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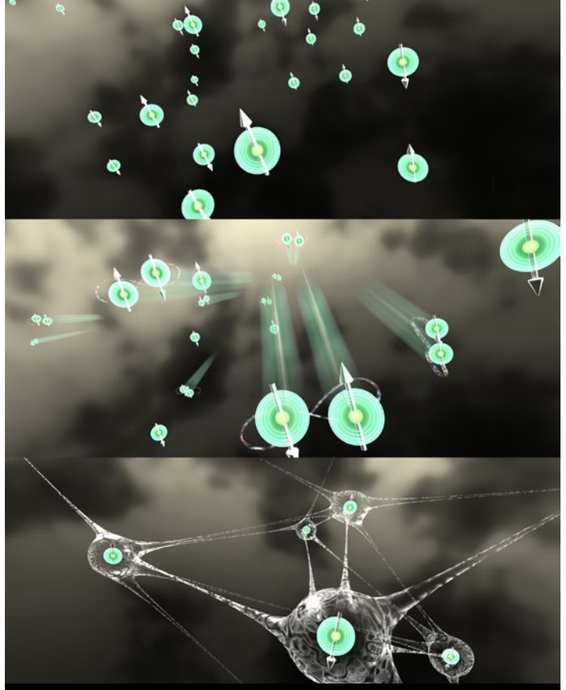
JILA LIGHT & MATTER

THE ENTANGLEMENT TANGO

P. 2



Simplified representation of simultaneous entanglement of many pairs of atoms in a relatively "warm" ultracold gas.

Credit: Michael Foss-Feig, the Rey group, the Thompson group, and Brad Baxley, JILA

THE ENTANGLEMENT TANGO

Scientists think it is hard to correlate, or entangle, the quantum spin states of particles in an ultracold gas of fermions. Fermions are particles like electrons (and some atoms and molecules) whose quantum spin states prevent them from occupying the same lowest-energy state and forming a Bose-Einstein condensate. Entanglement means that two or more particles interact and retain a connection. Once particles are entangled, if something changes in one of them, all linked partners respond.

Because of this exquisite connection, entanglement is usually destroyed by messing up the state of a single particle. Thus conventional wisdom has been that it would take precise measurements or control schemes to entangle the quantum spin states of thousands of atoms in an ultracold gas. However, graduate student Michael Foss-Feig, Fellows James Thompson and Ana Maria Rey, and former Visiting Fellow Andrew Daley from the University of Pittsburgh decided to consider what happens if the state of pairs of atoms are messed up together.

Foss-Feig and his colleagues discovered that when reactive fermions are at "warm" micro-Kelvin temperatures, entanglement evolves naturally. In fact, the atomic or molecular gas has to be 10–100 times warmer than a nano-Kelvin gas to encourage entanglement. Once the temperatures are low enough for fermions to collide and react in pairs, atoms or molecules that don't get knocked out of the experiment will be left entangled because they lose their individual identities as a result of being unable to collide. Fermions that behave this way include the atoms strontium (Sr) and ytterbium (Yb), which are used in atomic clocks, and molecules such as potassium-rubidium (KRb), which are used in JILA cold-molecule experiments.

To understand how this entanglement evolves, imagine that our quantum gas is a tango dance party. Strontium atoms, Yb atoms, or KRb molecules—all of which can exist in one of two possible spin states—are the dancers. Just as the atoms or molecules have two possible spin states, there are two kinds of tango dancers: men and women. And, at this quantum dance party, women must dance with men and vice versa. The catch is that the individual tango dancers all dance a little differently.

As the dance starts, pairs of tango dancers bump into each other. As they collide, each pair measures their mutual quantum state to discover whether they dance well together or dance poorly together. When a pair who dance well together find each other, they dance right out of the party and go home together. Soon, all the pairs who dance well have reacted with each other and left.

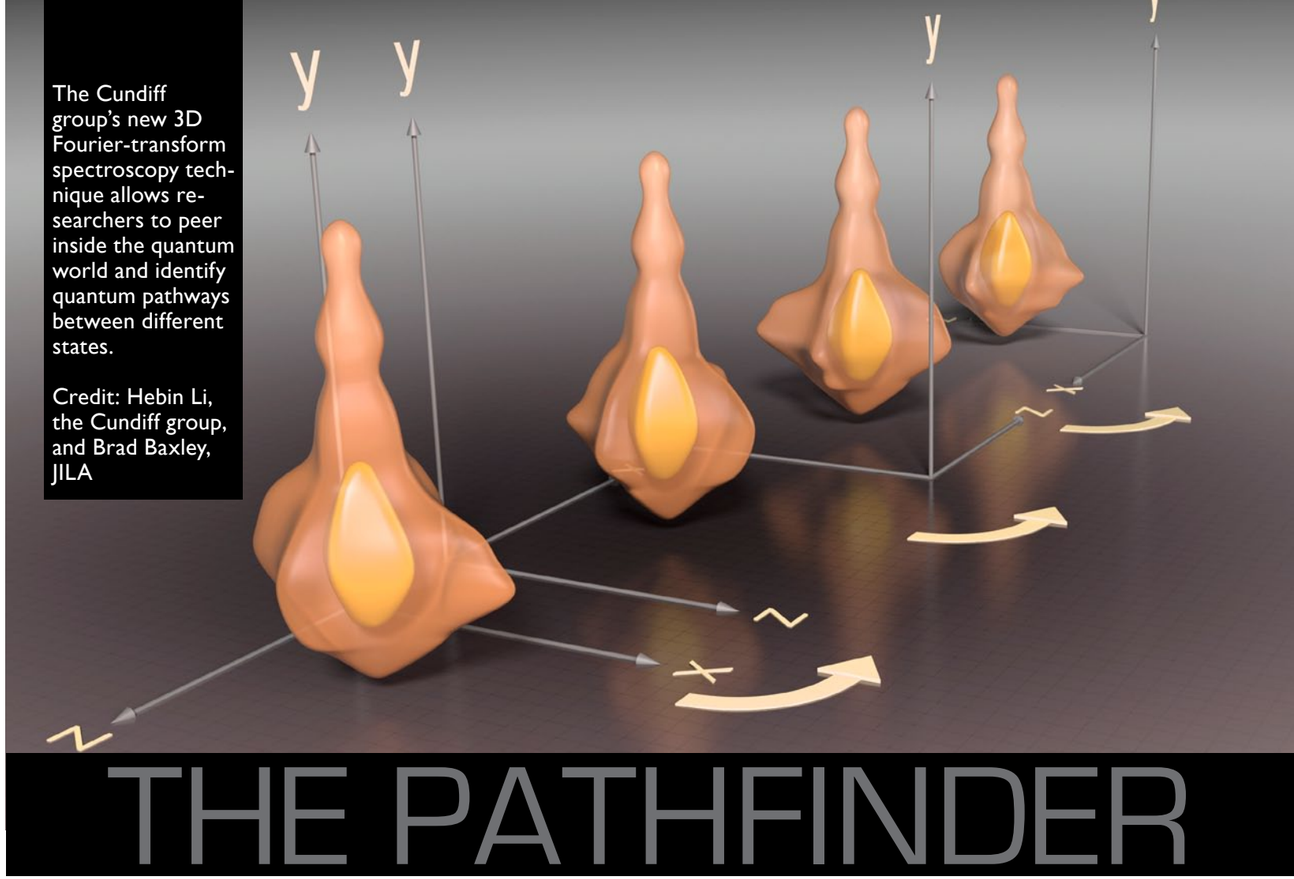
The only ones left at the dance are the people who don't dance well together. It's not that these individuals are bad or good dancers. They can't dance together because they are correlated with each other in a way that makes it impossible to dance in pairs (i.e., collide). And, because all the remaining dancers don't dance well together, no one can go home. Frustrated (but also slowly losing their individual identities), the party-goers check their watches to see when this boring dance will end. What they don't realize is that they're stuck in an unending (steady-state) party where nobody dances, but no one can escape.

