. Cox, Matthew A. Norcia, Joshua M. Weiner, Zilong Chen, and James K. Thompson, *Nature Photonics* **8**, 731–736 (2014).

### JILA Tower 10th Floor Renovation

**After many decades the JILA Tower's 10th floor was renovated in 2014. It has become a favorite spot for quiet study, group meetings in one of two conference rooms, and JILA festivities. To view an interactive 360° photo, see https://www.360cities.net/image/jila-tower-2014. Credit: Kristin Conrad, JILA**

# IN THE NEWS

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

## JILA LEADERSHIP CHANGES

Per JILA's organizational charter, JILA Fellows are nominated to serve two-year terms as JILA Chair and Co-Chair. At the end of December, 2014, Murray Holland stepped down as JILA Chair after a busy term and Deborah Jin became the JILA Chair for the 2015–2017 term. Dana Anderson takes Deborah Jin's place as the new JILA Associate Chair.

## NEW CLOCK MAY END TIME AS WE KNOW IT (NPR)

From National Public Radio, November 3, 2014:

> At the nearby University of Colorado Boulder [Ye Lab] is a clock even more precise than the [clock used for the U.S. Time standard].
>
> At the heart of this new clock is the element strontium. Inside a small chamber, the strontium atoms are suspended in a lattice of crisscrossing laser beams. Researchers then give them a little ping, like ringing a bell. The strontium vibrates at an incredibly fast frequency. It's a natural atomic metronome ticking out teeny, teeny fractions of a second.

Read the entire NPR story and listen to the radio feature at http://www.npr.org/2014/11/03/361069820/new-clock-may-end-time-as-we-know-it.

## DANA ANDERSON WINS CO-LABS 2014 GOVERNOR'S AWARD

Fellow Dana Anderson has won a CO-LABS 2014 Governor's Award for High-Impact Research in Foundational Technology. Anderson's work in the commercialization of cold-atom technology also received an Honorable Mention for the development of a strong public-private partnership.

In bestowing the award, CO-LABS highlighted Anderson's work on the practical applications of cold-atom technology. Applications include the development of cold-atom inertial sensors and the creation of a cold-atom research module to be placed on the International Space Station in 2016. In the future, Anderson's cutting-edge research in cold-atom technology may lead to revolutionary advances in navigation and guidance, gas exploration, advanced communication technologies, and quantum computing.

Anderson co-founded the company ColdQuanta, which was recently named Boulder Company of the Year by the University of Colorado's Technology Transfer Office.

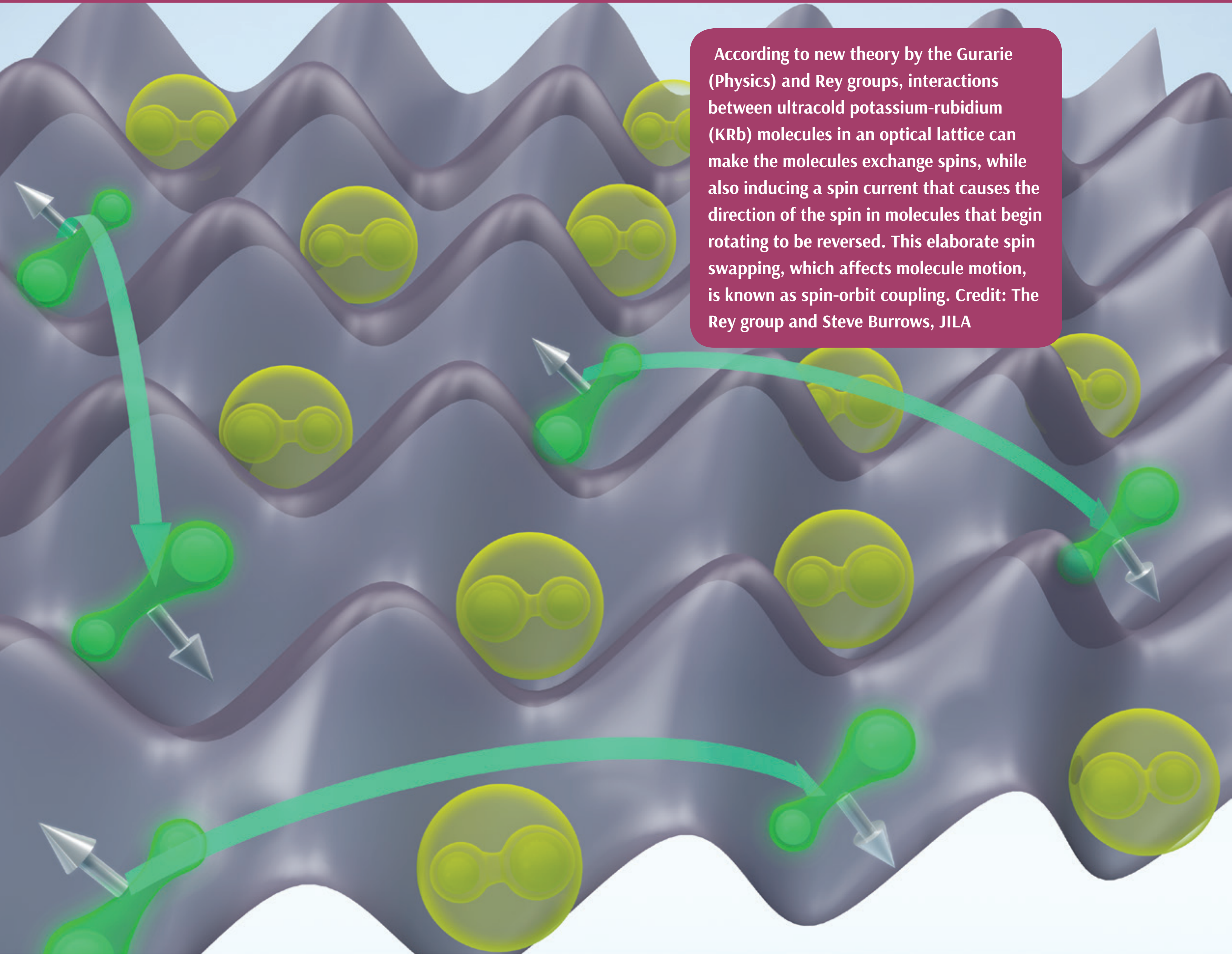
## MARGARET MURNANE WINS MOORE INVESTIGATOR AWARD

Fellow Margaret Murnane has won a Moore Experimental Investigator in Quantum Materials Award from the Gordon and Betty Moore Foundation. The award is part of the foundation's $90 million Emergent Phenomena in Quantum Systems Initiative. It is designed to facilitate scientific breakthroughs by giving Murnane and other awardees the opportunity to take risks, collaborate with other scientists, and develop new experimental techniques for exploring the physics of quantum materials. Murnane was selected for the five-year award following a national competition.

