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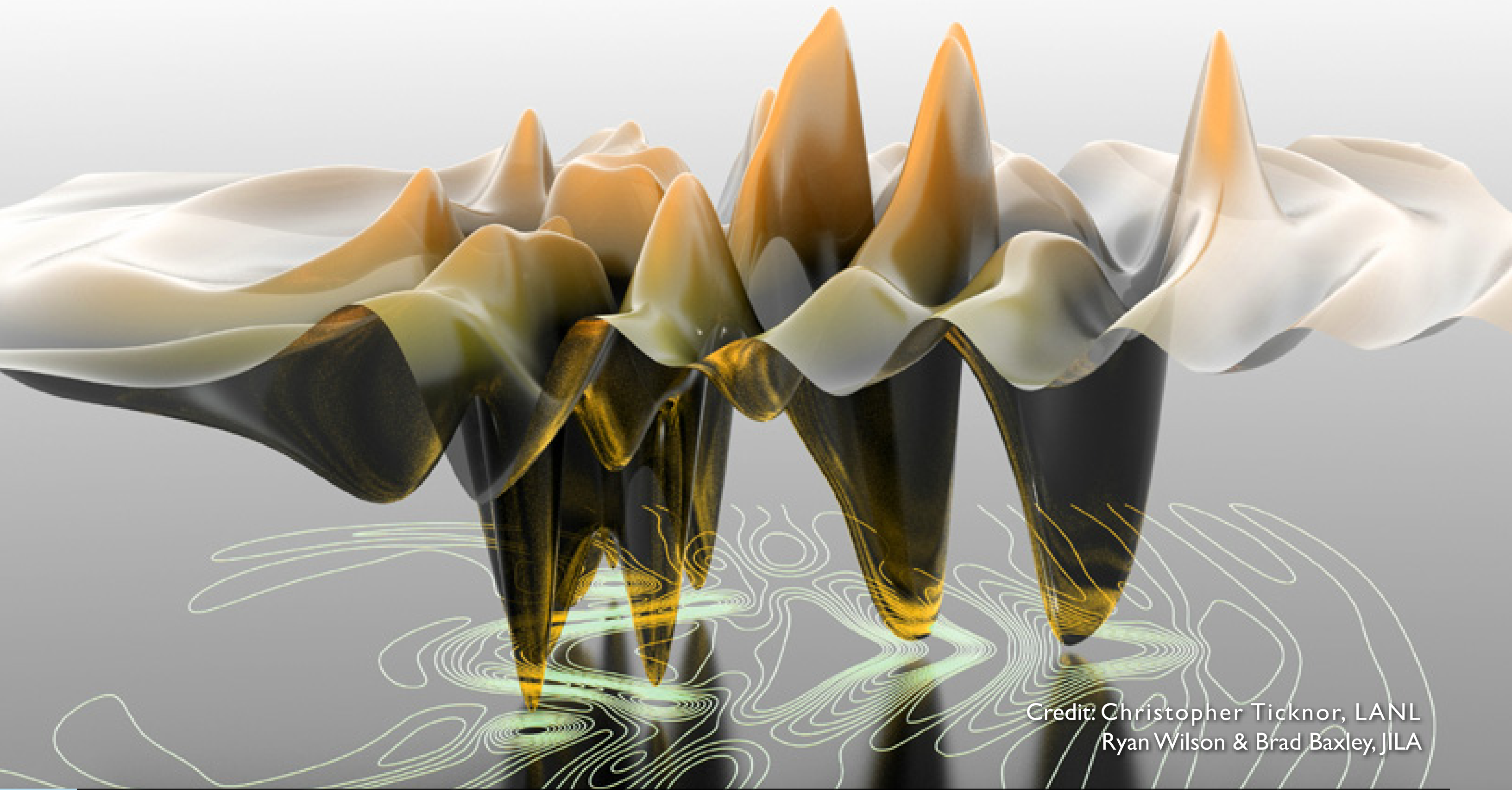


Credit: Christopher Ticknor, LANL
Ryan Wilson & Brad Baxley, JILA

The Fickle Finger of Fate

Putting the brakes on a superfluid dipolar Bose-Einstein condensate (BEC) just got a whole lot more interesting. Last year, the Bohn theory group explored what would occur in a dipolar BEC when a laser probe — think of it like a finger — tickled a BEC just hard enough to excite a roton (See *JILA Light & Matter*, Summer 2010).

The roton is a strange type of quasi particle formed when a number of strongly magnetic atoms or dipolar molecules come together and act like a different kind of particle. It is like a sound wave, with regions of high and low density. However, the relationship between its wavelength and frequency is decidedly strange. When a roton's wavelength gets small enough, its frequency stops growing; in fact, it gets smaller.

The onset of this oddball phenomenon determines the appearance of ripples that are associated with the drag on a laser probe, or finger, as it traverses a dipolar BEC. But that's not all that can happen, according to a new study by former JILA graduate student Chris Ticknor (now at Los Alamos National Laboratory), graduate student Ryan Wilson, and Fellow John Bohn. A sufficiently wide laser can also create vortices in the BEC, which are a lot easier to see in an experiment than a roton. There are other interesting experimental implications in the new study.

This work considers superfluid dipolar chromium atoms in a pancake-shaped trap created by two pairs of intersecting laser beams. This trap forces the dipolar atoms to line up side by side, and now they repel one another. The atoms can, however, be tilted slightly in one direction and this makes all the difference.

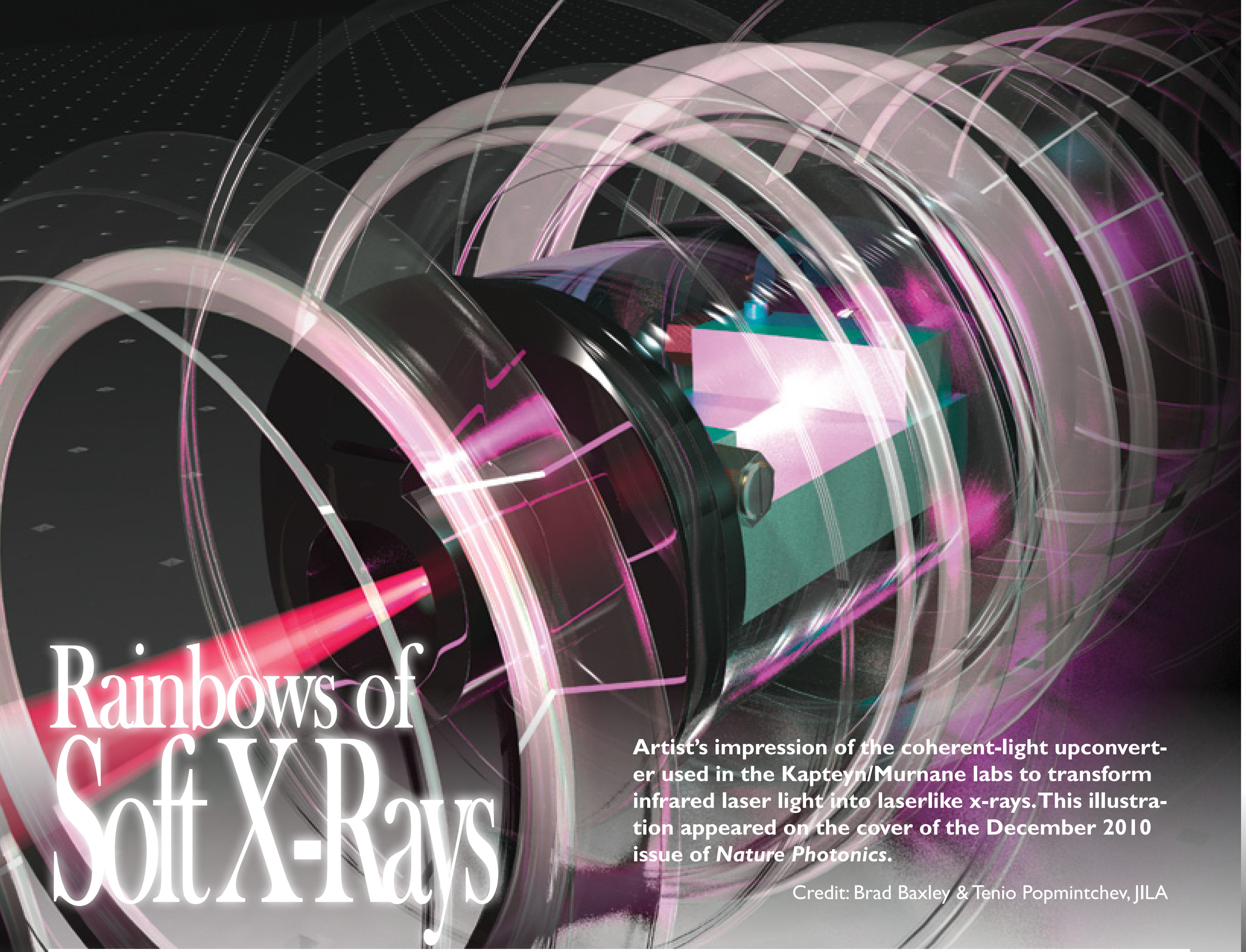
Under these circumstances, the rotons can be "fickle" when they're tickled. A roton only appears when a laser finger wanders through the BEC perpendicular to the head-to-toe orientation of the atoms. If the laser travels through parallel to the orientation of the atoms, nothing happens — no laughter, no drag, no friction, no roton. Clearly, the aligned dipoles can suppress the roton, but only in one direction.

This direction-dependent result proves that an ultracold superfluid consisting of dipolar atoms or molecules isn't necessarily uniform in all directions. This unexpected discovery was showcased in a recent article in *Physical Review Letters.*

Reference:

Christopher Ticknor, Ryan M. Wilson, and John L. Bohn, *Physical Review Letters* **106**, 065301 (2011).

Rainbows of Soft X-Rays



Artist's impression of the coherent-light upconverter used in the Kapteyn/Murnane labs to transform infrared laser light into laserlike x-rays. This illustration appeared on the cover of the December 2010 issue of *Nature Photonics.*

Credit: Brad Baxley & Tenio Popmintchev, JILA

The vision of a tabletop x-ray laser has taken a giant step into reality, thanks to Tenio Popmintchev, Ming-Chang Chen and their colleagues in the Kapteyn/Murnane group. By focusing a femtosecond laser into a gas, Popmintchev and Chen generated many colors of x-rays at once, in a band that stretched from the extreme ultraviolet into the soft x-ray region of the electromagnetic spectrum, spanning wavelengths ranging from about 6 to 2.5 nm. This broad x-ray band has so many different colors that all the waves can be added together to form the shortest strobe light in existence. This light lasts only 10 attoseconds [or 10 quintillionths of a second (10^{-17} s)]. Proof of the laserlike nature of the soft x-ray beams was featured on the cover of the October 22, 2010, issue of *Physical Review Letters*, shown above.