The nondancing pairs have entered a quantum mechanical state called a superposition. A superposition is a state in which a particle holds two different properties—such as two different spin states—at the same time. It turns out that such a state is very useful for measuring the passage of time in an atomic clock, for reasons that can be well understood through the connection to dancers.

According to the laws of quantum mechanics, atom pairs or molecules that react (dance well together) are useless for measuring time with an atomic clock. In fact, they are oblivious to the passage of time. The pairs that dance poorly together, however, are acutely aware of the passage of time. Consequently, a steady-state tango dance party, with everyone constantly checking their watches, could be an ideal starting point for measuring time with an atomic clock. — *Julie Phillips and Michael Foss-Feig*

Reference

Michael Foss-Feig, Andrew J. Daley, James K. Thompson, and Ana Maria Rey, *Physical Review Letters* **109**, 230501 (2012).



The Cundiff group's new 3D Fourier-transform spectroscopy technique allows researchers to peer inside the quantum world and identify quantum pathways between different states.

Credit: Hebin Li, the Cundiff group, and Brad Baxley, JILA

THE PATHFINDER

The Cundiff group has taken an important step forward in the study of the behavior of the quantum world. It has come up with an experimental technique to measure key parameters needed to solve the Schrödinger equation.

The amazing Schrödinger equation describes the time-dependent evolution of quantum states in a physical system such as the group's hot gas of potassium atoms (K). But, for the equation to work, someone has to figure out a key part of the equation known as the Hamiltonian. Unfortunately, Hamiltonians are really complicated for most real-life systems because they characterize a multitude of quantum states and pathways that exist inside a roiling quantum world.

For experiments involving many atoms or other particles that interact with each other and their environment, the only hope of ever figuring out the correct Hamiltonian may be to do it experimentally. And, the Cundiff group has just taken a giant step toward the goal of doing exactly that.

In a recent *Nature Communications* paper, research associate Hebin Li, former research associates Alan Bristow and Mark Siemens, graduate student Galan Moody, and Fellow Steve Cundiff report on their nifty new technique known as optical three-dimensional (3D) Fourier-transform spectroscopy. They used the technique to produce detailed spectra of a gas of hot (180 °C) K atoms. The spectra allowed them to see exactly what was happening inside the quantum world of the atoms in their experiment. Specifically, the researchers were able to disentangle all possible pathways between specific initial conditions of the K atoms (typically ground states) and final conditions (such as excited states or quantum mechanical superposition states). And, once they had identified all possible pathways, the researchers were able to make the measurements necessary for characterizing the pathways. With this information, they were able to figure out some pieces of the Hamiltonian they needed.

Li and his colleagues are excited about the many possibilities of their new technique, including the dream of coherently controlling chemical reactions. Coherent control requires an understanding of all possible quantum pathways in a particular reaction. The fact that optical 3D Fourier-transform spectroscopy made it possible to identify all of these pathways is a huge step forward in realizing this dream.

The new technique is also a huge step towards being able to experimentally determine a Hamiltonian for an even more complex system. Stay tuned.

Reference

Hebin Li, Alan D. Bristow, Mark E. Siemens, Galan Moody, and Steven T. Cundiff, *Nature Communications* **4**, 1390 (2013).

POSITION WANTED

Artist's concept of the Regal group's laser-light experiment to measure the position of a tiny drum measuring 0.5 mm on a side (about half the length of the world's smallest ant). The group has observed extra vibrations in the system caused by the drum shaking in response to impacts by 100 million photons. The extra vibrations (due to the laws of quantum mechanics) obscure the motion of the drum.

Credit: The Regal group and Brad Baxley, JILA

Researchers in the Regal group have gotten so good at using laser light to track the exact position of a tiny drum that they have been able to observe a limit imposed by the laws of quantum mechanics. In a recent experiment, research associate Tom Purdy, graduate student Robert Peterson, and Fellow Cindy Regal were able to measure the motion of the drum by sending light back and forth through it many times. During the measurement, however, 100 million photons from the laser beam struck the drum at random and made it vibrate. This extra vibration obscured the motion of the drum at exactly the level of precision predicted by the laws of quantum mechanics.

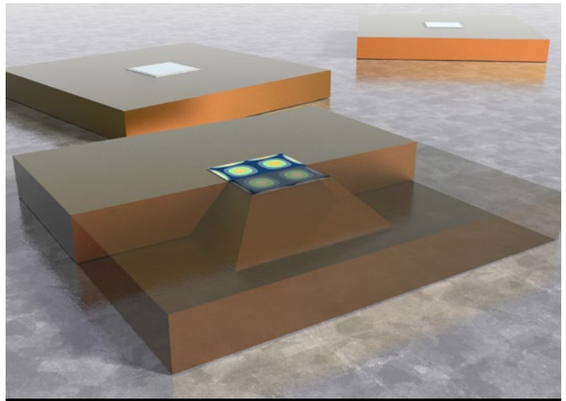
This extra vibration is interesting because its detection indicated that the experimenters had reached an important limit on successive measurements imposed by a particular law of quantum mechanics known as the Heisenberg Uncertainty Principle. The group's detection of the Heisenberg Uncertainty Principle in action in the drum was recently reported in the journal *Science*. The Heisenberg Uncertainty Principle dictates that the closer someone comes to measuring the exact position of an object, the less that can be known about how fast the object is moving. In other words, this law recognizes that it is not possible to both precisely measure the position of an object and how fast it is moving at the same instant. Of course, how fast something is moving has a whole lot to do with its exact position in the future. This paradox results in a conundrum for the experimental physicist: Do we make the best position measurement now or obscure the motion later?

Physicists pursuing precision measurements, including those working on the upcoming advanced Laser Interferometer Gravitational-Wave Observatory (LIGO), have been discussing what to do about this conundrum for a long time. Regal says the easiest way to get the best precision is to give up precise knowledge of an initial position to balance the combined uncertainty in position and velocity. However, there are fancy measurement techniques that, in theory, would allow the researchers to work around, or avoid, the limits to successive measurements imposed by the Heisenberg Uncertainty Principle.

The challenge of working around quantum limits is irresistible for several physicists at JILA. It's especially enticing for Regal, whose experimental system runs up against quantum mechanics even though it is relatively large. The square drum at the heart of the recent experiment measures about 0.5 mm on a side. It is large enough to be visible to the naked eye and about half the length of the world's smallest ant.

Two aspects of the recent experiment made it possible to observe very small vibrations due to quantum mechanical effects. First, the experiment was done at the very low temperature of 5 K (-451 °F). This temperature reduced the amount of vibration caused by heating of the experiment by the surrounding environment. Second, the researchers use special drums that lose vibrational energy to the environment very slowly.

Thus, when the researchers measured vibrations during the experiment, they were able to determine that quantum mechanical fluctuations of light were causing about half of them. Because the group now knows what these fluctuations look like in an experiment, the researchers' next big step is an experimental investigation of creative ways to work around the Heisenberg Uncertainty Principle in continuous position measurements. Stay tuned.



The inside of one of the Regal group's tiny two-layer drums. The drum's dampening pattern is shown on the surface.

Credit: The Regal group and Brad Baxley, JILA

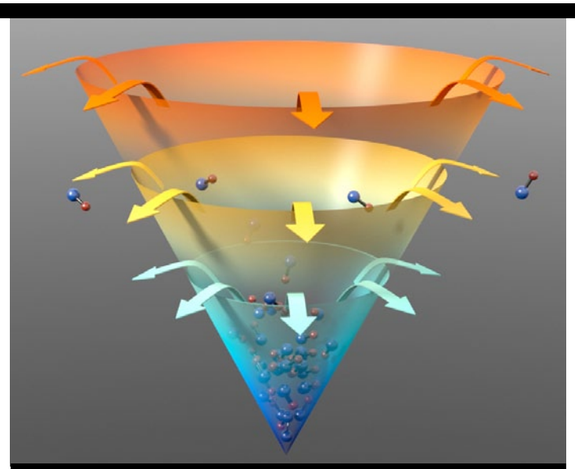
Reference

T. P. Purdy, R. W. Peterson, and C. A. Regal, *Science* **339**, 801–804 (2013).

THE BIG CHILL

The Ye and Bohn groups have made a major advance in the quest to prepare "real-world" molecules at ultracold temperatures. As recently reported in *Nature*, graduate students Ben Stuhl and Mark Yeo, research associate Matt Hummon, and Fellow Jun Ye succeeded in cooling hydroxyl radical molecules (*OH) down to temperatures of no more than five thousandths of a degree above absolute zero (5 mK).

