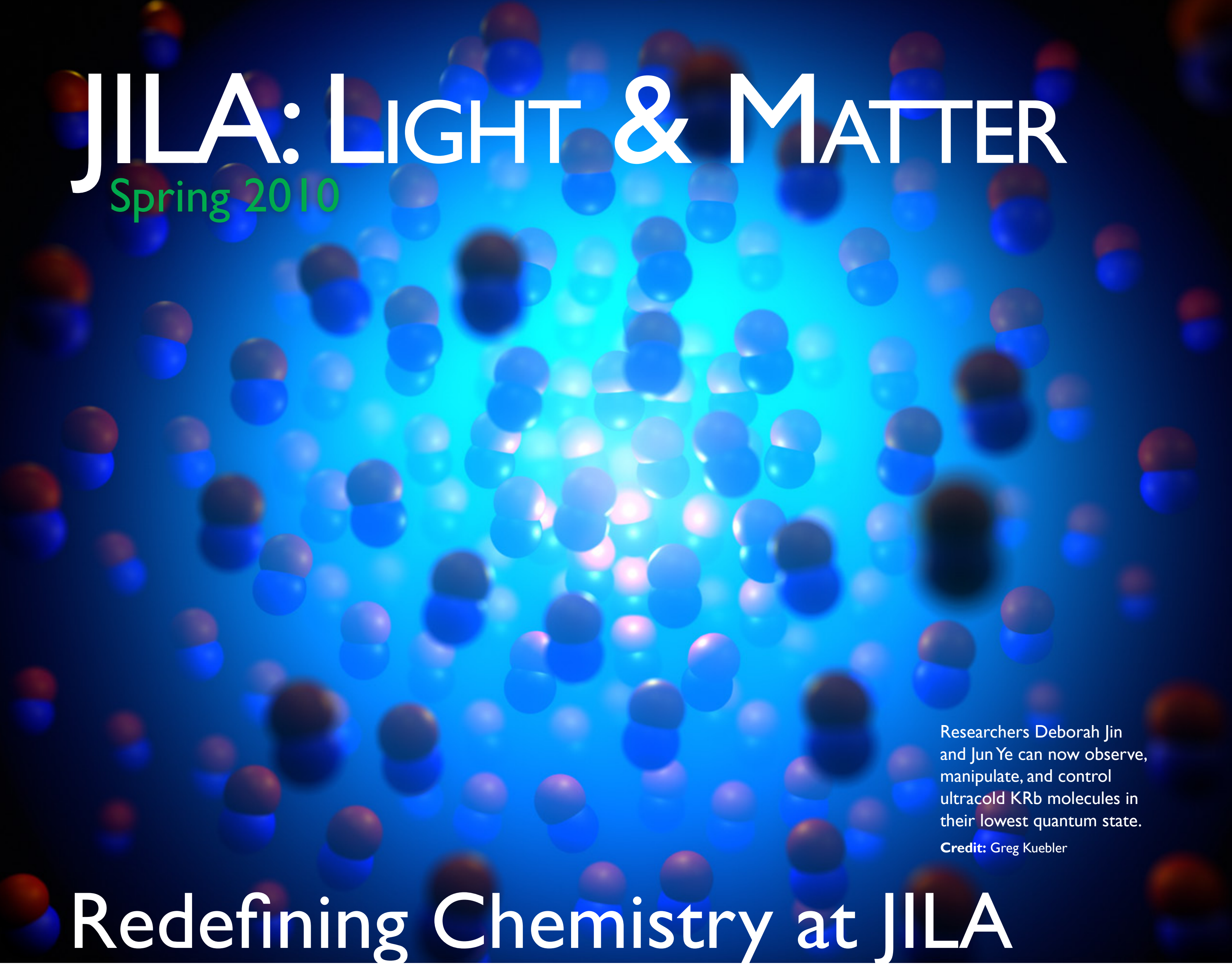
JILA: LIGHT & MATTER
Spring 2010



Researchers Deborah Jin and Jun Ye can now observe, manipulate, and control ultracold KRb molecules in their lowest quantum state.