The new rainbow of x-rays spans the "water window" region of the spectrum, where biological molecules rich in carbon, hydrogen, and nitrogen can be clearly imaged without being obscured by absorption due to water. Researchers can use this new technology to probe the internal structures of cells or nanostructures with x-rays produced by a tabletop setup. The new x-ray laser is, in essence, a coherent version of the Roentgen x-ray tube.

Remarkably, the Kapteyn/Murnane group accomplished more than just opening up the water window region to tabletop laser x-rays. Popmintchev has already predicted that by using longer driving laser wavelengths, high-harmonic generation (HHG) can reach the hard x-ray region of the spectrum. [HHG was described in "Exotic Probes" in the Spring 2008 issue of *JILA Light & Matter*.] And, incredibly, the even-broader x-ray rainbows that will be generated in the hard x-ray region have the potential to produce zeptosecond (10^{-21} s) laser pulses!

The invention of the ultrafast tabletop x-ray laser is opening up whole new worlds in research, including capturing electron dynamics in molecules and materials, developing high-resolution nanoscale microscopes, understanding the limiting switching speeds in magnets, following energy and charge transport at the nanoscale, imaging chemical reactions at the level of atoms and electrons, and the imaging of subcellular structures.

Nature Photonics recognized the importance of x-ray laser research in its December 2010 issue highlighting the generation and use of ultrafast coherent x-rays. The issue included cover art by JILAns Brad Baxley and Popmintchev, who was also the first author of an invited article on bright coherent x-ray generation by the Kapteyn/Murnane group.

References:

Tenio Popmintchev, Ming-Chang Chen, Paul Arpin, Margaret M. Murnane, and Henry C. Kapteyn, *Nature Photonics* **4**, 822–832 (2010).

M.-C. Chen, P. Arpin, T. Popmintchev, M. Gerrity, B. Zhang, M. Seaberg, D. Popmintchev, M. M. Murnane, and H. C. Kapteyn, *Physical Review Letters* **105**, 173901(4), (2010).

Big G isn't the Problem:

Measuring it is

Apparatus used to measure big G at JILA

Credit: James Faller

Of all the fundamental forces, gravity is the most difficult to precisely measure. This difficulty is reflected in how hard it is to accurately measure "Big G," a fundamental constant that is part of the measurement of the gravitational force. In fact, big G is the least precisely measured fundamental constant in physics. Who would have imagined that the very first fundamental force to be discovered would still be somewhat mysterious more than 300 years later? Or, that a force most of us take for granted in everyday life is actually very hard to precisely measure?

Fellow Jim Faller and his colleague Harold Parks of Sandia National Laboratories in Albuquerque, New Mexico, know first hand about the difficulties of making precision measurements of big G. The two physicists completed a measurement of big G in 2004, but their measurement was so much smaller than the currently accepted value (by about 10 standard deviations) that they spent another six years trying to figure out what they'd done wrong. When they couldn't figure out anything wrong with what they'd done, they published their measurements in September 2010.

With that, Faller has grown philosophical. "I feel like I've checked everything, and I have to wash my hands," he said, noting that for centuries physicists have been trying to improve on Henry Cavendish's initial measurement of big G in 1797. And, even though modern measurements, including Faller's and Parks', all claim accuracies of a few tens of parts per million, there's a lot more variation between the measurements than scientists expected to see.

In 2000, Jens Gundlach and Stephen Merkowitz of the University of Washington in Seattle came up with the most precise measurement of big G in history. As an added bonus, the uncertainty of this measurement was relatively low. Soon afterward, another group reported measurements that agreed with this measurement. It seemed that the precision measurement of big G had taken a big step forward.

Fast forward a decade, and two groups report smaller values for big G: Faller and Parks (10 standard deviations lower) and a group from China whose value for big G is about 3 standard deviations lower than the widely accepted 2000 value. In response to the new measurements, the Committee on Data for Science and Technology (CO-DATA) will likely revise down the value of G in its next set of values to be finalized in 2011 and, at the same time, increase the uncertainty associated with this value.

The more pressing issue, according to Faller, is: Who's right? Knowing that most metrologists around the world already thought that Gundlach's and Merkowitz's value for big G was correct made Faller's and Parks' experiment a lot harder.

"We looked under every rock we could to find systematic errors that we might have overlooked, but we found nothing," Faller says. Consequently, Faller and Parks decided to publish their results and let the chips fall where they would. So far, their new paper has been a newsworthy item in physics circles. Bloggers have started to weigh in on whose value for big G is correct.

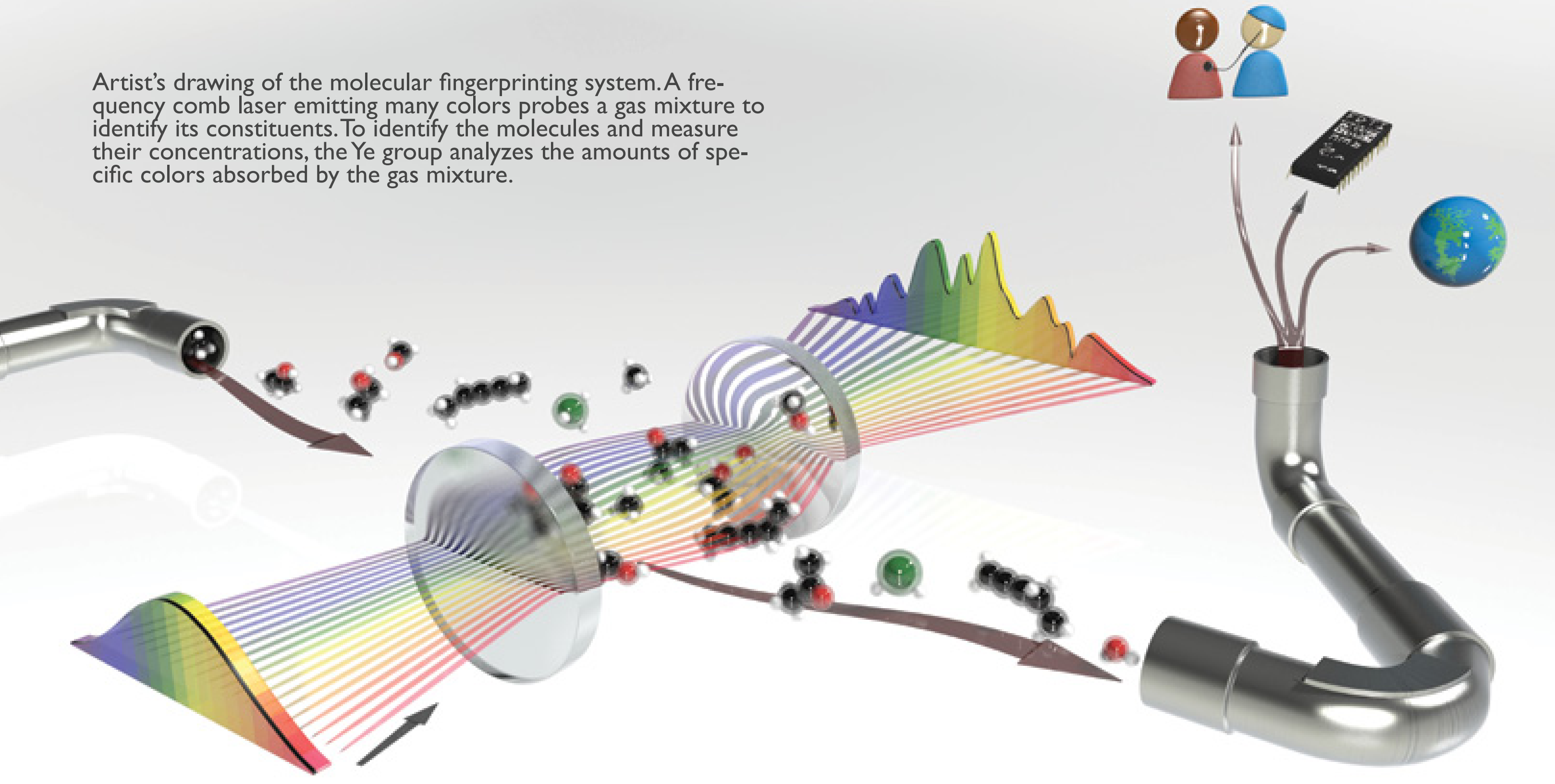
Even so, the controversy over big G also begs another question: What good will be accomplished with ever-more precise measurements of big G since physics, at least today, doesn't need a better number?

Faller knows the answer to this question: "Big G is the Mt. Everest of precision measurement science, and it should be climbed."

Reference:

Harold V. Parks and James E. Faller, *Physical Review Letters* **105**, 110801 (4), 2010.

Artist's drawing of the molecular fingerprinting system. A frequency comb laser emitting many colors probes a gas mixture to identify its constituents. To identify the molecules and measure their concentrations, the Ye group analyzes the amounts of specific colors absorbed by the gas mixture.



Credit: Brad Baxley, JILA

DECIPHERING NATURE'S FINGERPRINTS

Fellow Jun Ye's group has enhanced the molecular fingerprinting technique with the development of a mid-infrared (mid-IR) frequency comb. The new rapid-detection technique can now identify traces of a wider variety of molecules found in mixtures of gases. It offers many advantages for chemical analysis of the atmosphere, climate science studies, and the detection of suspicious substances. In addition, planning is already underway for clinical trials of a noninvasive medical breath analyzer that incorporates the technique (See *JILA Light & Matter,* Spring 2008).

The new trace gas detection system was developed by former research associate Florian Adler, who worked with research associates Piotr Maslowski and Aleksandra Foltynowicz, graduate students Kevin Cossell and Travis Briles, Fellow Jun Ye, and a colleague from IMRA America, Inc.

With the new mid-IR frequency comb as a source of light, the range of the molecular fingerprinting technique has been extended into spectral regions that cover frequencies associated with fundamental vibrations of many organic molecules (containing carbon and hydrogen atoms). As a result, the technique can now identify more molecules and at lower concentrations.

The comb is generated by an ultrafast laser that emits tens of thousands of different colors of light of specific frequencies that can be precisely measured. When comb light passes through a mixture of gases, different chemicals absorb different colors of the light. By analyzing which colors are absorbed and in what amounts, the researchers can determine the identity and concentration of the different molecules in a mixture. In a test of the new system, Adler and his colleagues measured the spectra of a dozen organic molecules, including the "greenhouse" gases methane, carbon dioxide, and nitrous oxide; air pollutants isoprene and formaldehyde; and two molecules probed in human breath analysis: ethane (a sign of asthma) and methanol (an indicator of kidney failure).