## CARL LINEBERGER HAS WON THE 2015 NATIONAL ACADEMY OF SCIENCES AWARD IN CHEMICAL SCIENCES

Fellow Carl Lineberger has won the 2015 NAS Award in Chemical Sciences. The award was given for his "development of molecular negative ion photoelectron spectroscopy, and the fundamental insights into molecular electron affinities and intramolecular dynamics derived therefrom." Lineberger is the E. U. Condon Distinguished Professor of Chemistry and Biochemistry at the University of Colorado Boulder, and a Fellow of JILA. The awardee is presented with a medal and a $15,000 cash prize.

Lineberger developed negative ion photoelectron spectroscopy to determine the electron affinity of the neutral version of an atom or molecule. Electron affinity–the change in energy that occurs when an electron is added to an atom or molecule–provides information about atoms and molecules and how they interact in chemical reactions. The "periodic table" of atomic electronic affinities now included in general chemistry textbooks is founded on Lineberger's early work with negative ion photoelectron spectroscopy. His development of anion photoelectron spectroscopy for studying small molecules is both an important method to characterize highly reactive, short-lived species known as free radicals and a new, direct way to observe the structure and evolution of molecules in the process of undergoing a chemical reaction. Lineberger's experimental methods are now in widespread use in laboratories worldwide.



According to new theory by the Gurarie (Physics) and Rey groups, interactions between ultracold potassium-rubidium (KRb) molecules in an optical lattice can make the molecules exchange spins, while also inducing a spin current that causes the direction of the spin in molecules that begin rotating to be reversed. This elaborate spin swapping, which affects molecule motion, is known as spin-orbit coupling. Credit: The Rey group and Steve Burrows, JILA

# Exciting Adventures in Coupling

New theory describing the spin behavior of ultracold polar molecules is opening the door to explorations of exciting, new physics in JILA's cold molecule lab, operated by the Jin and Ye groups. According to the Rey theory group and its collaborators, ultracold dipolar molecules can do even more interesting things than swapping spins.

For instance, spin swapping occurs naturally when ultracold potassium-rubidium (KRb) molecules are in two of their four possible excited and ground states. The differences in the two states are sufficient to cause a spinning molecule to slow down at the same time another molecule begins to rotate.

The exciting news is that when two KRb molecules are in three of the four possible states, they don't just swap their spins. The direction of the spin in the molecule that starts rotating gets reversed! This more elaborate spin swapping affects the motion of the molecules, a phenomenon known as spin-orbit coupling.

Spin-orbit coupling is something that happens in solids when electrons move inside the electric field of a crystal. This process is the key to understanding spin transport and spin currents, which are analogs of electron transport and electric currents. Spin-orbit coupling also plays a role in some very exotic phenomena such as the creation of a Majorana particle, which is its own antiparticle!

The theorists responsible for discovering these exciting new adventures in spin-orbit coupling are research associates Sergey Syzranov and Michael Wall, CU Associate Professor of Physics Victor Gurarie, and JILA Fellow Ana Maria Rey. Their discovery of spin-orbit coupling in ultracold molecules was reported online in *Nature Communications* on November 7, 2014.

The next step in this research is finding a model system for learning how to implement and control spin-orbit coupling. And, the JILA ultracold KRb experiment is ideally suited for this purpose. For example, KRb molecules are polar, which means that the K end of one molecule attracts the Rb end of another molecule, while two K ends or two Rb ends repel each other. These behaviors are known as dipole-dipole interactions. The new theory predicts that dipole-dipole interactions will spontaneously give rise to spin-orbit coupling in an ultracold gas of KRb molecules.

The exciting news is that when two KRb molecules are in three of the four possible states, they don't just swap their spins. The direction of the spin in the molecule that starts rotating gets reversed! This more elaborate spin swapping affects the motion of the molecules, a phenomenon known as spin-orbit coupling.

"The nice part is that with cold molecules, spin-orbit coupling just exists," Rey explained. "We don't need to zap anything with a laser to create it."

Rey and her collaborators predict that spin-orbit coupling in ultracold polar molecules will generate excitations called chirons. Chirons are similar to the quasi particles found in bilayer graphene. They are expected to show up in the spin behaviors, spin currents, and spin interactions that occur in an ensemble of ultracold polar molecules pinned inside a deep optical lattice (a crystal of light created by intersecting laser beams). In other words, just about everything predicted by the new theory could soon be tested in the ultracold molecule laboratory in JILA! Stay tuned. ✺