The final temperature of the experiment may well have been even lower because the group's temperature measurement system stopped working at 5 mK. This landmark experiment is the first one ever to succeed in cooling a molecule found in nature to ultracold temperatures. It comes after nearly two decades of similar, but unsuccessful, attempts to do the same thing in other laboratories.



The Ye group has shown that evaporative cooling can cool a gas of hydroxyl radical (*OH) molecules down to at least 5 mK. In this process, some *OH molecules get hotter upon colliding and rise up and out of the trap; the remaining molecular gas gets colder, as shown in this artist's conception.

Credit: The Ye group and Brad Baxley, JILA

continued from pg. 5

Earlier attempts to cool molecules to ultracold temperatures failed because the molecules studied had too few "elastic" collisions—the kind of collisions in which molecules bounce off one another. Thanks to some insightful theory work by senior research associate Goulven Quéméner and Fellow John Bohn, however, the Ye group opted to cool the *OH molecule, which the theorists predicted would have elastic collisions more than 90% of the time. This collision rate meant that the molecules have enough time to exchange energy, so that there are always some molecules with more energy than average, and some with less.

The experiment had several steps: First, the researchers used a jolt of electricity through a mixture of water vapor and krypton to form the *OH molecules. Second, they used a linear decelerator equipped with an array of highly charged electrodes to slow the molecules down to a speed of 34 meters per second. The molecules were brought to a complete stop in the center of a permanent magnetic trap. These two steps have been under development for a decade. They cooled the molecules down to ~50 mK.

Finally, the researchers initiated evaporative cooling, which required a neat trick to work. The usual approach of flipping a spin in the *OH molecules was not good enough in this case to let the hotter molecules escape from the trap. So the researchers applied an electric field, which opened up some little gateways in the trap that actually let the hot molecules out.

This creative process then selectively removed the most energetic (hotter) *OH molecules from the mixture after molecule-molecule collisions. By getting rid of the hottest molecules, the temperature of the remaining gas of molecules was lowered. The process could be speeded up by lowering the height of the trap holding the molecules to more rapidly concentrate colder molecules at the bottom.

Evaporative cooling worked exceptionally well with *OH molecules. In fact, as this molecular gas got colder, evaporative cooling worked better and better. Not only did the temperature fall precipitously, but also the density of the remaining molecules increased.

The results were so exciting that the Ye group believes that in the future, it will be possible to evaporatively cool *OH molecules to much colder temperatures in the micro- and nano-Kelvin ranges. It's now conceivable that the group will one day be able to cool a *OH molecular gas down to the point where every molecule in the gas enters its lowest quantum state—in a process similar to the one used by Fellows Eric Cornell and Carl Wieman to make the world's first Bose-Einstein condensate of rubidium atoms in 1995.

Reference

Benjamin K. Stuhl, Matthew T. Hummon, Mark Yeo, Goulven Quéméner, John L. Bohn, and Jun Ye, *Nature* **492**, 396–400 (2012).

Everything's Cool with Atom

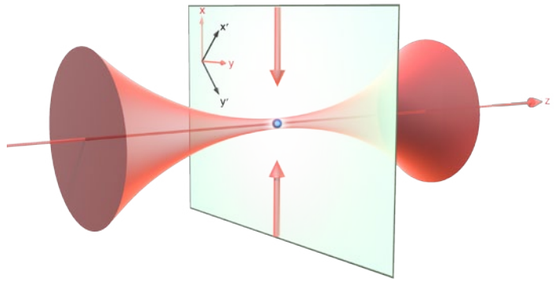
The Regal group recently completed a nifty feat that had never been done before: The researchers grabbed onto a single trapped rubidium atom (^{87}Rb) and placed it in its quantum ground state. This experiment has identified an important source of cold atoms that can be arbitrarily manipulated for investigations of quantum simulations and quantum logic gates in future high-speed computers.

Here's how graduate students Adam Kaufman and Brian Lester and Fellow Cindy Regal did it: First, the researchers captured a gas containing roughly 1 million ^{87}Rb atoms. Second, they illuminated the cloud with a very tightly focused beam of light, creating a tiny micron-sized trap. This trap is called an optical tweezer. From the cloud of atoms, about 10 atoms were loaded into the tweezer. However, when light was applied, the trapped atoms repeatedly collided in the tiny trap, forming molecules. These molecules were subsequently lost from the trap.

About half the time, nothing was left in the tweezer because there was an even number of atoms to start with, and all the atoms escaped as molecules. The other half of the time, however, there was an odd number of atoms at the beginning. In this case, a single atom was left in the tiny trap. The researchers could "see" this atom inside the optical tweezer. Then they were ready for the final step: cooling this atom to its quantum ground state.

To further cool the atom, the researchers first used two lasers to lower the energy of the atom by one quantum (of motion), while also flipping its spin. Second, they shined another laser on the atom, which caused the spin to flip back, while leaving the atom in its new lower energy state. Cooling the atom to its quantum ground state (in all three dimensions) simply required repeating this two-step cycle 75 times.

The optical tweezer was a key ingredient in the cooling process. During the second step in which a laser flips the atom back into its original spin state, for example, the tweezer holds the atom tightly in place. This confinement makes it far less likely that the laser will accidentally excite the atom to a higher energy state, something that would prevent the cooling from happening.



Single-atom trapping schematic.

Credit: The Regal group and Brad Baxley, JILA

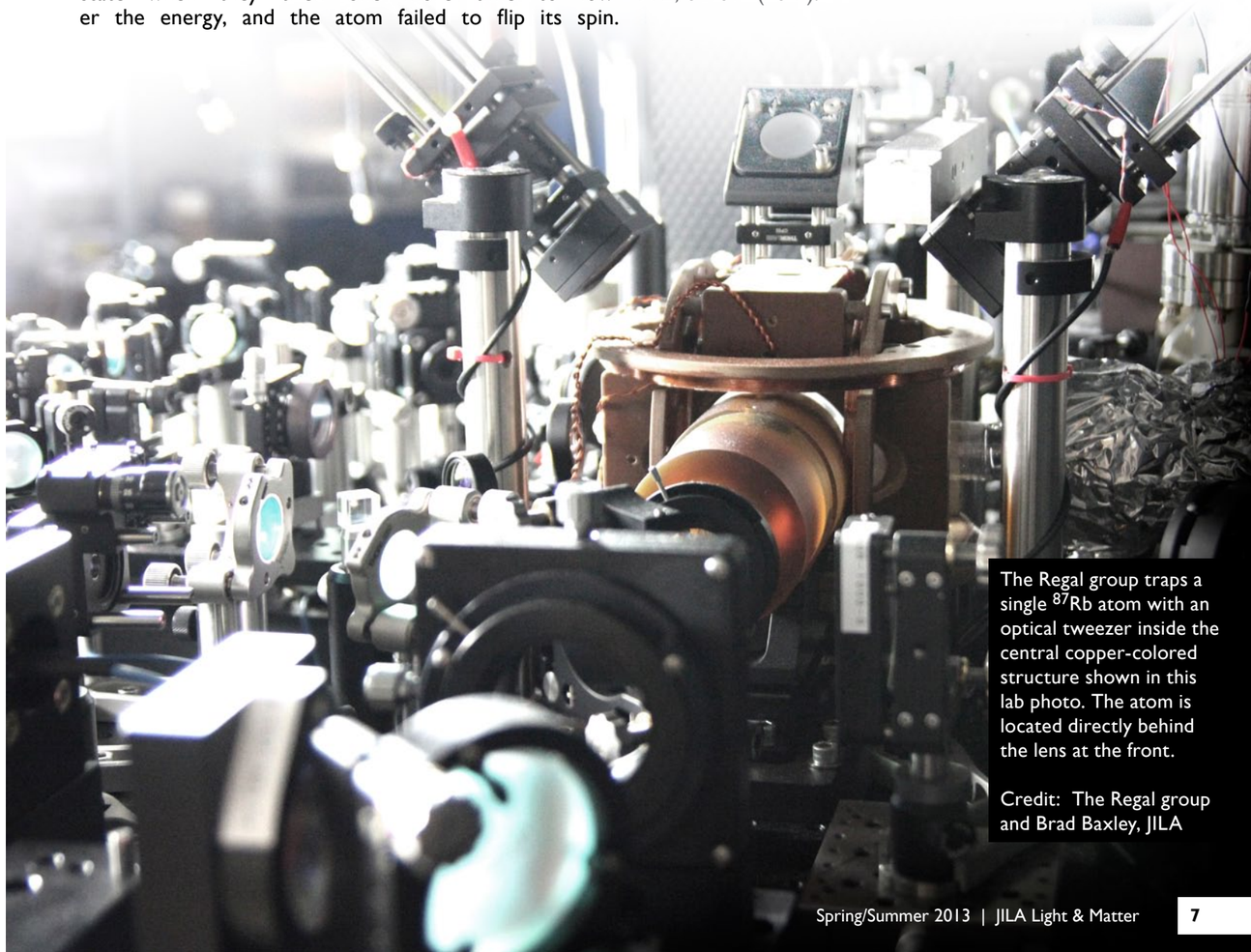
After the cooling, the researchers were able to tell when the atom had reached its quantum ground state. When the atom was in the ground state, it had no additional lower-energy states. It was no longer possible for the atom to lower its energy of motion. The researchers confirmed that the atom had reached its quantum ground state when they tried one more time to lower the energy, and the atom failed to flip its spin.