The new laser uses an optical parametric oscillator, or OPO, to shift the light from a near-IR frequency comb to the mid-IR. By combining the OPO-based laser with conventional Fourier-transform infrared spectroscopy (FTIR), Adler and his colleagues were able to devise a system that was much faster than conventional FTIR spectrometers. Their technique can identify and measure the concentrations of many molecules in less than one minute, as compared to hours. This speed is crucial for many practical applications.

The Ye group is now looking to extend the reach of frequency combs to wavelengths centered around 10 μm and probe another key region for molecular fingerprinting. Fellow David Nesbitt is particularly excited with this prospect as he foresees scientific opportunities for exploring a whole new landscape with high resolution comb sources. The group is also planning to work on modifying the equipment to make it portable — a key feature for such practical applications as airborne or satellite-based chemical analysis of the atmosphere.

Reference:

Florian Adler, Piotr Maslowski, Aleksandra Foltynowicz, Kevin C. Cossel, Travis C. Briles, Ingmar Hartl, and Jun Ye, *Optics Express* **18**, 21861–21872 (2010).

SEEDS OF CREATION:

MONSTER STARS OR QUASISTARS?

There are two competing ideas about the origin of the monster black holes at the center of galaxies. Both include exceptional stars that have never actually been observed: (1) massive population III (Pop III) stars (as big as a thousand suns) made of pure hydrogen and helium that would have formed less than 100 million years after the Big Bang, and (2) gigantic quasistars whose shining envelopes were powered, not by nuclear fusion, but by energy emitted by the black holes inside them. These black holes would have been formed directly from the partial collapse of dense gas clouds about 500 million to a billion years after the Big Bang. The quasistars would have evaporated about two million years after the formation of the black holes in their centers. They left behind "seed" black holes with masses of a hundred thousand suns, according to a theory developed by Fellow Mitch Begelman and his colleagues at JILA, Cambridge University, the University of Michigan, and the University of Kentucky (see *JILA Light & Matter,* Winter 2010).

In contrast with the quasistars, the equally short-lived Pop III stars would have formed black hole seeds of only about 50 stellar masses in stupendous supernovae explosions. However these seeds would have had up to a billion years longer to grow larger through galaxy mergers.

So, the question now is simple: Which theory can account for both the supermassive black holes believed to be at the center of most or all of today's galaxies and the luminous quasars that arose in the early Universe?

Quasars are the active galactic nuclei of ancient galaxies. The most luminous objects in the Universe, they are powered by accretion disks around monster black holes in their centers. Quasars figure prominently in discussions of the evolution of monster black holes because they (and their central supermassive black holes) appeared much earlier in the history of the Universe than the vast majority of galaxies organized around similarly gargantuan black holes.

Recently, Begelman and his colleague Marta Volonteri of the University of Michigan decided to model the evolution of black holes from both Pop III stars and quasistars to see whether either alone could account for the early quasars and the gargantuan black holes inside galaxies today. The researchers found that for Pop III stars to produce all the black holes in the Universe, everything, including approximately 10 mergers per galaxy, must have come together perfectly — with no ejections of black holes. Begelman says this scenario for forming monster black holes inside galaxies is possible, but unlikely.

Explaining quasars is another matter, however. The evolution of Pop III stars cannot explain the formation of the quasars' monster black holes as early as they appeared in the Universe. There simply would not have been enough time for the relatively small black hole seeds produced by Pop III stars to grow as large as those powering the quasars.

However, if quasistars were the progenitors of monster black holes, they could lead to both the modern distribution of monster black holes at the center of galaxies and the early quasars.

Of course, there is also the possibility that both processes may have been at work in the early Universe. If so, Begelman says it would have been unlikely for a quasistar to form in a galaxy that already had a black hole created by the supernova of a Pop III star. There shouldn't have been enough gas available for the direct collapse into another black hole.

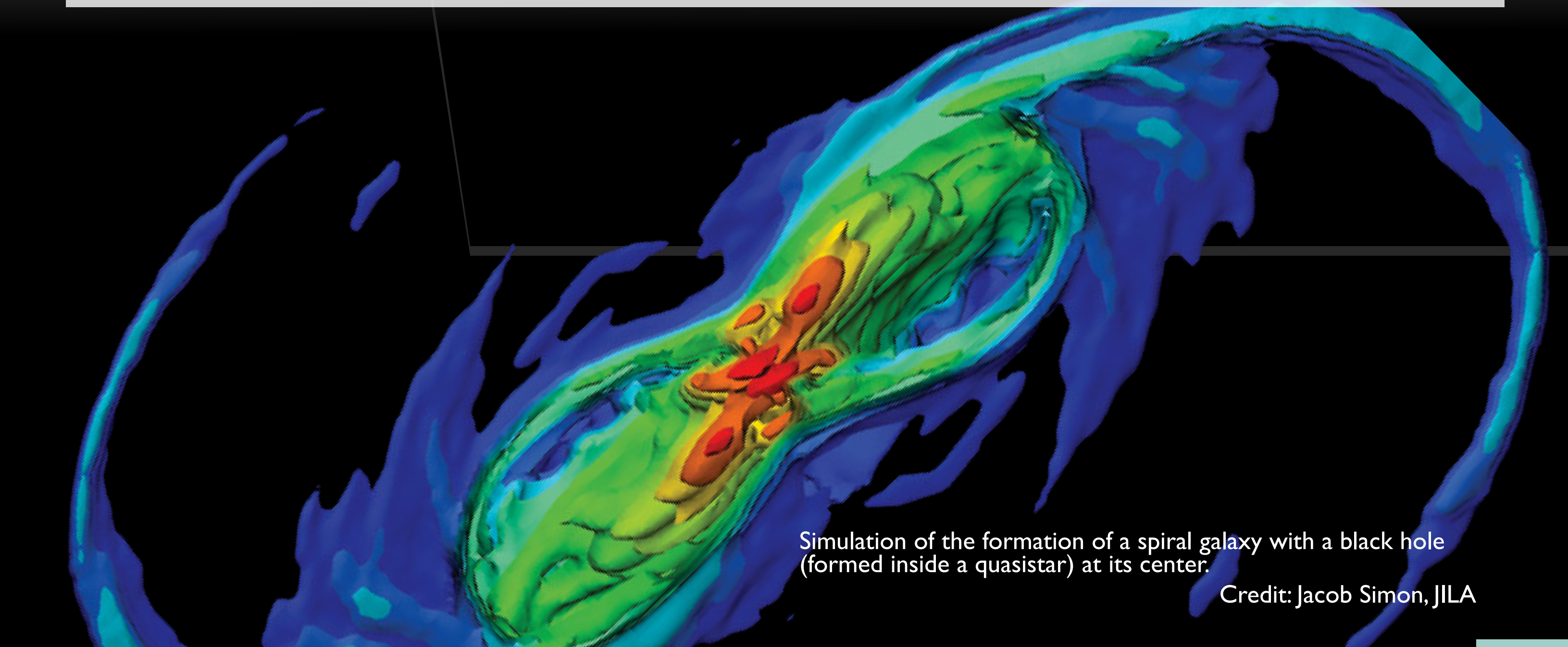
Interestingly, there may be way to discern if just one or both processes contributed to the formation of monster black holes — with observations from the new James Webb Space Telescope, scheduled for launch in 2014. If Pop III stars existed at the predicted sizes and distributions, the new telescope should easily be able to detect clusters of them. In principle, the same telescope could also detect quasistars. If they exist, there should be one in every field of view, according to Begelman. Right now, he's trying to think of a clever way to identify them, so it won't be like looking for a needle in a haystack.

To settle the question of the reality of quasistars, a powerful new wide-field telescope on Earth should work much better than the James Webb Space Telescope, says Begelman. The University of Colorado has joined a consortium led by Cornell University to build a new submillimeter radio telescope in the high Atacama Desert of Chile. This instrument should be able to observe galaxies in the process of formation and the early growth stages of monster black holes.

In the meantime, Begelman is investigating whether a quasistar could form in a galaxy already home to a Pop III black hole seed and refining his model for the growth of monster black holes from quasistars. As yet, there is no definitive answer on whether Pop III or quasistars gave rise to today's monster black holes. It may even turn out that both processes played a role in shaping the Universe. Stay tuned.

Reference:

Marta Volonteri and Mitchell C. Begelman, *Monthly Notices of the Royal Astronomical Society* **409**, 1022–1032 (2010).



Simulation of the formation of a spiral galaxy with a black hole (formed inside a quasistar) at its center.

Credit: Jacob Simon, JILA

The Long Goodbye

The dance of electrons as a bromine molecule (Br_2) separates into two atoms is intricate and complex. The process of breaking up takes far longer than expected (~150 vs 85 fs) because the cloud of electrons that bind atoms together in a molecule behaves as if it were still surrounding a molecule until the last possible moment — when the atomic fragments are about twice the normal distance apart (~.55 nm). At this point, there's simply not enough energy left in the system to hold the molecule together. When the two atoms finally appear as separate entities, it is as if someone had snapped a rubber band.

Bromine molecule's long goodbye was discovered in an experiment by former research associate Wen Li of the Kapteyn/Murnane group and explained theoretically by senior research associate Agnieszka Jaroń-Becker of the Becker group. Graduate student Craig Hogle, former research associates Vandana Sharma and Xibin Zhou, and Fellows Andreas Becker, Henry Kapteyn, and Margaret Murnane contributed to this seminal work.

Li and his colleagues initiated the dissociation of a Br_2 molecule with a violet (400 nm) ultrafast laser pulse. If a Br_2 molecule absorbs only a single photon at this wavelength, the molecule gets excited into a dissociative state where it begins to break apart into its constituent atoms. The researchers then used an infrared laser pulse to ionize the dissociating molecule and probe the progression of the dissociation at varying times after the molecule began to fall apart. The series of probe pulses allowed Li and his colleagues to follow the motions of all ten valence electrons as the molecular bond was breaking. This is the first experiment to capture the coordinated dance of multiple electrons at once.

What surprised the team was that the change from a molecule to two atoms could be observed over such a surprisingly long time and distance. (While times of 140 millionths of a billionth of a second and distances of .55 billionths of a meter may seem very small, they are much longer than would normally be expected in the exceedingly fast and small world where individual atoms interact.) To explain these unexpected results, the laboratory scientists turned to their theorist colleagues.