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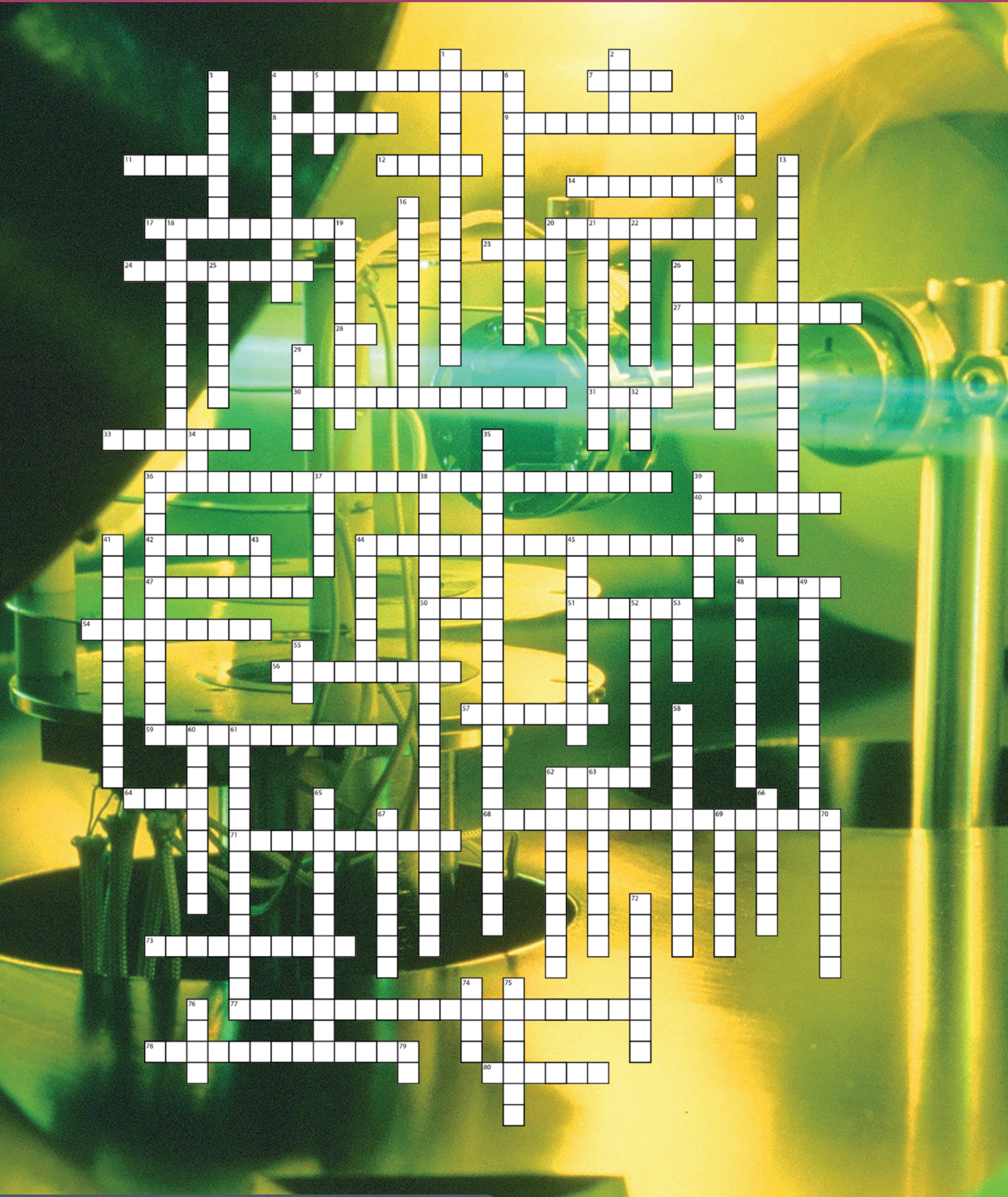
Sergey V. Syzranov, Michael L. Wall, Victor Gurarie, and Ana Maria Rey, *Nature Communications* **5**, 5391 (2014).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# The JILA Science Crossword

## ACROSS

4. Just showed up in a gas of (79 down) atoms
7. First name of theorist who predicted 4 across in those atoms
8. Making it shorter, lighter, and with less gold helps it work better
9. Accomplished 8 across clue
11. First name, JILA Time Lord
12. First name of 67 down
14. Un-neighborly quantum particles that won't occupy the same space
17. Microfluidics capital of JILA
20. Supermassive ones live at the center of galaxies
23. Gravitational wave detector
24. 46 down studies this behavior of RNA
27. New, stable liquid-like quasi particle
28. Ordinary molecule super cooled in the lab by 57 across
30. Around stars, it can give rise to planets
31. Atoms missing electron(s) or with extras
33. One PI studying strongly interacting BEC (last name)
36. Formed in materials in-between a conductor and an insulator
40. Married fellows, same last name
42. A strongly interacting BEC is a quantum __________.
44. It describes how a quantum state changes with time.
47. Terrific nature photographer (last name)
48. There are billions of them in the Milky Way
50. Nobel laser guru (last name)
51. One well-studied kind of physics at JILA
54. The Monster's coach's research topic
56. 2014 Isaac Newton medalist
57. Optical atomic clock makers
59. A new kind of laser made with Rb or Sr atoms
62. JILA's favorite research tool
64. First name of 47 across
68. Elaborate spin swapping that affects atom motion
71. Italian physicist who predicted "abstract" surface with 60 down
73. Studied solvation of Au with $CO_2$
77. NIST specialty pervading JILA
78. Invented synchrotron IR nanospectroscopy
80. He listens to the Sun (last name)

## DOWN

1. Lineberger pioneered this JILA specialty
2. Last name of 7 across
3. This material's defects were imaged by 78 across
4. This effect is also known as the "watched-pot" effect
5. Chilean radio telescope observatory that studies stars & planets
6. Existing partially in all possible states
10. It oversees four collaborative research thrusts
13. Phenomenon that occurs when quantum particles interact as a single system
15. Requirement for neutron star capture of lots of stardust from a Be star's decretion disk
16. Important property of ensembles of ultracold atoms
18. With "quantum," JILA's newest research area
19. Research area investigated by the Jimenez, Perkins, & Nesbitt groups
20. Neighborly particles that can all occupy the same quantum state
21. Study of cold-atom analogs of electronic devices and systems
22. It explores the frontiers of coherent ultrafast x-ray science
25. Microwave transporter developer (last name)
26. First name of 72 down
29. Leader of the JILA Monsters (title), with 55 down
32. Funder of JILA's five-year group grant
34. If the ________ of the electron exists, it's pretty darn small
35. Wild and noisy, this phenomenon can cause a quantum identity crisis
36. Major component of black-hole accretion disks
37. Extreme or excessive, often applied to cold at JILA
38. The Holland group used this to understand the quantum behavior of atoms in a laser
39. Chief, Quantum Physics Division (last name)
41. Heavenly scientific specialty at JILA
43. Initials of 2014 CO-LABS award winner
44. Fellow Adjunct who "shines light on things" (last name)
45. Proprietor of the Little Shop of Atoms