Credit: Greg Kuebler

Redefining Chemistry at JILA

Fellows Deborah Jin, Jun Ye, and John Bohn are exploring new scientific territory in cold-molecule chemistry. Experimentalists Jin and Ye and their colleagues can now manipulate, observe, and control ultralow-temperature potassium-rubidium (KRb) molecules in their lowest quantum-mechanical state. Theorist Bohn analyzes what the experimentalists see and predicts molecule behaviors under different conditions. No other group in the world has even succeeded in making molecules like these, much less observing them collide and undergo chemical reactions at temperatures just three-hundred billionths of a degree above absolute zero.

For its part, the JILA cold-molecule collaboration is charging ahead in its quest to understand the new form of matter created just one and a half years ago (see "The Polar Molecule Express" in the Fall 2008 issue of *JILA Light & Matter*). The collaboration's success is underscored by three seminal papers published between January and April of 2010 in *Physical Review Letters*, *Science*, and *Nature*. Team members responsible for this avalanche of discovery include former research associate Silke Ospelkaus (now at Germany's Max Planck Institute for Quantum Optics), former graduate student Kang-Kuen Ni (now a postdoc at CalTech), research associates Dajun Wang and Goulven Quéméner, graduate students Marcio de Miranda and Brian Neyenhuis, and theorist Paul Julienne of NIST's Joint Quantum Institute.

In 2009, Ospelkaus and the experimental team overcame major technical challenges to create ultracold KRb molecules in their lowest quantum-mechanical state. While it was a feat to create ultracold molecules in their lowest rotational and vibrational states, it proved to be even more challenging to move all the molecules into the lowest of 36 possible nuclear spin states. However, the team eventually developed a method that allowed them to prepare molecules either in the lowest-energy nuclear spin state or in a coherent superposition of selected spin states. The secret was figuring out how to use an interaction in an excited rotational state of the polar molecules to couple the molecules' nuclear spins with their rotations. Then, by zapping the molecules with two different wavelengths of microwave radiation, the team could move all the molecules into their quantum-mechanical ground state. This accomplishment was reported in the January 22, 2010, issue of *Physical Review Letters*.

Story continues on pg 2

Redefining Chemistry at JILA

Story continued from pg 1

Silke Ospelkaus in the cold molecule lab.
Credit: Greg Kuebler

The ability to create ultracold KRb molecules in their lowest quantum-mechanical state made it possible for the team to observe the behavior of the molecules colliding, as well as breaking and forming chemical bonds. This achievement was reported by Ospelkaus and colleagues in the February 12 , 2010, issue of *Science*, where the researchers described the first-ever study of the chemistry of ultralow-temperature KRb molecules.

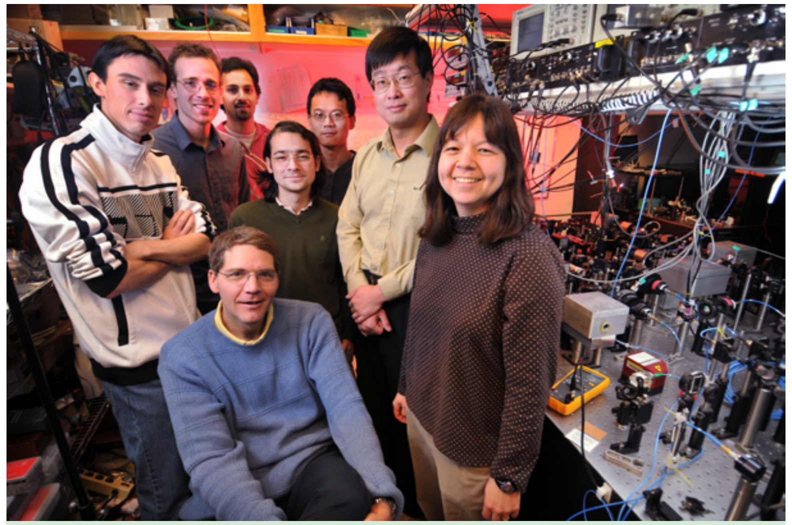
At ultralow temperatures, the molecules manifest themselves mostly in quantum mechanical waves, instead of behaving like ordinary particles. The molecular waves extend long distances inside a gaseous cloud. The behavior of molecules at ultralow temperatures includes chemistry, but chemistry in a strange world where the laws of quantum mechanics prevail.

The team observed molecular interactions that led to the breaking and formation of chemical bonds between atoms. These observations were possible because the researchers were able to control every aspect of the energy and motion of the molecules.

"What controls ultracold collisions is the nature of the molecules themselves," Ye said. "It depends on whether the molecules are fermions or bosons."