With the help of Jaroń-Becker, the laboratory scientists realized they were observing all 10 valence electrons evolving in time as the molecular bond was breaking. Jaroń-Becker's analysis showed that the researchers were not likely to see two separate atoms until 140–160 fs after the initial dissociative laser pulse — a prediction that dovetailed nicely with the experimental observations.

"What was interesting about this system was that there was a single excited initial state, but 30 possible final states, with many different ways to get there," said Jarón-Becker. She recalled that the experiment was already underway when she arrived at JILA. At that time, the Kapteyn/Murnane group thought that in Br_2 they had selected something nice to study, but not too difficult.

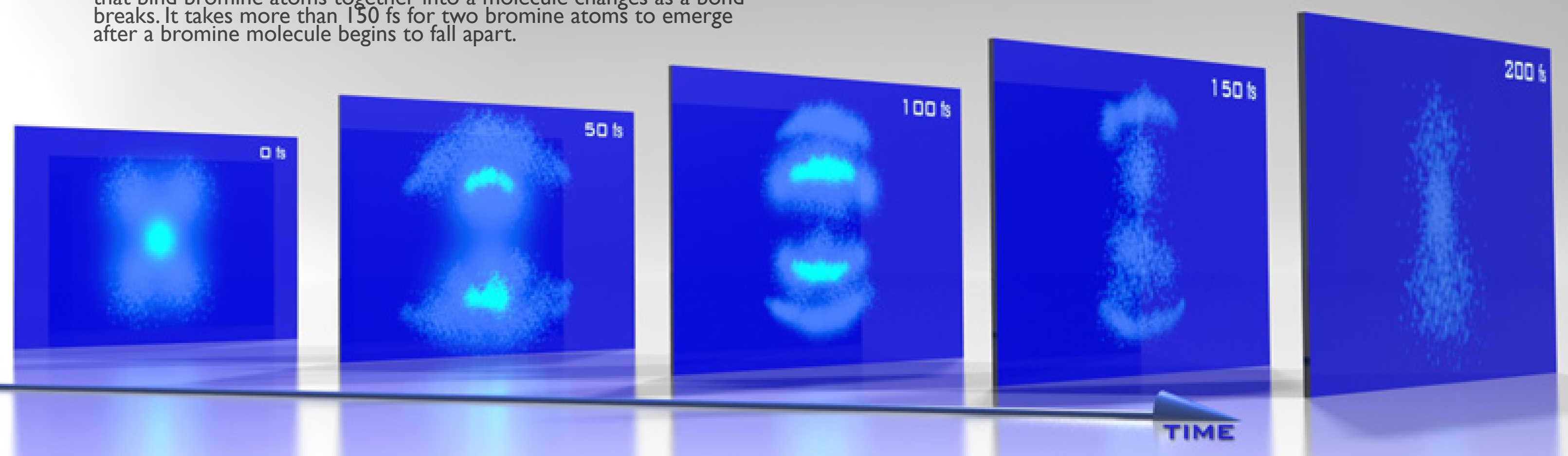
"But when we first looked at Br_2's potential energy surfaces, we thought 'Oh, God, that's a mess,'" said Jaroń-Becker's husband and colleague Andreas Becker. Jaroń-Becker said it took her half a year to get the potential energy surfaces and corresponding wave functions with sufficient accuracy to allow her to calculate the ionization rates of the Br_2 molecule. "But when we got the figures, we discovered they looked like the experimental data," Jaroń-Becker said. The Beckers believe the Kapteyn/Murnane group picked about the most difficult diatomic molecule for a theoretical analysis that they could have chosen. "But they did a beautiful experiment and saw what Agnieszka's calculations predicted they would observe," Becker said. He added that this work opens a new door in the theory of molecular dissociation. It is a proof of principle for observing and understanding electron rearrangements during molecular dissociations over long times and distances.

References:

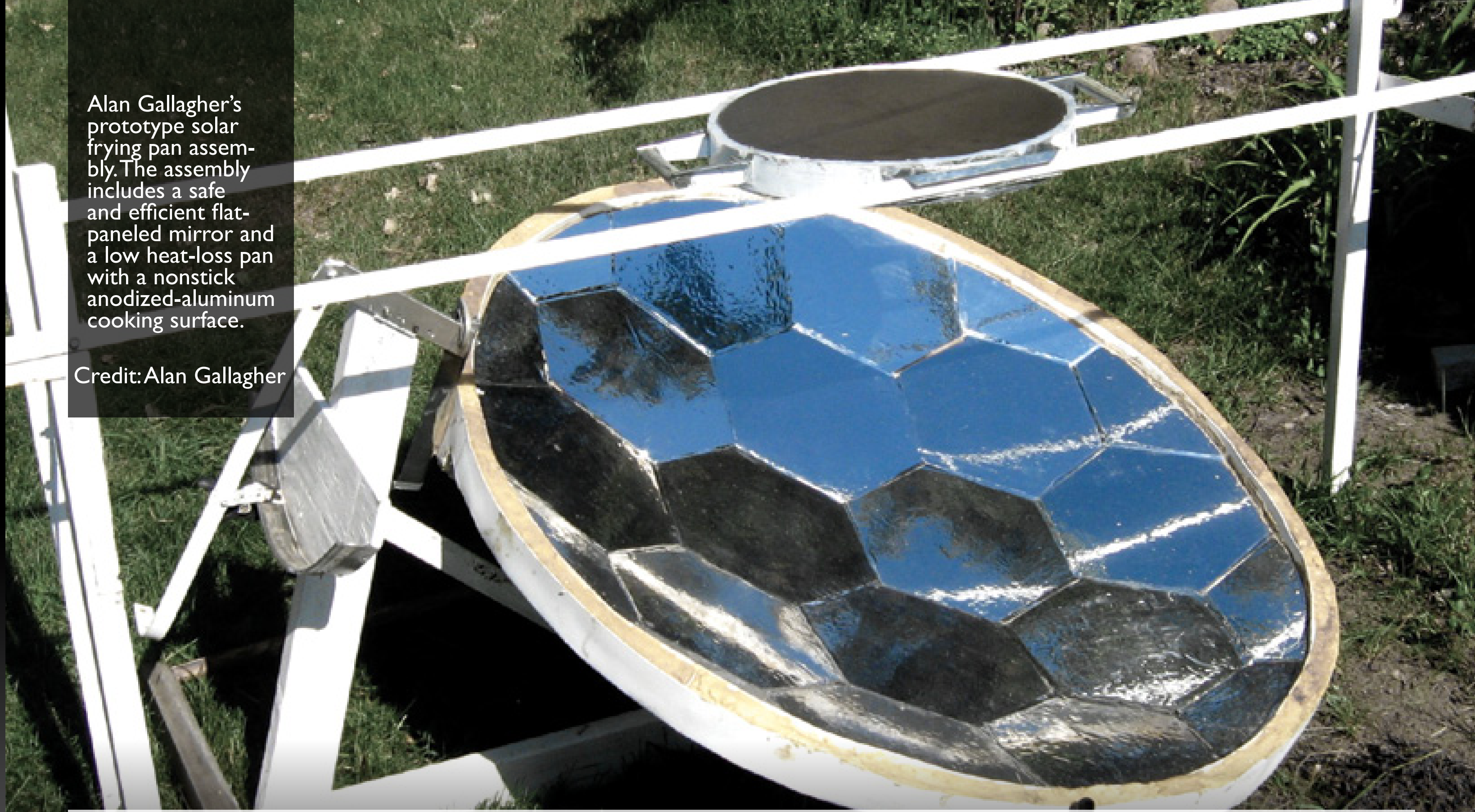
Wen Li, Agnieszka A. Jaroń-Becker, Craig W. Hogle, Vandana Sharma, Xibin Zhou, Andreas Becker, Henry C. Kapteyn, and Margaret M. Murnane, *Proceedings of the National Academy of Sciences U. S. A.* **107**, 20219 20222 (2010).

Agnieszka A. Jaroń-Becker, *IEEE Journal of Selected Topics in Quantum Electronics* **PP**(99), 1–8 (2011).

Experimental measurements showing how the density of the electrons that bind bromine atoms together into a molecule changes as a bond breaks. It takes more than 150 fs for two bromine atoms to emerge after a bromine molecule begins to fall apart.



Credit: Wen Li, JILA



Alan Gallagher's prototype solar frying pan assembly. The assembly includes a safe and efficient flat-paneled mirror and a low heat-loss pan with a nonstick anodized-aluminum cooking surface.

Credit: Alan Gallagher

THE INCREDIBLE SOLAR BREAD MACHINE

After he retired, Fellow Alan Gallagher decided to take his interest in solar energy in a whole new direction: He decided to design, build, and test a unique large-area frying pan heated by the Sun's energy. The new solar frying pan was specifically tailored to the cooking of injera bread in East Africa.

For more than 100 million people in East Africa, the thin, flexible, and pancakelike bread is a mainstay of their diet. It is usually eaten with a variety of thick sauces spread around the top of a large (~0.4 m diameter) slice, which serves as a shared "dinner plate." Once the sauces are consumed, the diners eat the sauce-soaked plate.

In villages, a typical "slice" of injera bread can be more than half a meter in diameter. The bread is cooked for about 2 minutes in a covered pan preheated to ~180 °C. When wood is used to cook this bread, cooking contributes to severe forest and environmental degradation because of the high demand for wood. In contrast, solar cooking would benefit the local environment by (1) decreasing deforestation and desertification, (2) curtailing the generation of particulates and greenhouse gases, and (3) reducing the health hazards associated with indoor-fire cooking. Solar cooking would also lower the cost of gathering or purchasing firewood.

To encourage East Africans to save on the cost of firewood, Gallagher designed his solar frying pan to be efficient, safe, easy to construct, and inexpensive. For example, the mirror consists of flat hexagonal panels of aluminized Mylar inside of a parabolic framework. The flat panels uniformly illuminate (evenly heat) the bottom of the frying pan, which sits above the mirror. The flat panels make this mirror safe to use for cooking because they don't ever concentrate the Sun in just one place, which can burn the cooks or start fires.

The pan bottom is coated with a special black surface that only emits very low levels of radiation. The black surface keeps the fryer from losing as much as half the power it gets from the Sun. The pan's nonstick surface is made from anodized aluminum whose pores are filled with cooking oil. On a sunny day, the pan preheats to 180 °C in 15–20 minutes. It can cook slices of injera bread as large as 0.42 m in diameter.

The solar fryer can be used eight hours a day throughout the year. An easy-to-use mirror adjustment allows users to track the Sun during the day, and a mounting adjustment makes it possible to correct for seasonal variations in the position of the Sun. The prototype solar fryer provides about 640 W of heating power and can cook about 32 kg of bread per day, or enough bread to feed ~160 people.