CLUES CONTINUE NEXT PAGE -------->

** First person to turn in a correct puzzle to SCO wins a $25 Amazon gift card.*

CROSSWORD "DOWN" CLUES, CONTINUED

46. Studies chemistry of the cosmos and lots more
49. Chemical physics theorist
52. Another kind of physics at JILA
53. First name of 62 down
55. Monster leader nickname, with 29 down
58. Fiber laser developer
60. Surface collaborator with 71 across
61. Home of intrepid explorers of ultracold quantum magnetism
62. Long-time JILA chemical physicist specializing in molecular ions (last name)
63. Inhabits clocks and a new laser at JILA
65. Cross-disciplinary field of physics, chemistry, biochemistry, and nanotechnology
66. Specialty of 47 across
67. Wrote "Turn Right at Orion" (last name)
69. Coordinated universal time scale maintained by NIST
70. Stars and planets are formed in them
72. Black hole visualizer (last name)
74. Really small science
75. Invisible ruler of light
76. First name of 80 across
79. Complex atom where 4 across found

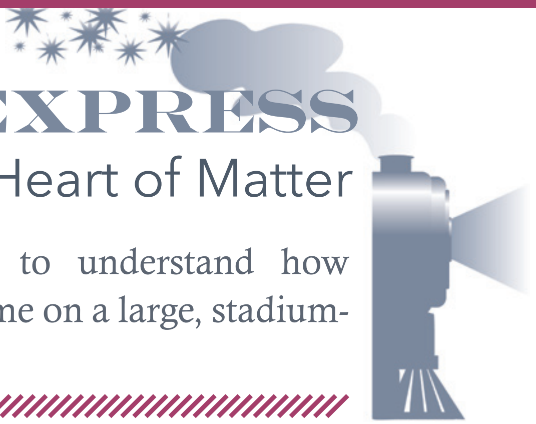
Congratulations to the winner of the Fall 2014 crossword and gift card, Ben Knurr (Weber group)!

# Amelia Earhart Day

Amelia Earhart Day at JILA, July 24, 2014. Fold your best paper airplane...

...see if design + luck take yours soaring the farthest! Photos credit: Steven Burrows, JILA

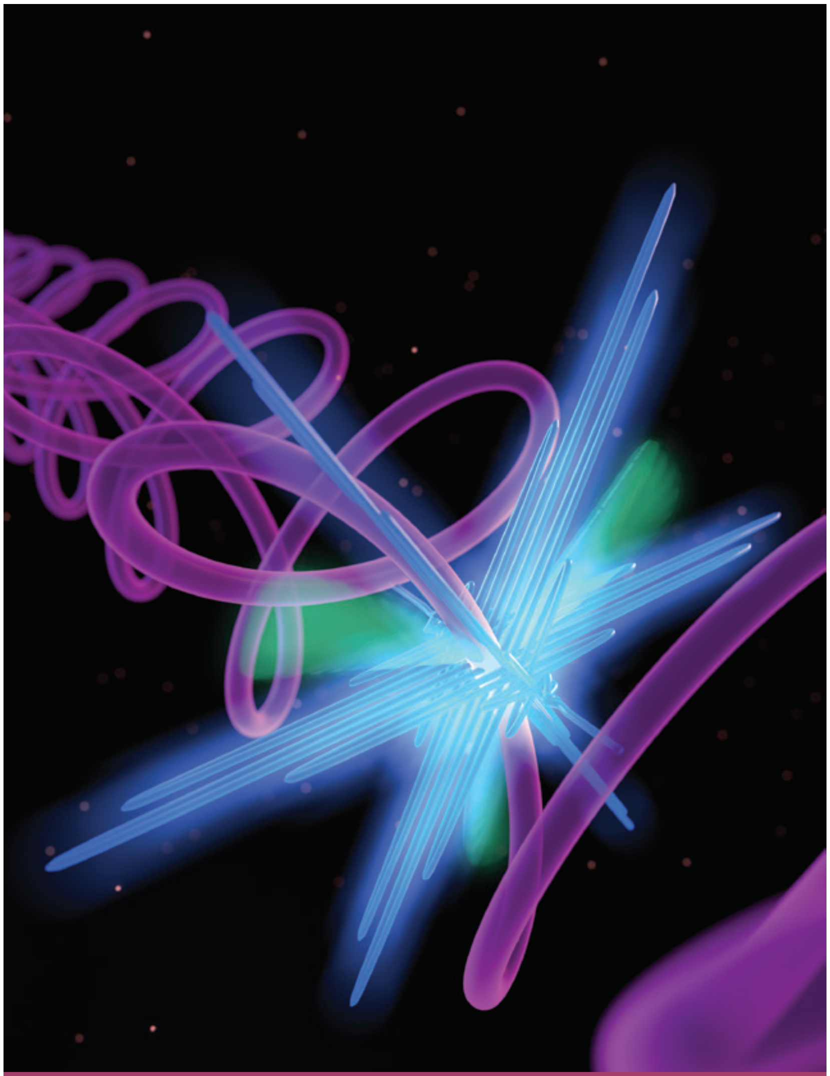

RUNBELIEVABLE



# THE POLARIZED EXPRESS

## Destination: The Heart of Matter

Until recently, researchers who wanted to understand how magnetic materials work had to reserve time on a large, stadium-sized x-ray machine called a synchrotron.