Now that the Regal group has figured out how to prepare single neutral atoms in their quantum ground state, a whole new field of research is opening up. For instance, these cold atoms may be placed near complicated optical patterns near surfaces, e.g., on a chip destined for a quantum computer. This placement should be possible because neutral atoms do not usually interact with their surroundings as do charged ions, which were the first single particles to be cooled and trapped.

Currently, Kaufman and his colleagues are working on trapping multiple single ^{87}Rb atoms in optical tweezers to see if it is possible to observe quantum tunneling between different tweezers after each of their single atoms is cooled to its quantum ground state. Quantum tunneling is a phenomenon where a tiny particle, such as an atom or an electron, tunnels through an energy barrier that it would not be able to surmount according to the laws of classical physics.

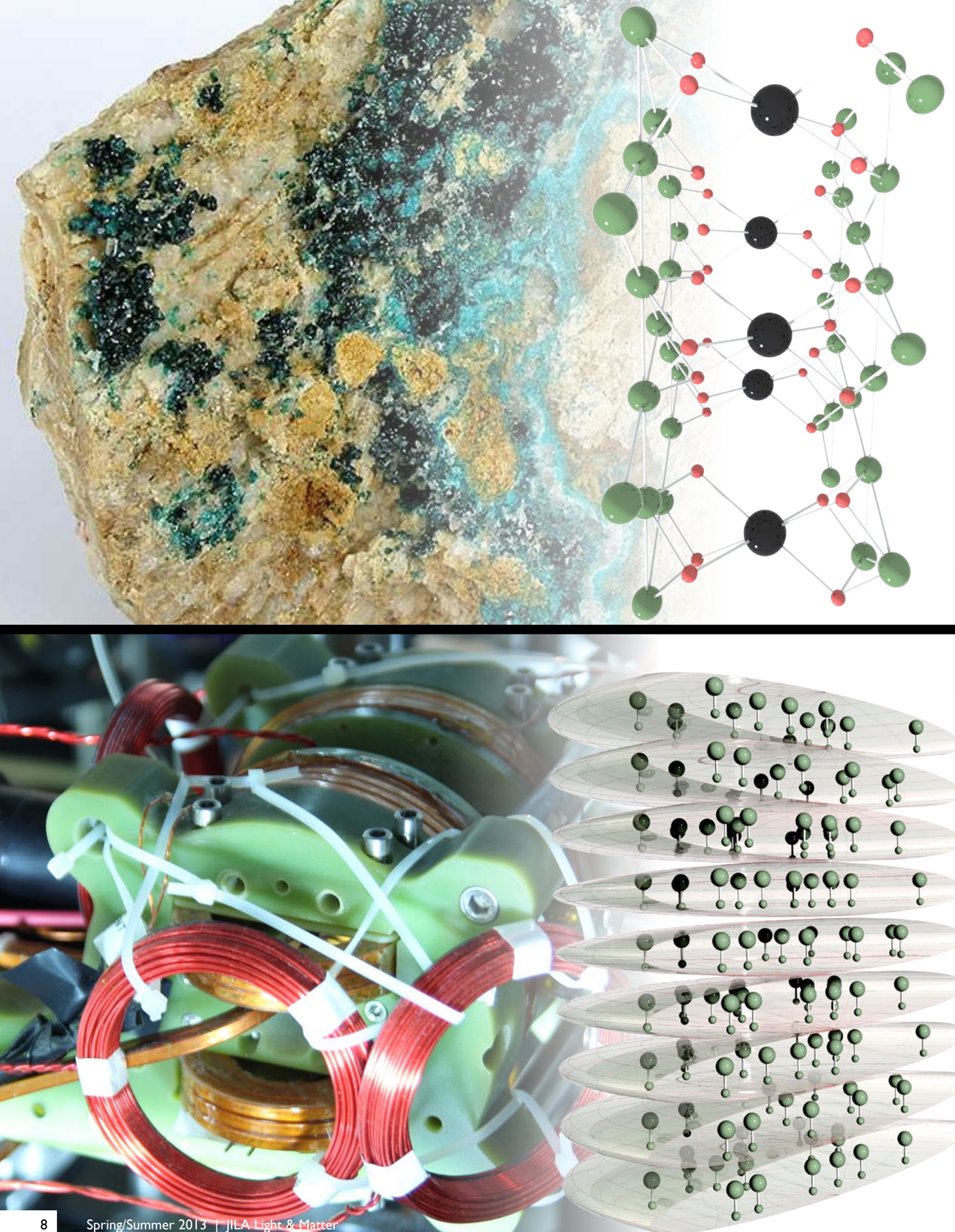
Reference

A. M. Kaufman, B. J. Lester, and C. A. Regal, *Physical Review X* **2**, 041014 (2012).



The Regal group traps a single ^{87}Rb atom with an optical tweezer inside the central copper-colored structure shown in this lab photo. The atom is located directly behind the lens at the front.

Credit: The Regal group and Brad Baxley, JILA



MODEL BEHAVIOR

For its part, the new theory's behavior has already yielded an innovative approach to using a quantum simulator based on ultracold KRb molecules. The new approach suggests starting a quantum simulation by zapping previously prepared quantum states in the simulator with microwave pulses. These pulses drive the quantum states far from equilibrium, resulting in a roiling mass of quantum states.

"Aiming microwaves into a quantum simulator kicks the system from its placid state," Hazzard said. "If conventional techniques create a gently rippled pond, then this technique generates something more like a cascading waterfall." The good news is that a cascading waterfall of quantum states makes it a lot easier for the experimentalists to assess the accuracy of their quantum simulator as well as enhance precision spectroscopy and time measurements. Nonequilibrium simulations can be run at 200 nK instead of temperatures 10–100 times lower.

The bad news is that wildly roiling quantum states are harder to model theoretically. Fortunately, Hazzard and his colleagues were able to combine conceptual insights and mathematical skill with supercomputer calculations to come up with a new description of a quantum simulator working far out of equilibrium.