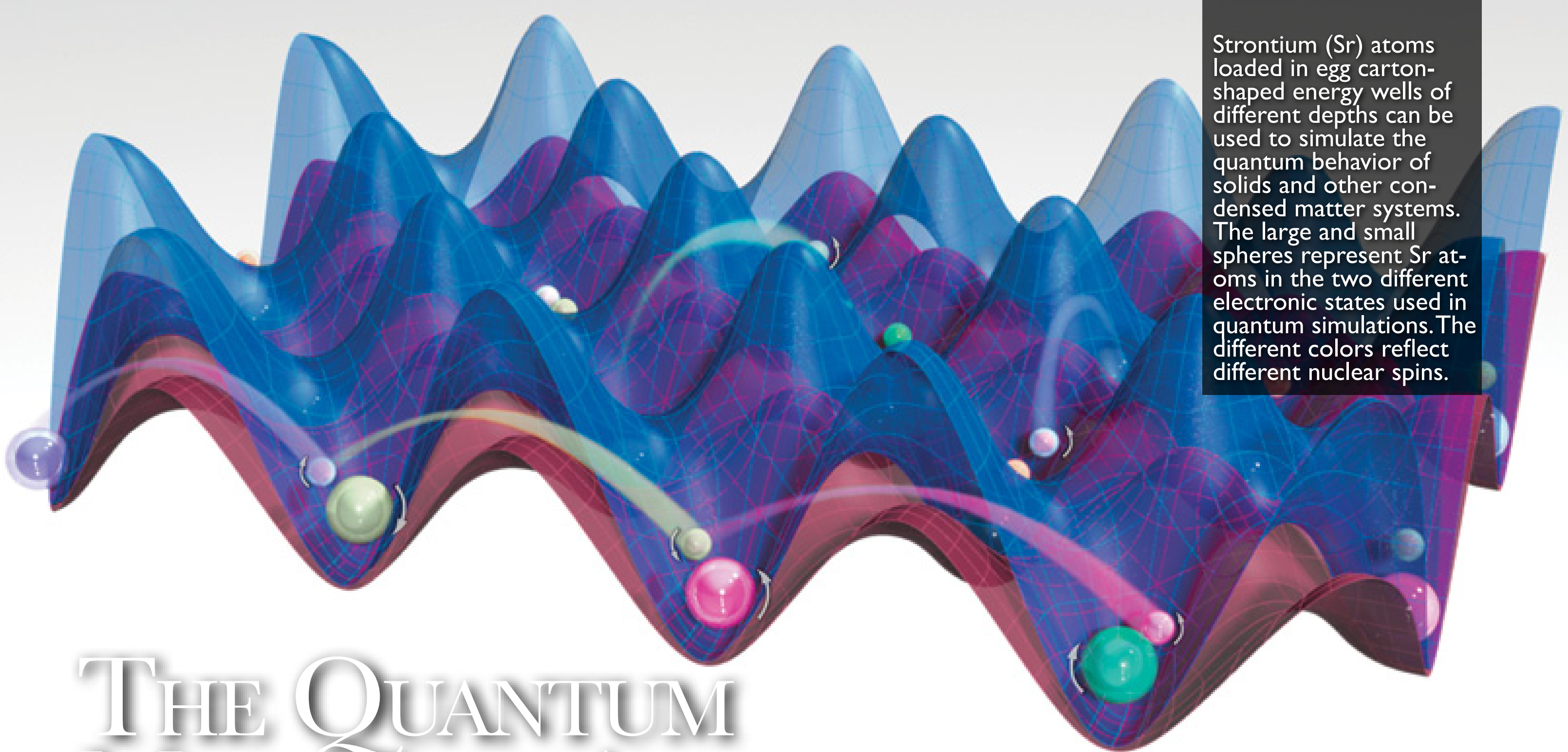
The large cooking capacity allows multiple options for using the solar fryer: (1) Several families could chip in to buy one and share it, (2) The owner of the solar fryer could sell cooked bread or cooking time as a means of paying for the device, or (3) a restaurant might purchase one to save on (wood) fuel costs.

The retail cost of the materials (in the United States) to construct the solar fryer is about $100 dollars, but the estimated cost for bulk manufacturing is only about $25. Most of the construction requires only hand tools, which is ideal for local production in East Africa. The design is scalable, making it relatively easy to construct smaller or larger fryers, if desired.

Reference:

Alan Gallagher, *Solar Energy* **85**, 496–505 (2011).

Fellows Probe the New Turf



Strontium (Sr) atoms loaded in egg carton-shaped energy wells of different depths can be used to simulate the quantum behavior of solids and other condensed matter systems. The large and small spheres represent Sr atoms in the two different electronic states used in quantum simulations. The different colors reflect different nuclear spins.

Credit: Brad Baxley, JILA

THE QUANTUM MODELING AGENCY

"Nature is built quantum mechanically," says Fellow Jun Ye, who wants to understand the connections between atoms and molecules in complex systems such as liquids and solids (aka condensed matter). He says that the whole Universe is made of countless interacting particles, and it would be impossible to figure out the myriad connections between them one particle at a time, either theoretically or experimentally.

Fortunately, in 1986 Richard Feynman envisioned a work-around for the challenge of understanding complex systems one particle at a time: He suggested building quantum mechanical simulators complete with well-understood knobs to control the interactions in the system, then sitting back and watching the system evolve.

"The idea is to let Nature solve the problem," Ye explains. "You can assemble precisely controlled atoms or molecules to mimic complex materials, add in well-defined interactions between particles, and then watch the system dynamics unravel themselves. For example, the state of the matter might jump from one configuration to another simply because of quantum fluctuations."

Ye will soon get a chance to try his hand at building a quantum simulator, thanks to Fellow Ana Maria Rey and her theorist colleagues from the University of Colorado, Harvard, the Joint Quantum Institute, the Harvard-Smithsonian Center for Astrophysics, and the University of Innsbruck. Rey and her colleagues have come up with a "perfect simulator of condensed matter systems" made from ultracold alkaline earth atoms. One such atom, strontium (^{87}Sr), is already famous for its roles in the Ye group's creation of a high-accuracy optical atomic clock and the Jin group's creation of both the world's first degenerate quantum gas of fermions and the first fermionic condensate. Alkaline earth atoms may also one day play a role in quantum information processing (See *JILA Light & Matter*, Spring 2009).

When alkaline earth atoms are loaded in optical lattices (egg carton-shaped energy wells formed by interacting laser beams), they can be used as quantum simulators of many-body phenomena, according to Rey and her colleagues. They have shown that one of the features of alkaline earth atoms is particularly important for creating quantum simulators: the nuclear spin states of alkaline earth atoms are decoupled from the states of their two valence electrons. This decoupling means that the atoms can be used to create relatively large systems with an unprecedented degree of symmetry, something that is very attractive for a laboratory quantum simulator.

The proposed quantum simulator would allow researchers to simultaneously study ^{87}Sr atoms in the ground state and in a stable optically excited state. The atoms would be placed in different optical lattices; the lattice filled with ground-state atoms could be moved relative to the stationary lattice containing the optically excited atoms. The two optical lattices could be prepared either deeper or shallower as compared to one another. This setup would make it possible to investigate interactions of the behavior of electron orbitals, nuclear spin states, and electron charge as the spins of the valence electrons are adjusted.

The new quantum simulator promises to open the door to understanding the physics of some very exotic materials, including (1) heavy fermion materials, which become surrounded by so many positively charged particles during spin flipping that they get too heavy to move, (2) spin liquids predicted to form during the magnetic ordering of excited alkaline earth atoms, (3) exotic high-temperature superconductors, and (4) ^{87}Sr atoms that act like anyons when cooled to 100 pK. Anyons are weird particles with fractional charges that seem to be something in-between a boson and a fermion.

If all this isn't enough, the quantum simulator could even make alkaline earth atoms interact with a Bose-Einstein condensate (BEC), causing the formation of vortices in the BEC when the atoms formed a spin liquid. Richard Feynman would be proud.

Jun Ye is excited. "Ana Maria has proposed a very challenging, but doable experiment for us to do in the future," he says, noting that he can employ the precision measurement technology he uses with the optical atomic clock to control the quantum simulator. "This is a very exciting exchange between theory and experiment that is leading us in new scientific directions."

References:

V. Gorshkov, M. Hermele, V. Guarie, C. Xu, P. S. Julienne, J. Ye, P. Zoller, E. Demler, M. D. Lukin, and A. M. Rey, *Nature Physics* **6**, 289–295 (2010).

Michael Hermele, Victor Guarie, and Ana Maria Rey, *Physical Review Letters* **103**, 135301(4) (2009).

Graduate student Allison Churnside and Fellow Tom Perkins use a focused laser beam to identify a purple membrane patch for further study with an atomic force microscope.

Credit: Brad Baxley, JILA

The Guiding Light

Atomic force microscopy (AFM) just got a whole lot more efficient for studying proteins and other biomolecules. Graduate student Allison Churnside, former research associate Gavin King, and Fellow Tom Perkins recently used a laser to detect the position of sparsely distributed biomolecules on a glass cover slip. Since the same laser is also used to locate the AFM tip, it is now possible to align the microscope tip and sample with a precision of 40 nm — before the AFM tip even touches the sample. The researchers say that the new sample detection scheme solves the “needle in a haystack” problem of nanoscale microscopy.

Until now, scientists employing AFM to study nanostructures had to use a kind of brute-force method to locate a single sample on a microscope substrate more than a million times bigger than the target biomolecule. The brute-force method involves rapidly scanning back and forth across the stage until the tip encounters something interesting. There are several problems with this method: (1) Since an AFM tip is only a few atoms wide, it is delicate and easy to break. (2) It's easy to contaminate an AFM tip with unwanted atoms or molecules encountered during the scan, and AFM tips can form chemical bonds with both contaminants and biomolecules. Such chemical bonds could be a big advantage in studies of individual membrane proteins, for example, but only if the risk of tip contamination is low. (3) Biological samples, such as proteins or membranes, can be damaged by uncontrolled collisions with an AFM tip. A squished sample defeats the purpose of investigating intact biological nanostructures.

The new laser-detection system protects both the AFM tip from physical damage and contamination as well as the sample from harm. Plus, it's much more efficient. “From a practical perspective, instead of Alison starting to do real science at 4 p.m. after she's spent most of a day looking for a good sample, she can start doing science at 10 a.m.,“ Perkins says. From here on, Perkins expects the use of AFM to be less frustrating and more likely to lead to interesting scientific results. For example, Churnside recently employed a focused laser beam to optically detect a purple membrane patch, which she then studied in more detail using AFM.