During high-harmonic generation (HHG) of extreme ultraviolet beams using blue and red circularly polarized lasers, electrons ripped from noble gas atoms recombine with their parent ions three times during one optical cycle, in a cloverleaf pattern (purple). Because millions of atoms do this at the same time, a bright circularly polarized EUV beam is created that allows the Kapteyn/Murnane group to investigate magnetic materials. Credit: The Kapteyn/Murnane group and Steve Burrows, JILA

Synchrotrons can produce x-ray beams that can be sculpted very precisely to capture how the spins in magnetic materials work together to give us beautiful and useful magnetic properties—for example to store data in a computer hard drive. But now, thanks to Patrik Grychtol and his colleagues in the Kapteyn/Murnane group, there's a way to conduct this kind of research in a small university laboratory.

The JILA team, with their collaborators from Oren Cohen's group at Technion in Israel, developed a method for creating coherent (laser-like) polarized extreme ultraviolet (EUV) and soft x-rays that are bright enough to investigate how magnetic materials work on the fastest time and smallest length scales. This new method is an extension of high-harmonic generation (HHG). In ordinary HHG, a strong laser field rips an electron from an atom such as argon or some other noble gas. The electrons then smash back into their parent ions three times during the laser optical cycle, producing coherent x-rays in the process.

> On the polarized express, it's like the laser field is the conductor of an orchestra and billions of noble gas atoms are the musicians. In the lab, the goal is to get as many atomic musicians (atoms) as there are people on Earth all singing in tune and under the conductor's (laser) baton. If the atoms all "play" at the same time, you get the loudest music (brightest beam of EUV light).

The new approach uses two laser light beams with different colors, each circularly polarized, but in opposite directions. With these two beams, the electrons are ripped away from the atoms and recombine three times in a cloverleaf pattern! More importantly, billions of atoms do this all at the same time, creating a bright beam of circularly polarized EUV light that can be used for studying the magnetic properties of many important materials.

On the polarized express (as with other HHG research), it's like the laser field is the conductor of an orchestra and billions of noble gas atoms are the musicians. In the lab, the goal is to get as many musicians (atoms) as there are people on Earth all singing in tune and under the conductor's (laser) baton. If the atoms all "play" at the same time, you get the loudest music (brightest beam of EUV light). Grychtol and his colleagues figured out how to perform this amazing feat! This important work was reported online in *Nature Photonics* on December 8, 2014.

The experimentalists responsible for this breakthrough include research associate Patrik Grychtol, recent JILA Ph.D. Emrah Turgut, graduate students Dmitriy Zusin and Dimitar Popmintchev, senior research associate Tenio Popmintchev, and Fellows Margaret Murnane and Henry Kapteyn, as well as, NIST colleagues Ronny Knut, Hans Nembach, and Justin Shaw. The theorists were Ofer Kfir, Avner Fleischer, and Oren Cohen of Technion [Israel Institute of Technology (Haifa)]. Cohen also conducted preliminary experiments on generating circularly polarized EUV light at Technion and was a recent JILA Visiting Fellow.

Once they had made the first bright beam of circularly polarized EUV HHG beams, the researchers had to prove how bright it was since it was undetectable by human eyes or lab electronics. So, they showed they could use it to study the magnetic properties of cobalt. The transmission of magnetic materials, such as cobalt, depends on whether the magnetic spins of the atoms inside the material are oriented up or down. Because they had a new source of circularly polarized EUV HHG beams, the researchers were able to measure the magnetic properties of cobalt using their tabletop setup. In the process, they replicated a similar study performed at a synchrotron, showing that the tabletop method in the lab is complementary to a synchrotron—but less expensive and easier to access.

This important work is expected to lead to a new understanding of complex magnetic materials by detecting how different atoms and spins behave inside them. ✺