Figure p. 8: The quantum behavior of atoms (upper right) in an everyday solid (upper left) can be emulated in a quantum simulator (lower left) built by the Jin-Ye collaboration. The simulator uses ultracold KRb molecules in a lattice (lower right) in place of the atoms. A new idea from Ana Maria Rey's group proposes running the simulator far out of equilibrium to benchmark its accuracy as well as to enhance precision spectroscopy and time measurements.

Credit: Kaden Hazzard, the Rey Group, the Jin-Ye collaboration, and Brad Baxley, JILA

Ana Maria Rey's group is devising new theoretical methods to help experimentalists use ultracold atoms, ions, and molecules to model quantum magnetism in solids. Research associate Kaden Hazzard, former research associate Salvatore Manmana, newly minted Ph.D. Michael Foss-Feig, and Fellow Rey are working on developing new tools to understand these models, which describe both solids and ultracold particles. The theorists are collaborating with three experimental teams at JILA and the National Institute of Standards and Technology (NIST). The experimental collaborations allow the theorists to test and improve their theory with precision measurements of quantum magnetism in action. The action occurs in novel quantum simulators based on neutral strontium atoms (Sr), beryllium ions (Be^+), or potassium-rubidium molecules (KRb).

Each simulator uses hundreds of particles whose collective magnetic behavior is far too complex to be solved theoretically even with the most powerful supercomputers. However, experimental observations of quantum behavior in ultracold systems are expected to allow Hazzard and his colleagues to better understand the behavior of their theory. That understanding, in turn, may one day be used to describe real-world materials.

As an added bonus, the new theory will be able to guide future experiments with optical atomic clocks as well as quantum simulators based on neutral Sr atoms, ultracold KRb molecules, or Be^+ ions. As a result of its collaboration with the John Bollinger group at NIST, for example, the Rey group has completed an important theoretical investigation of nonequilibrium dynamics in NIST's trapped-ion quantum simulator. This work provided support to the Bollinger group in its detection of quantum magnetism inside a trapped-ion quantum simulator in 2012.

Thanks to the collaborations between JILA theorists and experimentalists from JILA and NIST, the field of quantum simulation is literally exploding!

References

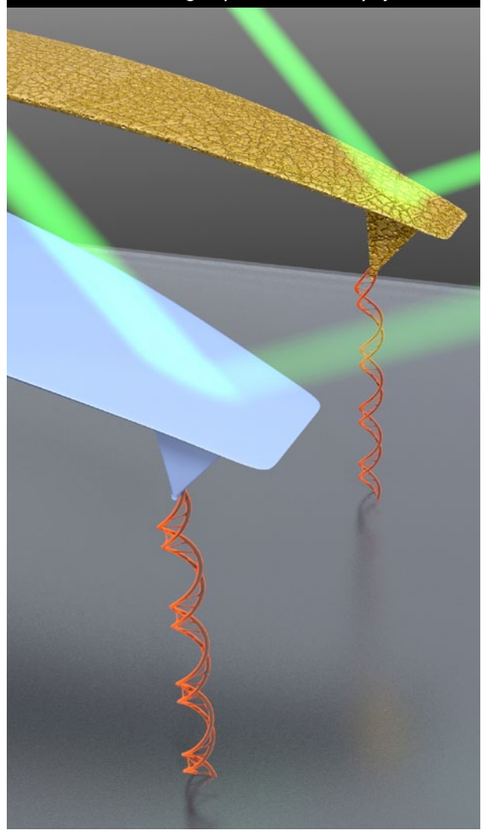
Kaden R. A. Hazzard, Salvatore R. Manmana, Michael Foss-Feig, and Ana Maria Rey, *Physical Review Letters* **110**, 075301 (2013).

Michael Foss-Feig, Kaden R. A. Hazzard, John J. Bollinger, and Ana Maria Rey, *Physical Review A* **87**, 042101 (2013).

GOING FOR THE GOLD

Artist's concept of an experiment comparing gold-coated (gold) and uncoated (blue) atomic force microscope probes. Lasers used to detect the probes are shown in green. The uncoated probe makes measurements that are ten times more stable and precise that those with the gold-coated probe.

Credit: The Perkins group and Brad Baxley, JILA



Gold glitters because it is highly reflective, a quality once considered important for precision measurements made with gold-coated probes in atomic force microscopy (AFM). In reality, the usual gold coating on AFM probes is a major cause of force instability and measurement imprecision, according to research done by the Perkins group. The group has shown that gold-coated probes are a particular problem for high-precision measurements of the tiny forces involved in the folding and stretching of large biomolecules, such as proteins and DNA, in liquid.

The best commercial AFM probes are very thin diving-board-shaped cantilevers made of silicon or silicon nitride. Since these thin structures barely reflect the laser beams used to detect their positions, they are coated with gold to enhance reflectivity.

The Perkins Group uses the technique of AFM-based force spectroscopy in liquid environments—precision measurement of piconewton-level forces—to learn about the dynamics of large biomolecules that are crucial to normal physiology and disease. Force spectroscopy requires both exquisite control of the position of the AFM tip on the atomic scale and stable force measurements.

The Perkins team previously made great advances in stabilizing AFM position. But their research on force spectroscopy was limited by substantial drifts in force measurements that plague all users of gold-coated AFM cantilevers. Although the gold coating gives a much stronger optical signal, the coating moves around slightly on the cantilever, causing the cantilever to move unpredictably. So instead of the AFM cantilever moving only in response to the molecule being studied, the gold coating itself was causing cantilever motion and creating significant measurement errors.

Not surprisingly, the group decided to go after the gold that was interfering with their research. Graduate student Allison Churnside, research associate Ruby May Sullan, undergraduates Duc Nguyen, Sara Case, and Matthew Bull, former research associate Gavin King, and Fellow Tom Perkins used a short chemical treatment to strip the gold off a commercial cantilever. Then, they compared this cantilever's behavior with that of a traditional gold-coated one.

The Perkins group's comparison showed that measurements made with the uncoated cantilever were ten times more precise in a measurement time of one second. It also showed that the gold coating was a primary source of force drift over the course of hours. Force drift is a measure of how far the probe's starting position drifts during a series of experiments. With the normal gold-coated cantilevers, this drift was about 1,000 nm; it was only 70 nm when the gold had been stripped away.

The improvements in stability and precision were evident just 30 minutes after the uncoated probe was readied for an experiment. In contrast, gold-coated probes often require more than two hours or overnight to settle down enough to allow an experiment to proceed.

The Perkins group anticipates that the advantages of doing away with gold coatings on AFM cantilevers will benefit all sorts of experiments in biophysics and nanoscience. — *Julie Phillips and Tom O'Brian*

Reference

Allison B. Churnside, Ruby May A. Sullan, Duc M. Nguyen, Sara O. Case, Matthew S. Bull, Gavin M. King, and Thomas T. Perkins, *NANO Letters* **12**, 3557–3561 (2012).

THE AMAZING PLASMON

The Nesbitt group has figured out the central role of "plasmon resonances" in light-induced emission of electrons from gold or silver nanoparticles. Plasmons are rapid-fire electron oscillations of freely moving (conduction) electrons in metals. They are caused by light of just the "right" frequency.

In metal nanoparticles, the right frequency exquisitely depends on the shape of the particle as well as its size and material. Master glass blowers actually figured this out during the Middle Ages! They learned to add tiny particles of gold and silver during glass making to produce the vibrant reds, blues, yellows, and purples of the stained glass windows in the great cathedrals of Europe. The tiny metal particles were not only responsible for the gorgeous colors, but have also prevented the hues from degrading over time, in some cases for more than a thousand years.

Today chemical physicists are working to understand the intricacies of plasmon resonances and their relationship to the photoelectric effect, which was first explained by Albert Einstein more than a hundred years ago. In the photoelectric effect, a photon of light of sufficiently high frequency will eject an electron from a metal surface. Even if the frequency of a single photon is not high enough to dislodge an electron, intense light can also cause electron ejection when the metal surface simultaneously absorbs several photons whose collectively energy is high enough.

This multiphoton photoelectric effect is particularly amazing since it usually takes three, four, or even more photons to eject a single electron. Then, if the frequency of the light hitting the metal surface happens to resonate with the metal surface's plasmon oscillations, billions more electrons will be ejected than would normally occur!