“Now we can use our new optical method to find a structure that looks like what we want to study, then drop the AFM tip and land “dead on” the exact spot we're seeing,” Perkins says. As the new technique becomes more refined, he expects to be able to “see” smaller and smaller things. Currently, the lateral resolution of optical images is ~200 nm, a resolution that is set by the diffraction limit for optical microscopy. Nevertheless, optical images can “resolve” patches of purple membrane that are only 6 nm tall. The enhanced height resolution is due to the ability to distinguish the average height of a patch rather than having to distinguish two closely spaced objects, as must occur in lateral resolution. The Perkins group expects to be able to refine the vertical resolution down to ± 1 nm or less.

Reference:

Allison B. Churnside, Gavin M. King, and Thomas T. Perkins, *Optics Express* **18**, 23924–23932 (2010).

Ionize Me!

Plucking the two electrons out of a helium atom should allow researchers to study how helium atoms interact during a double ionization process — at least in theory. Recently, Fellow Andreas Becker explored whether an ultrashort vacuum ultraviolet (VUV) laser pulse could be used to probe the interactions of helium's electrons during a double ionization in the presence of an intense infrared (IR) laser field. Becker collaborated with research associate Shaohao Chen and a colleague from the Centro de Laseres Pulsados Ultraintensos Ultracortos (Salamanca, Spain) on the project.

Becker hoped that by monitoring the intricate dance of electrons during ionization, he could open the door to a better understanding of electron dynamics not only in atoms, but also in molecules, and larger structures. However, as often happens in fundamental research, monitoring the behavior of electrons during ionization of a helium atom turned out to be more challenging than expected. Rather than probing the dance of electrons, the VUV laser pulse induced new dynamics into the ionization process that couldn't be separated from what was occurring in response to the IR laser field.

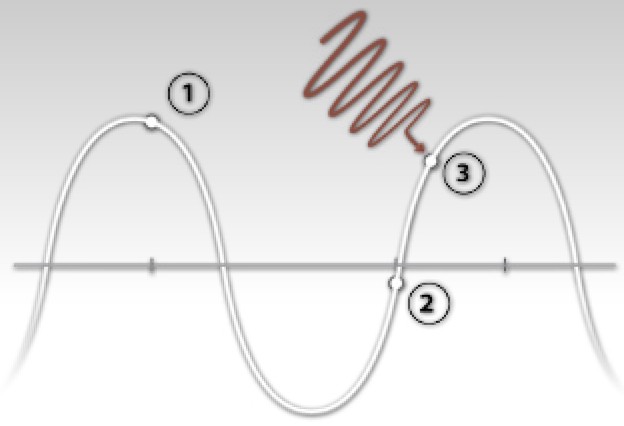
For instance, the researchers had hoped to better understand the behavior of excited states of a helium atom (He^+) that had lost one of its electrons, but they were unable to find a trace of the excited states of He^+ among all the other signals in their models of the interaction of the IR and VUV pulses. They also hoped to be able to use the VUV pulse to control the effects of the IR laser on helium ionization. Instead, they found that they could use the IR pulse to control the fate of an electron set free by the VUV pulse!

The researchers also learned that after an IR laser had knocked one electron out of the atom (exciting the second electron), a VUV pulse could easily knock the second electron out of the atom. Since the IR laser by itself can cause a double ionization, this finding underscored the complexity of the system Becker and his colleagues were trying to study.

Part of the difficulty was that the researchers are as yet unable to perform the full six-dimensional calculation required to fully model the double ionization of a helium atom. Becker and his colleagues are currently working to improve their three-dimensional model by expanding it into four and then five dimensions. They also plan to continue to investigate correlations between the two electrons during laser illumination.

Reference:

Shaohao Chen, Camilo Ruiz, and Andreas Becker, *Physical Review A* **82**, 033426(7) (2010).

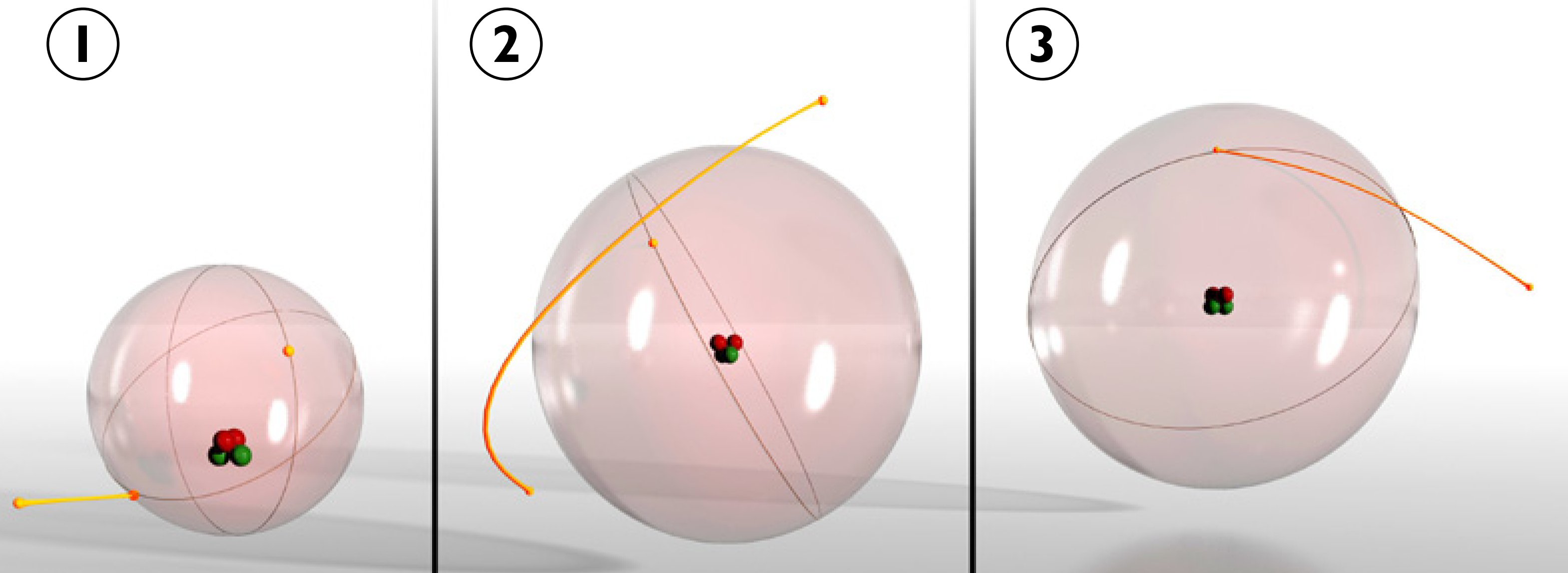


Oscillation (white) of an intense infrared (IR) laser field as two electrons are removed from a helium atom. The numbers correspond to the behavior of the electrons shown in the other figures. The red pulse is the vacuum ultraviolet (VUV) pulse that is used to probe the excited state of the second electron after the free electron recollides with the helium ion.

① When the IR field reaches its peak intensity, it rips the first electron out of the helium atom.

② The free electron swings back by the nucleus of the helium ion, excites the ion, and escapes.

③ The VUV pulse easily knocks the second electron out of the helium ion before the IR pulse can ionize it.



Credit: Brad Baxley, JILA

Artist's concept of a puffed-up "Hot Jupiter" orbiting very close to its fiery star.

Credit: *NASA/JPL-Cal tech/T. Pyle (SSC)*

PUFF THE MAGIC PLANET

Hot Jupiters — giant gas planets orbiting close to their parent stars — aren't just scorched (at temperatures of >1000 K). They are also swollen up larger than can be explained by the intense heat from their host stars. Recently, Fellow Rosalba Perna and her colleagues from Columbia University and the Kavli Institute for Theoretical Physics suggested a reason why these planets are so puffed up: The swelling results from heat dissipated from electric currents generated by the interaction of robust magnetic fields (generated from deep within the giant planets) with strong atmospheric winds carrying charged particles called ions.

Ionization in the winds occurs as a result of the tidal locking of the planets to their parent stars. This tidal locking keeps one side of the planet facing the blistering stellar heat. The heat is intense enough to literally strip electrons from some of the atoms and molecules in the planet's atmosphere, creating ions that blow in the winds.

When ionized atmospheric winds cross a hot Jupiter's magnetic field lines, the magnetic lines bend, inducing electric currents that give off enough heat to puff up the planet. Because this heat is produced in the deepest layers of a hot Jupiter's atmosphere, it can substantially modify the evolutionary path of these planets and account for their large sizes. The amount of heat produced deep in the atmosphere could equal as much as, or even more than, 1% of the heat due to the nearby star, which affects mostly the outermost regions of the planets, according to Perna and her colleagues.

The researchers showed how this process works with a three-dimensional model of the atmospheric circulation of a real hot Jupiter (HD 209458b, the first transiting planet[1] discovered outside the solar system). Their model showed that the dissipation of the electric currents caused by the interaction of HD 209458b's magnetic field lines with its weakly ionized atmospheric winds could indeed heat up the atmosphere enough to account for the planet's increased bulk if the planet's magnetic field strength was at least 10 Gauss (as compared to Earth's magnetic field strength of 0.5 Gauss at its surface).

This calculated magnetic field strength for a hot Jupiter falls in the middle of the range of magnetic field strengths (4.2–14 Gauss) measured for the planet Jupiter in our own solar system. However, it is still difficult to determine the magnetic field strengths for planets outside the solar system, both observationally and theoretically. While observations of hot Jupiters continue, Perna and her collaborators are also enhancing their atmospheric circulation model with winds that consistently incorporate ionization, magnetic drag, and dissipation of electric currents. They are also developing evolutionary planet models that include the newly discovered source of heat.

References:

Rosalba Perna, Kristen Menou, and Emily Rauscher, *The Astrophysical Journal* **719**, 1421–1426 (2010).

Rosalba Perna, Kristen Menou, and Emily Rauscher, *The Astrophysical Journal* **724**, 313–317 (2010).