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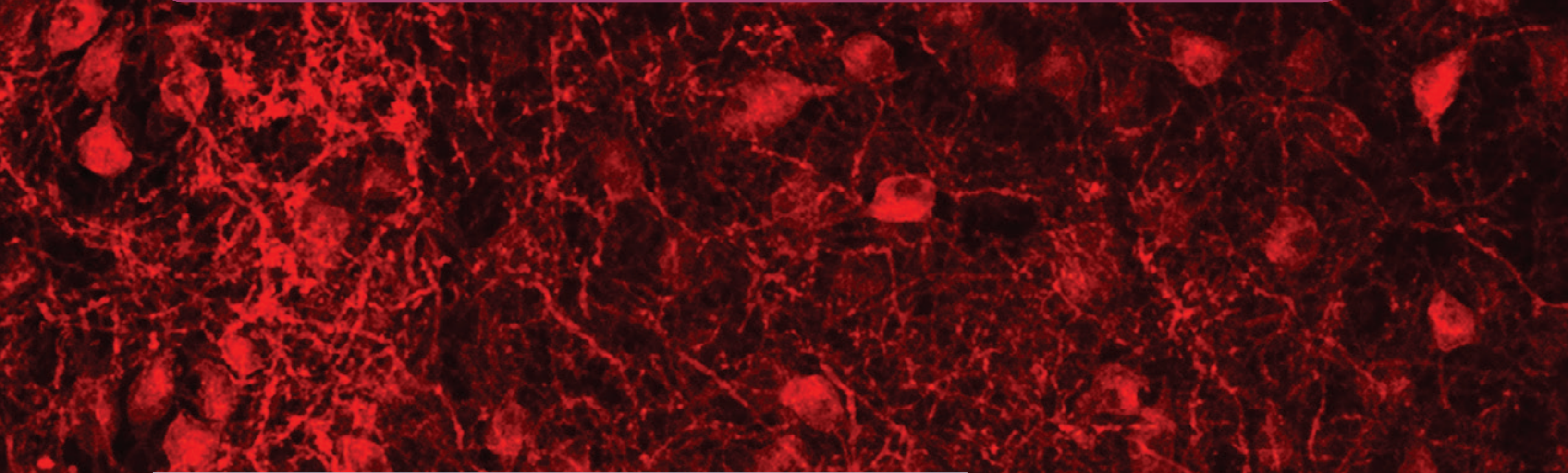
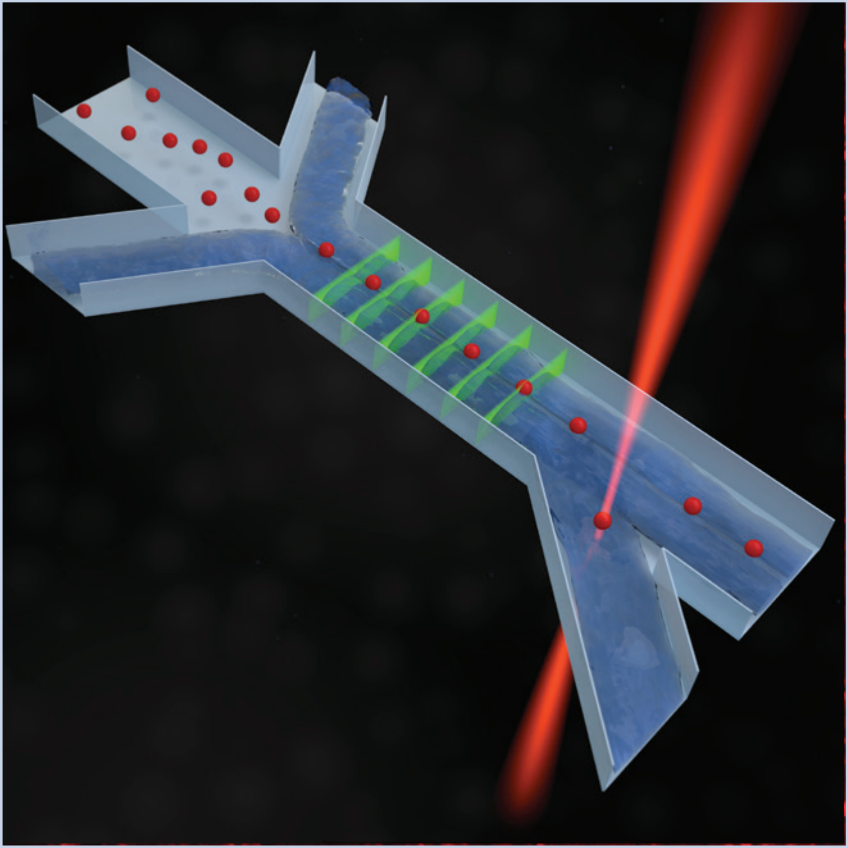
Ofer Kfir, Patrik Grychtol, Emrah Turgut, Ronny Knut, Dmitriy Zusin, Dimitar Popmintchev, Tenio Popmintchev, Hans Nembach, Justin M. Shaw, Avner Fleischer, Henry Kapteyn, Margaret Murnane, and Oren Cohen, *Nature Photonics* **9**, 99–105.



Background: Red-fluorescent protein labeling cellular structure in Zebra finch rotundus. The picture is one of many examples of the remarkable insight into cellular structure and dynamics obtained by using fluorescent proteins. The development of new red-fluorescent proteins resistant to inactivation by laser light and oxygen is a goal of the Jimenez group. Credit: Photo courtesy of Dr. Richard Mooney, Duke University School of Medicine



Inset: Microfluidics system used in the Jimenez lab to select the top-performing cells during a directed evolution experiment. Lasers measure the fluorescent properties of mutated fluorescent proteins in each cell passing through the system, and another laser provides a "tractor beam" to grab onto the best mutant cells for further investigation. This system allows the group to rapidly investigate tens of thousands of different proteins. Credit: The Jimenez group and Steve Burrows, JILA

# Mutant Chronicles

## I. The quest for a better red-fluorescent protein

Because red-fluorescent proteins are important tools for cellular imaging, the Jimenez group is working to improve them to further biophysics research. The group's quest for a better red-fluorescent protein began with a computer simulation of a protein called mCherry that fluoresces red light after laser illumination.

The simulation identified a floppy (less stable) portion of the protein "barrel" enclosing the red-light emitting compound, or chromophore. The thought was that when the barrel flopped open, it would allow oxygen to degrade the chromophore, thus destroying its ability to fluoresce.

The group decided that its next step(s) would be to tweak the natural protein to make it more stable. Tweaking proteins is a huge challenge because most combinations of mutations result in a complete loss of the necessary structure to maintain fluorescence. Even so, the group succeeded in developing a new approach to real-world protein improvement that employs a laboratory strategy for directed evolution.

Directing evolution is challenging. The first step requires creating a library of hundreds of thousands of cells containing different mutations of a single protein. This step is now relatively easy, thanks to the tools of molecular biology. The second step requires screening the fluorescence properties of each cell to select only those few that contain top-performing mutant proteins.

To accomplish the selection process, the group uses microfluidics combined with several laser beams. Its microfluidics system contains micron-sized three-dimensional transparent channels that carry small streams of liquid and allows cells to flow through them one at a time. As the mutant cells pass through the microfluidics channel, lasers measure the fluorescent properties of each mutant cell to assess how well the cells maintain their fluorescence when repeatedly excited by the series of laser beams. Another laser acts as an optical trap that works like a tractor beam to grab the best mutant cells for further investigation. The microfluidics setup itself removes the cells that are poor performers by simply allowing them to flow out of the device.

Directed evolution requires repeating the two steps described above multiple times. The Jimenez group is currently in the middle of round three of its quest to evolve a better red-fluorescent protein.

Although the group has already shown that the specific improvements suggested by the computer simulation don't work, the first round of the directed evolution experiment has come up with an improved red-fluorescent protein with a less floppy barrel that is 2–4 times more stable than mCherry. The combination of mutations that resulted in this improvement has not been previously observed in nature and was completely unexpected.