This plasmon-induced photoelectron emission is the subject of intense scrutiny in the Nesbitt laboratory these days. Research associate Andrej Grubisic, former research associate Volker Schweikhard, recently minted Ph.D. Tom Baker, and Fellow David Nesbitt recently completed a study of the critical role of the intense electric field accompanying plasmon resonances in photoelectron emission. The presense of such plasmon resonances significantly increased the coherent multiphoton photoelectron yield from gold nanorods.

The researchers discovered that they could maximize electron emission from the gold nanorods if they (1) aligned the laser along the long axis of the nanorod and (2) used a laser whose frequency vibrated in sync with the plasmon oscillation. The combined effect of the laser's frequency with the plasmon resonance created an electric field whose impact on the photoelectron emission from a gold nanorod's surface was truly mind-boggling. The resulting light-induced emission rate of electrons increased by a factor of 10 billion!

These startling results bode well for future investigations of plasmon resonances and metallic nanoparticles in general. Such research is expected to yield such exciting new applications as ultrashort-pulsed electron sources, more efficient solar cells, light-activated anticancer agents, high-density storage drives, and ultrasensitive chemical detectors.

References

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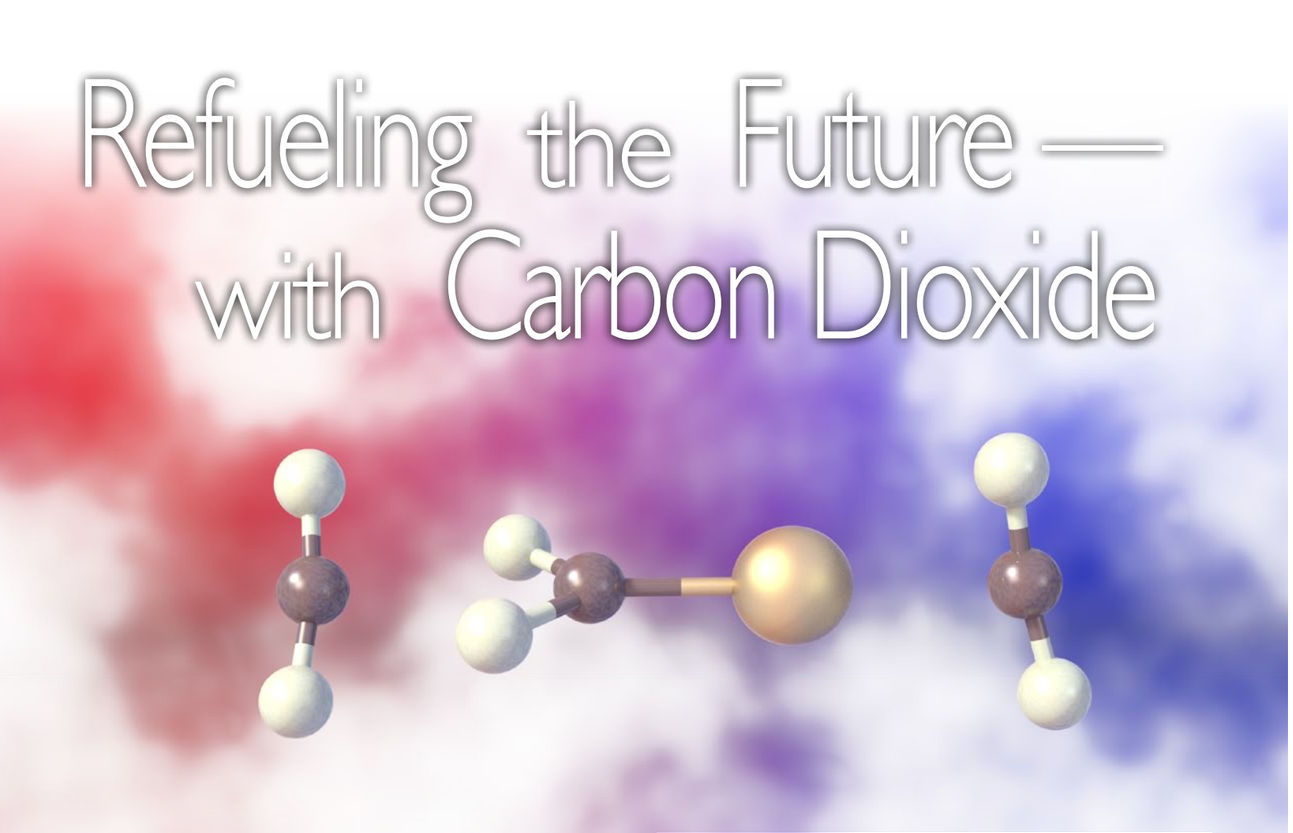
Andrej Grubisic, Emilie Ringe, Claire M. Cobley, Younan Xia, Laurence D. Marks, Richard P. Van Duyne, and David J. Nesbitt, *Nano Letters* **12**, 4823–4829 (2012).

A laser with a frequency vibrating in sync with the plasmon oscillation aligned along the long axis of a gold nanorod causes electron emissions to increase by a factor of 10 billion compared to an unaligned nanorod.

Credit: The Nesbitt group and Brad Baxley, JILA

Refueling the Future — with Carbon Dioxide



Orientation of solvent molecules around a negatively charged gold-carbon dioxide complex ($AuCO_2^-$). Up to eight solvent molecules will attach themselves to the CO_2 end of the $AuCO_2^-$ complex, enhancing a catalytic reaction that creates a more reactive-activated CO_2^-. Activated CO_2^- can be used to make recycled liquid fuels as part of a carbon-neutral fuel cycle. (O, white; Au, gold; C, brown)

Credit: The Weber group and Brad Baxley, JILA

Graduate student Ben Knurr and Fellow Mathias Weber have added new insight into a catalytic reaction based on a single gold atom with an extra electron that transfers this electron into carbon dioxide molecules (CO_2). This reaction could be an important first step in future industrial processes converting waste CO_2 back into chemical fuels. As such, it could play a key role in a future carbon-neutral fuel cycle.

What the Weber group did was use vibrational spectroscopy to probe the effect of solvent CO_2 molecules as they came in contact with a gold-CO_2 complex ($AuCO_2^-$). This complex is the first step in a catalytic reaction of gold and CO_2 that adds back chemical energy to a CO_2 molecule.

Before the researchers even did the experiment, they knew that if solvent molecules of CO_2 attach themselves to the CO_2 end of the $AuCO_2^-$ complex, they would enhance the chances of the CO_2 acquiring an extra electron, freeing itself from the gold atom, and completing the first step of the conversion reaction. The newly formed and highly reactive (i.e., activated) CO_2^- ions could then be used in a series of additional steps to make recycled liquid fuels.

Knurr and Weber found that the first eight solvent molecules of CO_2 preferentially attached themselves around the CO_2 end of the $AuCO_2^-$ complex. As the number of solvent molecules increased from 1 to 8, the activation of the complex-bound CO_2 also intensified, enabling it to grab more and more of the needed excess electron.

The activation reaction was most favored when all eight solvent molecules were in place around the complex.

But, adding even one more solvent molecule around the complex diminished the chances of activation. The reason was that there was no longer any room around the complex-bound CO_2 for more solvent. Additional solvent molecules ended up around the gold atom, where they pulled the extra electron nearer the gold atom, diminishing the chances for activation of the bound CO_2.

This work clearly shows how solvation can both enhance and diminish the effects of a catalyst like gold. It promises to inform the design and engineering of industrial systems aimed at creating carbon-neutral fuel cycles.

Reference

Benjamin J. Knurr and J. Mathias Weber, *Journal of the American Chemical Society* **134**, 18804–18808 (2012).