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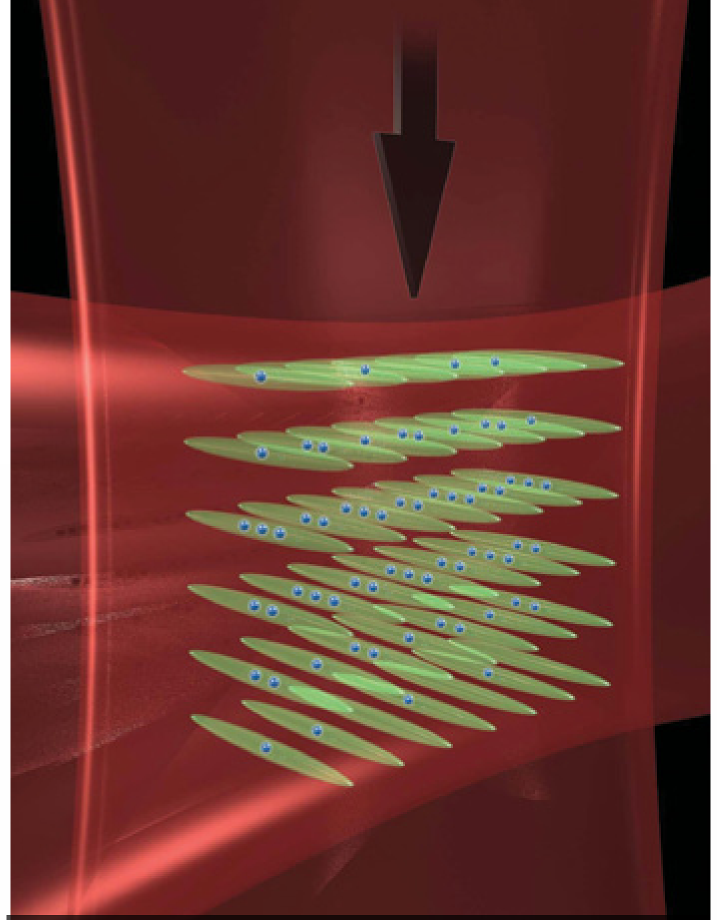
[1] A transiting planet is one that passes in front of its parent star while the star is being observed by an Earth- or space-based telescope.

Strontium Clock Performance Skyrockets

Quantum Paradox Derails Unwanted Collisions



A two-dimensional–cigar-shaped trap reduced the frequency shifts due to collisions between fermions by 50-fold.

Credit: Brad Baxley, JILA

In 2008-2009, much to their amazement, researchers working on the Jun Ye group's neutral Sr optical atomic clock discovered tiny frequency shifts caused by colliding fermions! They figured out that the clock laser was interacting slightly differently with the Sr atoms inside a one-dimensional (pancake-shaped) trap. The light-atom interactions resulted in the atoms no longer being identical. And, once they were distinguishable, formerly unneighborly atoms were able to run into each other, compromising clock performance (See *JILA Light & Matter*, Spring 2009).

Ever since this discovery, the Ye group has been looking for strategies to reduce the number of atom-atom collisions and the resulting frequency shifts. Now, thanks to help from theorist Ana Maria Rey, the group has solved the problem of colliding fermions. In solving the problem, a team led by research associate Matt Swallows reduced the inaccuracy of the optical atomic clock arising from atomic collisions by 50-fold, reaching the level of 1×10^{-17}! This result has eliminated the need for compromise between precision and accuracy in the on-going development of the group's Sr-lattice clock, which uses many quantum particles.

In addition to Swallows, Rey, and Ye, the clock team included graduate students Michael Martin, Michael Bishof, and Sebastian Blatt as well as a visiting scientist Yige Lin. The team was presented with a JILA Scientific Award in August of 2010 for their accomplishment. Their breakthrough research was published online in *Science Express* on February 3.

To stop the fermions from colliding, the team used a new two-dimensional trap design that ensures strong interactions among the atoms. Paradoxically, strong interactions actually suppress collisions among the Sr atoms! Here's how: When Sr atoms are first loaded into the clock's optical traps, they are identical and cannot collide. However, when the Sr atoms interact with the clock laser, some of them enter slightly different states and become distinguishable. Once they're distinguishable, they can collide.

In the old pancake trap, the atoms interacted weakly and had no trouble jumping back and forth between identical and distinguishable states. However, when atomic interactions get strong enough, a large energy gap appears between the two states. The energy gap prevents identical atoms from becoming distinguishable and colliding. It's as if all the Sr atoms are forever frozen in identical states.

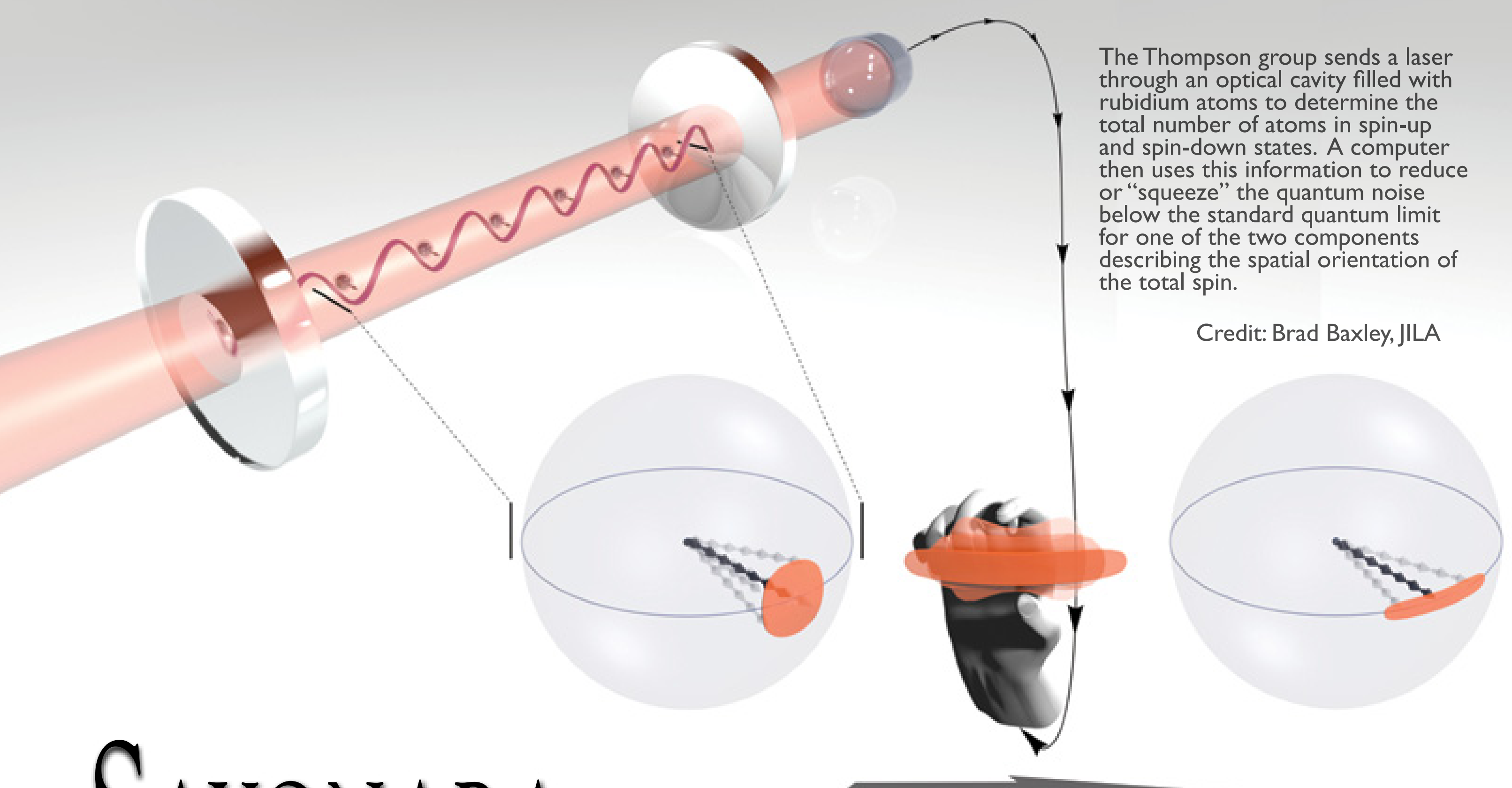
To create this quantum effect, Swallows and his colleagues sliced up the original pancakes with another laser beam, creating optical tubes that look like cigars. This trap confines the Sr atoms tightly. In fact, it squeezes the atoms so much that they enter the strongly interacting regime. It doesn't push them as far into the new regime as possible, but it's far enough to suppress most, if not all, of the frequency shifts.

The new method should work even better in a trap with a larger number of atoms, because the suppression effect becomes more effective as the number of atoms per site and thus the interaction strength increases. Now that they understand the quirky quantum mechanical behaviors of their clock atoms, Ye and his colleagues are working on developing a faster, more stable clock laser that is expected to further increase the clock's accuracy and precision.

References:

Matthew D. Swallows, Michael Bishof, Yige Lin, Sebastian Blatt, Michael J. Martin, Ana Maria Rey, and Jun Ye, *Science* **331**, 1043–1046 (2011).

G. K. Campbell, M. M. Boyd, J. W. Thomsen, M. J. Martin, S. Blatt, M. D. Swallows, T. L. Nicholson, T. Fortier, C. W. Oates, S. A. Diddams, N. D. Lemke, P. Naidon, P. Julienne, Jun Ye, A. D. Ludlow, *Science* **324**, 360–363 (2009).



The Thompson group sends a laser through an optical cavity filled with rubidium atoms to determine the total number of atoms in spin-up and spin-down states. A computer then uses this information to reduce or "squeeze" the quantum noise below the standard quantum limit for one of the two components describing the spatial orientation of the total spin.

Credit: Brad Baxley, JILA

SAYONARA DEMOLITION MAN

The secret for reducing quantum noise in a precision measurement of spins in a collection of a million atoms is simple: Premeasure the quantum noise, then subtract it out at the end of the precision measurement. The catch is not to do anything that detects and measures the spins of individual atoms in the ensemble. If states of individual atoms are measured, then those atoms stop being in a superposition, and the subsequent precision measurement will be ruined.

So, whatever measurement technique is used, it must be a nondemolition measurement that doesn't alter the quantum state of specific atoms. It must also preserve coherence, i.e., the quantum mechanical phase of each atom before they are probed. If all this sounds hard, that's because it is. However, Fellow James Thompson and graduate students Zilong Chen, Justin Bohnet, Shannon Shankar, and Jiayan Dai recently succeeded in making a precision coherence-preserving quantum nondemolition measurement of a million cold rubidium (^{87}Rb) atoms inside an optical cavity.

"If we were trying to investigate Schrödinger's cat (which exists inside a box in a superposition between being alive and being dead)," Thompson says. "We'd be trying not to open the box while we were figuring out what's in there. What we do with our atom ensembles is like putting lots of cats in one box and counting the yowls. We can tell how many cats are still alive, but not which cats!"

The Thompson's group's "yowls" are all the signals from the energy levels of the ^{87}Rb atoms. Its "box" is an optical cavity that uses an optical lattice to keep the ^{87}Rb atoms well localized between two mirrors. There, the atoms interact, or "talk" to the cavity resonances. This quantum conversation causes the cavity resonance to split into two (a phenomenon physicists call a vacuum Rabi splitting). The size of the frequency difference between the two resonances depends directly on the number of atoms in a spin-up state.