The group named its new mutant protein Kriek, after a Belgian beer made via the fermentation of cherries. Clearly, the researchers are adept at doing more than biophysics. They include JILA Ph.D. Jennifer Lubbeck (2013) and Fellow Ralph Jimenez, Kevin Dean and Amy Palmer of CU's Department of Chemistry and Biochemistry, as well as colleagues from the University of Tennessee Space Institute and Florida International University.✷

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Kevin M. Dean, Jennifer L. Lubbeck, Lloyd M. Davis, Chola K. Regmi, Prem P. Chapagain, Bernard S. Gerstman, Ralph Jimenez, and Amy E. Palmer, *Integrative Biology*, published online November 21, 2014, doi: 10.1039/C4IB00251B.

# The Quantum Identity Crisis

Dynamical phase transitions in the quantum world are wildly noisy and chaotic. They don't look anything like the phase transitions we observe in our everyday world. In Colorado, we see phase transitions caused by temperature changes all the time: snow banks melting in the spring, water boiling on the stove, slick spots on the sidewalk after the first freeze.

Quantum phase transitions happen, too, but not because of temperature changes. Instead, they occur as a kind of quantum "metamorphosis" when a system at zero temperature shifts between completely distinct forms.

For instance, one kind of quantum phase transition takes place when a researcher uses lasers to force atoms from a Bose-Einstein condensate (BEC) inside a "crystal" of light, where the atoms solidify into a lattice pattern. Because the ground state arrangement of the atoms has totally changed from the indistinct blur of a BEC to a regular array inside the light crystal, the physical manifestation of the atoms is completely different.

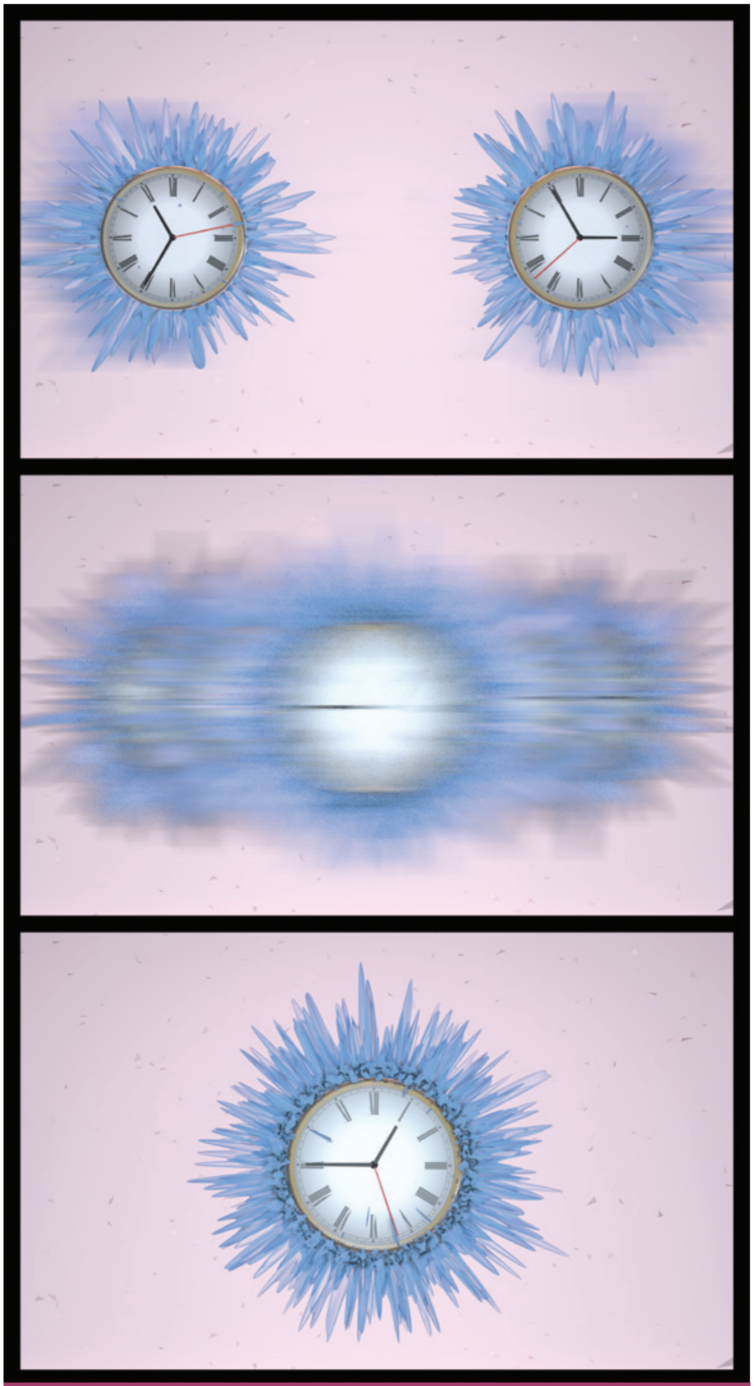
We now know that quantum phase transitions also occur in dynamical systems, thanks to the Holland group. Dynamical systems are systems that can be a long way from equilibrium, like atomic clocks, clocks that are always evolving in time, or superradiant lasers that have photons continuously moving in and out of them. Not surprisingly, all sorts of things happen in such dynamical systems when they change their quantum phase. The new understanding of dynamical quantum phase transitions was gained during the Holland group's theoretical investigation of the quantum aspects of classical synchronization.

Classical synchronization theory explains why fireflies suddenly start emitting light simultaneously, crickets spontaneously sing in unison, metronomes or pendulum clocks synchronize their ticking (if they're physically connected), or why audiences clap in unison after a minute or two. To study the effects of quantum synchronization as compared to ordinary, everyday synchronization, the Holland group looked at what would happen if two atomic clocks containing identical ensembles of atoms moved close enough to one another to merge into a single, larger atomic clock.

The group discovered that things got really interesting when the clocks moved very close together. Suddenly, it was as if every atom in both clocks was trying to decide, "Should I be in a separate clock or in one clock?" The quantum noise from this process went off the scale! The clocks, which had been accurate, with nice sharp, narrow hands, became so noisy and fuzzy that it was impossible to determine the exact time. The clocks had moved into the region of "quantum criticality." And in the quantum criticality region, the uncertainty inherent in the laws of quantum mechanics is in full play.