The Most Stable Clock in the World

The world's most stable optical atomic clock resides in the Ye lab in the basement of JILA's S-Wing. The strontium (Sr)- lattice clock is so stable that its frequency measurements don't vary by more than 1 part in 100 quadrillion (1×10^{-17}) over a time period of 1000 seconds, i.e., 17 minutes. This impressive result was obtained by lead graduate student Travis Nicholson, graduate students Mike Martin, Ben Bloom, Mike Bishof, and Sara Campbell, research associate Jason Williams, former senior research associate Matt Swallows, and Fellow Jun Ye.

The two key measures of atomic clock performance are stability and accuracy. A clock's accuracy measures how well it keeps time against a mythical perfect standard. But all clocks are noisy, and averaging over hours is necessary to reach the ultimate accuracy. Stability is a measure of how noisy a clock is, and thus how long the clock has to operate to achieve its ultimate accuracy. Recent research in the Ye group has focused on improving stability. This work has now led to the Sr-lattice clock being the most stable in the world by a large margin.

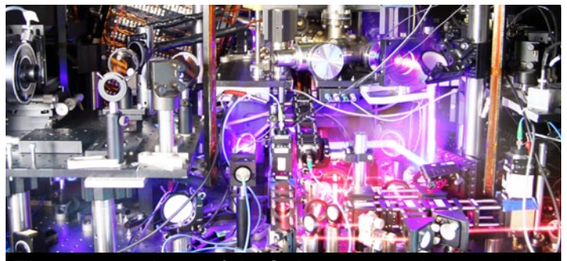
In addition to improved stability, the Ye group continues to rapidly improve the accuracy of the Sr-lattice clock. The most accurate clocks in the world are currently clocks based on single trapped ions of Al^+ or Hg^+ at the National Institute of Standards and Technology (NIST) in Boulder, Colorado. But the Ye group's Sr-lattice clock is about 40 times more stable than the NIST Al^+ clock (i.e., the Sr-lattice clock reaches its ultimate accuracy in a much shorter time).

The two main sources of noise or jitter that limit stability in optical atomic clocks are clock laser noise and quantum projection noise, which comes from not being able to measure the exact quantum state(s) of the atoms at the heart of these devices. This uncertainty is due to the laws of quantum mechanics.

Until recently, the Sr-lattice clock laser was the dominant source of noise in the Ye group's optical atomic clock. However, Martin has now built a new ultrastable clock laser that has been shown to have the world's best performance (with a stability of 1×10^{-16} from 1 to 1000 s). The new laser has greatly improved the clock's overall stability. It has also turned attention towards the reduction of quantum projection noise.

Quantum projection noise cannot be entirely eliminated, however. A certain amount of fluctuation in quantum measurements is intrinsic to any system where the laws of quantum mechanics predominate. This amount of intrinsic "noise" is known as the quantum projection noise limit. The stability of the Ye group's Sr-lattice clock is now within a factor of two of this quantum limit.

One reason the Sr-lattice clock is more stable than ion clocks is that the Sr clock contains thousands of atoms. The quantum fluctuations of these atoms tend to average out, thereby reducing the overall quantum projection noise of the clock. In contrast, the ion clocks have only a single ion, which constantly flips back and forth between quantum states. With only one particle instead of thousands of particles, it takes a lot longer to average down the intrinsic quantum fluctuations.



The inner workings of the Sr-lattice optical atomic clock under development in the Ye labs.

Credit: The Ye Group and Brad Baxley, JILA

Regardless of the details, however, the new stability value is particularly exciting for the Ye group and optical atomic-clock developers around the world. It is the first time a neutral atom-based clock has bested the top-performing trapped-single-ion clocks in a key measurement of clock performance. This improved stability will facilitate the group's current efforts to continually increase the Sr-lattice clock accuracy.

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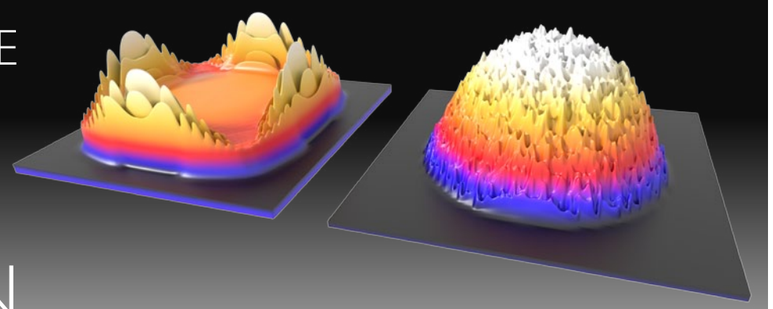
PHYSICS ON THE VERGE OF A MEAN-FIELD BREAKDOWN



The fort-like expansion pattern predicted by the mean field model (left) compared to the observed distribution (right) resulting from quantum entanglements of Rb atoms.

Credit: The Rey group and Brad Baxley, JILA

When experimental physicists at Penn State were unable to observe some of the predicted behaviors of ultracold rubidium (Rb) atoms expanding inside a two-dimensional crystal of light, they turned to their theorist colleagues at the City University of New York and JILA for an explanation. Graduate student Shuming Li and Fellow Ana Maria Rey were happy to oblige.

A theoretical model of the experiment indicated that the atoms, when allowed to expand, would be clustered inside a slowly moving square-shaped fort-like barrier (the shape of the cloud predicted by the mean-field model). This barrier would prevent the atoms inside from moving any faster than the fort itself, as predicted by the mean-field model. The model assumes that one atom interacts with the average behavior of all the other atoms inside the cloud inside the fort. This simplified model only predicted the behavior observed when the energy wells forming inside the crystal of light were shallow. However, when the experimenters adjusted the intensity of the laser that creates the crystal to make the energy wells deeper, the model could not reproduce the much slower atom expansion that occurred in response.

Rey and her collaborators figured out that as the wells grew deeper, it became harder for the strongly interacting atoms to move back and forth between adjacent wells. Eventually, the atoms could only move vertically—even though the deeper wells themselves were not impeding their movement. Curiously (because this is the quantum world), under these "frozen" conditions, the atoms became correlated or entangled. They actually seem to "know" what the other atoms around them were doing, even though none of the atoms had a cell phone.

What's interesting about correlated atoms is that they lose their individual identities and become something altogether different from single atoms: They become a superposition of all possible characteristics of their component atoms. And the correlations themselves somehow give rise to a new type of self-trapping.

Correlated states usually appear when interactions are strong. Very strong interactions prevent the atoms from passing over or through other particles, especially if the atoms are confined in the same energy well. On occasion, some correlated Rb atoms can even stop acting like neighborly bosons (which can occupy the same quantum state) and start acting like fermions, which do everything they can to avoid getting close to each other. These quantum correlations within energy wells can also suppress motion between adjacent quantum wells, according to Rey. Consequently, as soon as most of the atoms in the experiment became correlated and stopped moving, the entire cloud of Rb atoms seemed to become frozen in place, or trapped. In other words, because of the correlations in the quantum world inside the experiment, the Rb atoms in the lattice were actually trapping themselves!

The mean-field model does not capture quantum correlations and consequently predicts a much faster expansion rate than was observed when the energy wells were deeper. The mean-field theory's assumption that there exists some kind of "average" atomic behavior breaks down under circumstances that favor entanglement.

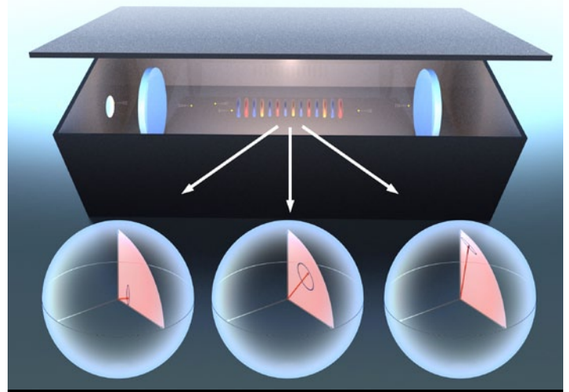
Clearly, a new theory is required to explain the quantum behavior of strongly interacting ultracold atoms. This theory must take account of quantum correlations and interactions. It must also map out the details of how the behavior of ultracold atoms in a lattice leads to self-trapping.