With their setup, the researchers can accurately and precisely count the total number of atoms in spin-up and spin-down states by scanning a laser across the two resonances. But, they aren't counting individual atoms, and they have no way of telling which atoms are in a particular spin state.

Coherence is preserved only to the extent that the atoms talk to the Universe via the cavity mode. Atoms love to talk to everyone, and as with a teenager, it is difficult to get them to hang up the phone. Instead of making them hang up the phone, the atoms are made to talk really quickly to the cavity mode, with the goal of finishing the conversation before the atoms have shared very much information with the rest of the Universe. This rapid interaction is accomplished by making the atoms all talk in unison to the cavity mode at a speed that is 1400 times greater than the sum of all the other conversations with the Universe.

The researchers found they could reduce quantum noise by using a longer atom-cavity conversation to measure the cavity resonances. However, a longer conversation led to a reduced signal size. Taking this tradeoff into account, the Thompson group was able to surpass the standard quantum limit on quantum phase estimation by a factor of two.

Crucially, their work demonstrated that useful entanglement could be generated in a sample of half a million atoms — comparable to the number of atoms used for state-of-the-art precision measurements. The researchers anticipate that the technique will become an important tool for quantum metrology and spur the development of more precise atomic sensors, magnetometers, rotation and inertial sensors, gravity meters, and atomic clocks.

Reference:

Zilong Chen, Justin Bohnet, Shannon Sankar, Jiayan Dai, James K. Thompson, *Physical Review Letters* **106**, 133601 (2011).

Quantum Control Room

In 2008, the Ye and Jin groups succeeded in making ultracold potassium-rubidium (KRb) molecules in their ground state (See *JILA Light & Matter*, Spring 2010). Their next goal was to figure out how to precisely control chemical reactions of these ultracold polar molecules by manipulating the quantum states of the reactants. But first the researchers had to discover how to calm those reactions down enough to study them. Under the conditions in which they were made (an optical trap allowing motion in all three dimensions), ultracold KRb molecules were so chemically reactive, they disappeared almost as soon as they were formed.

Then, with help from their theorist colleagues in the Bohn group, the researchers found out that when an electric field is present, the KRb molecules would get even more reactive. In an electric field, the fast chemical reactions started looking like explosions. Explosions are pretty cool for chemists. But they're a nightmare for experimental physicists, especially if their goal is to cool a gas of polar KRb molecules down to the temperature where all their quantum states occupy the lowest possible energy levels. This state of affairs is called quantum degeneracy. To get there, the KRb molecules have to collide, but not react.

Fortunately, research associate Goulven Quéméner and Fellow John Bohn developed a theory for seriously suppressing the reaction rate of KRb molecules. Then, a team from the Ye and Jin groups proved the method worked! The experimental team was led by Marcio de Miranda (now at the Universidade de São Paulo), research associate Amodsen Chotia, graduate student Brian Neyenhuis, and former research associate Dajun Wang (now at the Chinese University of Hong Kong). The team also included former research associate Silke Ospelkaus (now at the University of Hanover in Germany) as well as Fellows Jun Ye and Debbie Jin.

Here's what the experimental team did to slow down the chemical reactions: First, the researchers squeezed ultracold KRb molecules into a two-dimensional pancake trap. This trap forced the molecules to line up side by side with identical ends of the molecules next to each other. This step mostly prevents the molecules from aligning head-to-tail, which enhances chemical reactions in a major way because opposite ends of dipoles attract one another.

Second, the experimentalists made sure the squeezed molecules were in the same quantum state. This step is really important because KRb molecules are fermions. Fermions in the same state mostly bounce off each other rather than reacting. However, fermions that are in slightly different states can collide and react. For example, if otherwise identical fermions are rotating at different rates, they can react inside a pancake trap. Third, the Ye/Jin team turned on an electric field that increased the repulsion between the side-to-side molecules.

The new method increases the lifetime of the KRb molecules to one second. It also makes it nearly a hundred times more likely that KRb molecules will bounce off one another rather than chemically react. This important result (reported in *Nature Physics*) means that the experimental team should be able to cool their gas of dipolar KRb molecules with evaporative cooling. In evaporative cooling, repeated collisions that don't change the quantum states of the molecules will result in the gas getting colder and colder — ideally, until the gas reaches quantum degeneracy. Making a quantum degenerate gas of KRb molecules will open the door to exploring the quantum nature of dipolar molecules and their reactivity over long distances. It may even one day lead to the creation of states of matter never before seen in a laboratory!

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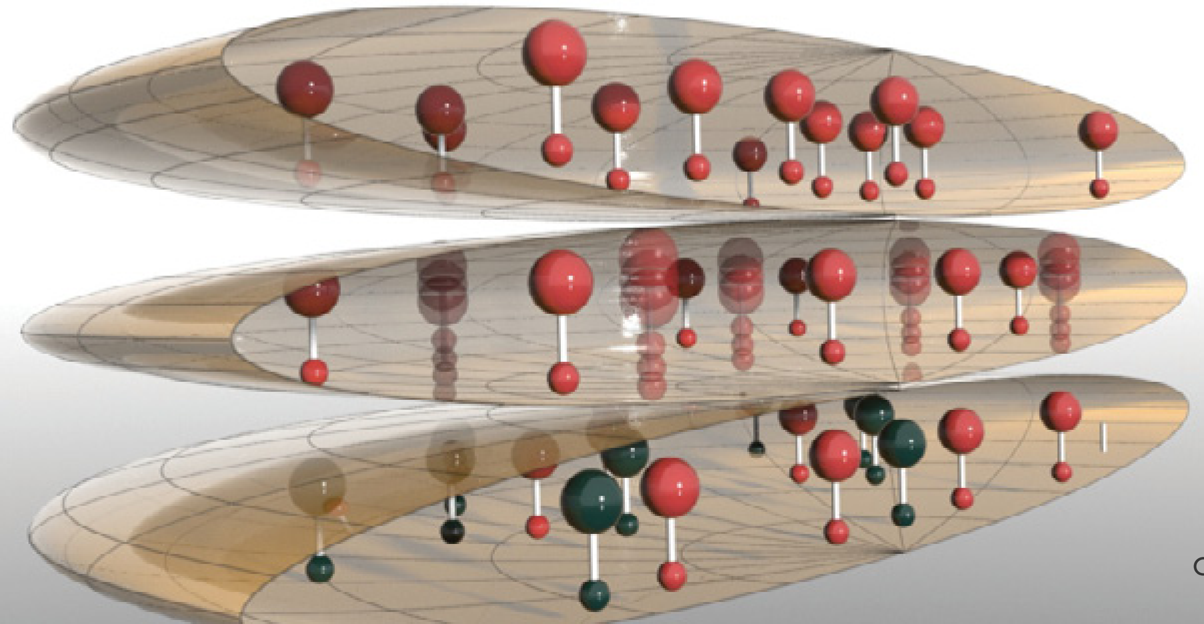
M. H. G. de Miranda, A. Chotia, B. Neyenhuis, D. Wang, G. Quéméner, S. Ospelkaus, J. L. Bohn, J. Ye, and D. S. Jin, *Nature Physics*, published online March 21, 2011, doi:10.1038/nphys1939.

Goulven Quéméner and John L. Bohn, *Physical Review A* **83**, 012705 (2011).

Goulven Quéméner and John L. Bohn, *Physical Review A* **81**, 060701 (2010).



Collisions between ultracold KRb molecules can be suppressed a hundredfold in two-dimensional pancake traps in which identical molecules are forced to line up side by side (top layer). However, some collisions can still occur if (1) otherwise identical KRb molecules are vibrating at different rates (middle layer) or (2) the KRb molecules are in different quantum states (bottom layer).

Credit: Brad Baxley, JILA

Sharing the Adventure of Science

Graduate students or research associates at JILA have the option of signing up to help teach after-school science classes to elementary and middle school students in the St. Vrain School District. The volunteers expect to stimulate the children to learn to think critically, enjoy science activities, and become confident in their own abilities to master difficult concepts. What they may not anticipate at first is that they will learn some important skills themselves, including the ability to communicate scientific concepts in everyday language and, with that new ability, gain a better understanding of education.

The program that brings young scientists from JILA together with the St. Vrain students is called Partnerships for Informal Science Education in the Community (PISEC). The after-school science program is part of the JILA NSF Physics Frontier Center (PFC). It's the brainchild of the PFC's Outreach & PISEC Program Director Dr. Laurel Mayhew, who is collaborating with CU's Physics Education Research group on developing the program.

In 2009, Mayhew and Noah Finkelstein, a CU physics professor, used the Communication in Everyday Language Assessment to evaluate improvement in the ability of PISEC instructors to communicate science concepts in everyday language. The assessment included two videotaped sessions of each of nine instructors, the first before the instructors had any teaching experience with children and the second after a semester of regular science lessons. In both the pre and post videotaped presentations, the participants were told to imagine they were teaching a lesson to a group of children 11–14 years old.

In the first set of videotapes, most study participants stood in one place, used few gestures, failed to connect the concepts they were explaining to children's lives, and used complex scientific terms to describe the concepts of motion, speed, and velocity. However, the ability of most participants to explain motion-related concepts improved significantly by the end of the semester.

The participants who taught the most classes showed the greatest improvement on the assessment. One participant, who performed much better the second time, had helped teach 6 hour-long classes of 15 fourth graders. At the end of the semester, he effectively used the example of an exciting snowball fight to teach the concept of velocity. In contrast, two participants whose scores declined in the post assessment had acquired no new teaching experience during the semester.

Mayhew and Finkelstein are currently working on improving and validating their Communication in Everyday Language Assessment.

Reference:

Laurel M. Mayhew and Noah D. Finkelstein, *Proceedings of the Physics Education Research Conference 2009*, held in Ann Arbor, Michigan: July 29–30, 2009, AIP Conference Series 1179, p. 205–208.

Kudos to...

Carl Lineberger for his upcoming nomination by President Obama to the National Science Board, one of the nation's most important science policy organizations.

Tom O'Brian for being awarded the NIST Gold Medal "for leadership in developing and disseminating the nation's standard of civilian time, the world's most precise measurement of any kind."

Jun Ye for being selected as the 2011 Frew Fellow by the Australian Academy of Science. He will present the Frew Lecture at the Australasian Conference on Optics, Lasers, and Spectroscopy (ACOLS), which is incorporated in the International Electronic Conference/CLEO Pacific Rim 2011 meeting to be held in Sydney, Australia, from August 29 to September 1, 2011.

Steve Cundiff for winning the Optical Society of America's Meggers Award.

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