Interestingly, when the two clocks finally "decided" to become a single, larger clock, everything quickly settled back down. The hands on the new clock became narrow and sharp as soon as the quantum phase transition was complete. The new, stable quantum phase was a larger atomic clock containing a completely restructured–and synchronized–ensemble of atoms.

The researchers responsible for this new understanding of quantum synchronization during a dynamical phase transition include graduate students Minghui Xu



The laws of quantum mechanics make it impossible to determine the exact time during the synchronization (merger) of two atomic clocks (top panel) into one. As the clocks get closer and closer together, quantum noise skyrockets because of the uncertainty of whether the clocks will merge or stay separate (middle panel). The bottom panel shows the merged and larger atomic clock. Credit: The Holland group and Steve Burrows, JILA

> The group discovered that things got really interesting when the clocks moved very close together. Suddenly, it was as if every atom in both clocks was trying to decide, "Should I be in a separate clock or in one clock?" The quantum noise from this process went off the scale!

and Dave Tieri, former graduate student Elizabeth Fine, as well as Fellows James Thompson and Murray Holland.

Their work promises to impact research well beyond physics as quantum synchronization is thought to play important roles in brain activity as well as in photosynthetic light harvesting and energy transfer. Because it is also involved in the transition between superconductivity and Mott-insulating behavior in copper-containing metals, quantum synchronization may be an important factor in the design of advanced electronic devices.✺

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Minghui Xu, D. A. Tieri, D. C. Fine, James K. Thompson, and M. J. Holland, *Physical Review Letters* **113**, 154101 (2014).

# How Did They Get Here?

Award-winning physicist **Margaret Murnane** began her journey to becoming a world-renowned expert on ultrafast lasers in the countryside of midwest Ireland. Her father, an elementary school teacher, loved science and used to reward his young daughter with chocolates or a new science book from the library when she solved math puzzles. When she was 8, one of those books, with an illustration of Archimedes in the bathtub, kindled a lifelong desire to learn about the world by observing it.

She reveled in her high-school physics class, even though “it was my worst subject.” Undeterred, she attended University College Cork (Ireland), earning Bachelor’s and Master’s degrees in physics. Her university courses were academically challenging, but fascinating. She graduated hooked on the idea of having a career in physics, even though it meant leaving Ireland to pursue a Ph.D. at the University of California at Berkeley.

Murnane did her thesis work building an ultrashort-pulse laser in Roger Falcone’s laboratory. It took her a year to build the laser, another six months to refine and characterize it, and two years to demonstrate that it could generate fast x-ray pulses. Murnane graduated in 1989 and a year later received the American Physical Society’s (APS’s) Simon Ramo Award for her thesis.

During her graduate studies, Murnane met fellow student Henry Kapteyn, who became her husband in 1988 and a life-long collaborator. In 1990, the couple moved to Washington State University, where they set up a joint laboratory dedicated to the fast-moving and competitive field of ultrafast laser science.

During their time at Washington State, Murnane and Kapteyn played key roles in advancing the technology for generating ultrafast laser pulses. Their group was responsible for the design and rapid adoption of the ultrashort-pulse-mode-locked titanium-sapphire laser that is now a standard fixture in hundreds of laboratories around the world. Murnane received a Sloan Research Fellowship in 1992.

In 1996, Murnane and her husband left Washington State for the University of Michigan at Ann Arbor, where Murnane was awarded the American Physical Society's Maria Goeppert Mayer Award in 1997. At Michigan, Murnane and Kapteyn continued their laser development and began exploring the possibility of using ultrafast lasers to produce laser-like beams of x-rays. This early work at Michigan culminated in the design and development of a tabletop x-ray laser in 2009—by the Kapteyn/Murnane (K/M) group at JILA.

The couple moved to JILA in 1999. At JILA, the K/M group has continued their work on creating laser-like beams at short wavelengths. The group also pioneered the use of lasers to study such processes as electron motion inside atoms and molecules, the motion of molecules on surfaces, acoustic oscillations in materials and nanostructures, and the motion of atoms inside molecules.

Murnane has won many awards for her cutting-edge research in JILA. In 2000, she was awarded a prestigious John D. and Catherine T. MacArthur Fellowship. In 2008, she and Kapteyn received the American Chemical Society's Ahmed Zewail Award in Ultrafast Science and Technology. The same year, Murnane was named a University of Colorado Professor of Distinction. Murnane and Kapteyn jointly won the American Physical Society's Arthur Schawlow Prize and the Optical Society of America's R. W. Wood Prize in 2010. She won the RDS Irish Times Boyle Medal in 2011. In 2013, Murnane was elected an honorary member if the Royal Irish Academy. She is a Fellow of the American Association for the Advancement of Science, the American Physical Society, the Optical Society of America, the Association for Women in Science, and the National Security Science and Engineering Faculty, as well as a member of the American Academy of Arts and Sciences and the National Academy of Sciences.

In addition to her scientific work, Murnane is known for her efforts to get women involved in science and to support them once they enter an academic environment. She has been a member and/or Chair of the American Physical Society Committee on the Status of Women in Physics and the Site Visit Team to Improve the Climate for Women in Physics. She strongly supported JILA's recent efforts to recruit and retain more women faculty.

In her spare time, Murnane finds time to enjoy the Colorado outdoors with mountain biking, hiking, and skiing.

To read other online bios, visit http://jila.colorado.edu/faculty/profiles-science

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

University of Colorado **Boulder**

NIST

# About JILA

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

JILA's faculty includes two Nobel laureates, Eric Cornell and John Hall, as well as three John D. and Catherine T. MacArthur Fellows, Margaret Murnane, Deborah Jin, and Ana Maria Rey. JILA's CU members hold faculty appointments in the Departments of Physics; Chemistry and Biochemistry; Astrophysical and Planetary Sciences, 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 eight broad categories: Astrophysics, Atomic & Molecular physics, Biophysics, Chemical physics, Laser Physics, Nanoscience, Precision Measurement, and Quantum Information.

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