Theorists Li and Rey have their work cut out for them.

Reference

Aaron Reinhard, Jean-Félix Riou, Laura A. Zundel, David S. Weiss, Shuming Li, Ana Maria Rey, and Rafael Hipolito, *Physical Review Letters* **110**, 033001 (2013).

The Heart of Darkness



A look inside the Thompson group's superradiant laser reveals that the atoms at the heart of the laser wobble (and enter different atomic states) in response to disturbances in their environment. The laser exhibits a kind of self-awareness in which it can detect if its atoms are wobbling and adjust itself to reduce the amount of wobble.

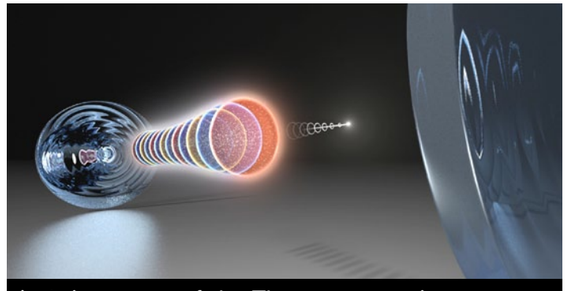
Credit: The Thompson group and Brad Baxley, JILA

When the Thompson group first demonstrated its innovative "superradiant" laser, the team noticed that sometimes the amount of light emitted by the laser would fluctuate up and down. The researchers wondered what was causing these fluctuations. They were especially concerned that whatever it was could also be a problem in future lasers based on the same principles.

In the group's superradiant laser, a million laser-cooled rubidium atoms at the heart of the laser act as the primary repository of information. In contrast, the light field inside the laser is relatively empty, or dark. The light field can be so dark that it contains, on average, one or fewer photons (quantum light particles).

Since the light field is so empty, the researchers deduced that if the amount of light leaving the laser was fluctuating, it must mean that there is some kind of oscillation occurring in the atoms that store the information. So they decided to peer inside the laser and see for themselves what was going on. In particular, the group wanted to discover how the process of superradiant lasing was affected by what was happening to the atoms in the heart of the laser.

Graduate students Justin Bohnet, Zilong Chen, Josh Weiner, and Kevin Cox worked with Fellow James K. Thompson to investigate the superradiant laser's stability in response to specific changes in its surroundings. This experiment was somewhat like investigating the stability of a bell by hitting it with a hammer and listening to it ring. But instead of hammering the superradiant laser, the researchers tickled it and used an innovative quantum-measurement technique they had previously developed to precisely determine how the atoms were responding.



Artist's concept of the Thompson group's new superradiant laser.

Credit: The Thompson group and Brad Baxley, JILA

To tickle their superradiant laser, the researchers decided to use the ordinary everyday laser that routinely makes rubidium atoms run around between quantum states. They simply made the power fluctuate in this tickling laser. The researchers found that under certain conditions their laser was not very ticklish. But, in other situations, the atoms wobbled like crazy—if the tickling was done at just the right speed (frequency).

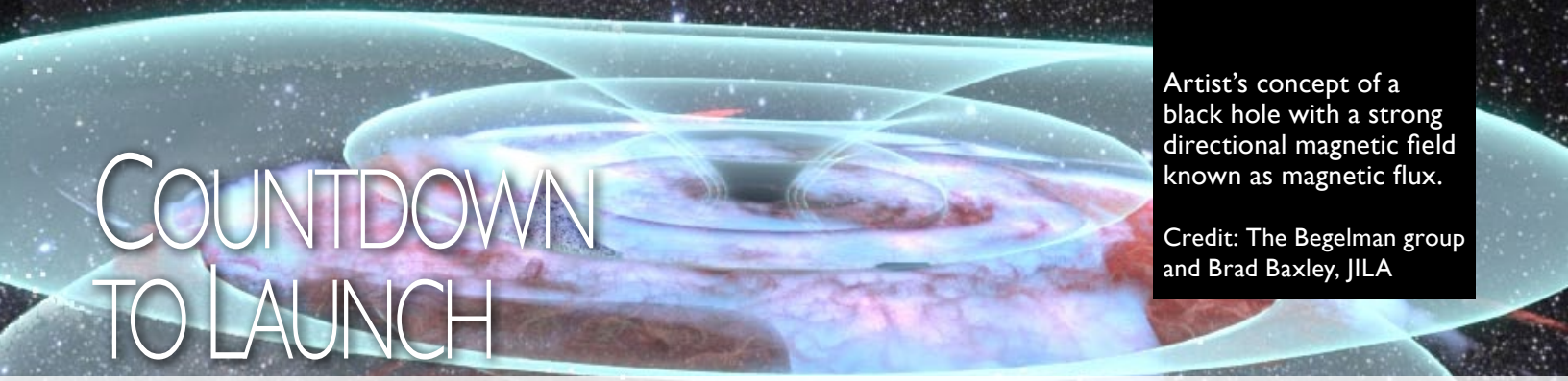
The researchers also discovered that the superradiant laser exhibited a kind of self-awareness in which it measured the atomic wobblings and then adjusted itself to reduce the amount of wobble. The researchers even figured out how to get the superradiant laser to increase the wobbling of its atoms.

"What the atoms are doing is really important for understanding this kind of laser," Thompson said. "We had to open the black box (laser) and look inside to get a complete picture of what was happening."

The results of this experiment are expected to guide the future development of superradiant lasers made with strontium and ytterbium atoms. Such lasers will likely improve the precision measurement of time, gravity, and fundamental constants. — *James Thompson and Julie Phillips*

Reference

Justin G. Bohnet, Zilong Chen, Joshua M. Weiner, Kevin C. Cox, and James K. Thompson, *Physical Review Letters* **109**, 253602 (2012).



Artist's concept of a black hole with a strong directional magnetic field known as magnetic flux.

Credit: The Begelman group and Brad Baxley, JILA

Countdown to Launch

Fellow Mitch Begelman and colleague Marek Sikora of the Polish Academy of Sciences have proposed a solution to the long-standing puzzle of what causes black holes to launch powerful jets. Jets are extremely energetic material (plasma) traveling at close to the speed of light and spanning distances of up to hundreds of thousands of light years. The key factor in the creation of jets is the presence of a strong directional magnetic field (magnetic flux) threading the black hole. And, because magnetic flux threading a black hole is relatively rare, the new paradigm also explains why less than 10% of the "active" supermassive black holes at the center of galaxies emit jets.

Active black holes voraciously feed on relatively thin clouds of cold gas. These writhing, twisting gas clouds typically create strong magnetic fields. But, the cold gas is too turbulent to carry much of the magnetic field near the black hole. And it's unusual for the black holes feeding on cold gas clouds to start emitting jets.

The trigger for jet emergence is the buildup of magnetic flux in a sequence of events involving a merger between an elliptical galaxy and a spiral galaxy. Elliptical galaxies contain large masses of hot gas that drag magnetic fields into the vicinity of the black hole—but not inside it. Then, when an elliptical galaxy merges with a spiral galaxy, the cold gas in the spiral galaxy pushes the magnetic field the rest of the way into the black hole. This two-step process threads the magnetic field through the black hole. At the same time, it causes the magnetic field to become organized with well-defined north and south poles. The black hole is now like a gargantuan bar magnet with a mass of millions to billions of suns. It emits powerful jets traveling close to the speed of light in opposite directions. The amount of power propelling these jets is a function of the strength of the magnetic flux running through the black hole.

Begelman and Sikora say that this mechanism explains the origin of jets from quasars. Observations have shown that quasars with jets are surrounded by thin cold disks of swirling gas. The researchers argue that these quasars must have previously encountered hot gas from an ancient elliptical galaxy before an encounter with a spiral galaxy that created the cold disk.

This work is an excellent example of the fruitful international collaborations JILA is known for throughout the world.

Reference

Marek Sikora and Mitchell C. Begelman, *The Astrophysical Journal Letters*, **764**, L24 (2013).

Kudos to...

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David Nesbitt for being elected as a 2013 member of the American Academy of Arts and Sciences.

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