Neighborly bosons happily pile up in the same place at ultralow temperatures. When bosons get close to each other, they collide, forming new chemical bonds or breaking old ones. In contrast, the independently minded fermions cannot share the same piece of real estate. So when these standoffish molecules approach each other, they can only get so close before they start warily circling around each other. But even so, some pairs of these molecules can still manage to slowly form new chemical bonds.

Kang-Kuen Ni practicing her physics skills at home.
Credit: Kang-Kuen Ni



Today's cold molecule team (counterclockwise from bottom left): John Bohn, Deborah Jin, Jun Ye, Dajun Wang, Marcio de Miranda, Amodsen Chotia, Brian Neyenhuis, Goulven Quéméner.
Credit: Glenn Asakawa

"At some point while fermionic molecules are dancing around each other, the molecules may quantum mechanically tunnel through the barrier between them and undergo a chemical reaction," Jin explained. She added that her work with Ye and Bohn has shown that the chemistry of ultracold molecules is far richer than anticipated.

For instance, the team was able to adjust its experiment to allow collisions between KRb molecules, all of which are fermions. The secret was preparing two groups of KRb molecules that were different from each other in terms of the energy state of their nuclei. Both sets of molecules were still fermions, but they were no longer identical. In this system, the identical fermions that got close together still circled around each other as before. However, nonidentical fermions collided with each other head on, resulting in reaction rates that were 10–100 times faster.

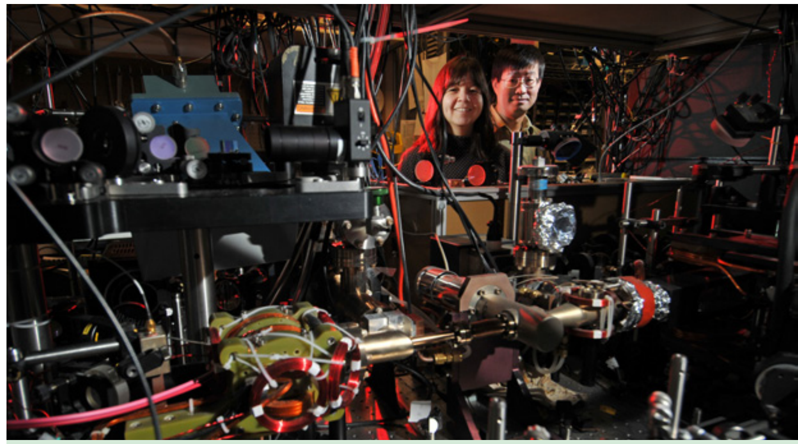
At first, it surprised Jin and Ye that such relatively fast reaction rates could occur at ultralow temperatures. However, they realized that these molecules are like waves and can overlap with each other even when they are far apart.

"When molecules are waves, their sphere of influence is much, much bigger than when they are particles," Ye explained, adding that the collisions and reactions were occurring with pairs of molecules. "When we lower the temperature of KRb molecules even further, we expect to see other exotic quantum-mechanical behaviors, including chemical reactions influenced by an entire gas in a collective fashion."

The next step, however, was an investigation of KRb collisions in a modest applied electric field. An electric field can increase the KRb molecules' electric dipole moment, or charge separation between the slightly more negatively charged K atom and the slightly more positively charged Rb atom. The capability of tuning the strength of the dipole moments is expected to make it possible to control ultracold chemical reactions and create novel ultralow-temperature structures.

With the assistance of theorist John Bohn and his group, the team, now with Ni leading the effort, was able to observe a dramatic increase in the molecule collision rate when an electric field was applied. This rate increase was directly tied to the strength of the induced electric dipole moment in the molecules. The effect was so strong that the creation of a long-lived cloud of polar molecules may require a two-dimensional optical trap to suppress the influence of the attractive head-to-tail dipolar interactions. Nevertheless, these early results showed how long-range dipolar interactions can be used for electric-field control of chemical reaction rates at ultralow temperatures. The work on dipolar collisions in the quantum world was reported in the April 29, 2010, online issue of *Nature*.

The amazing thing is that the three new experiments reported here make up just the first chapter in an entirely new book being written at JILA on ultralow-temperature chemistry.



Deborah Jin and Jun Ye in the cold molecule lab.
Credit: Glenn Asakawa

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S. Ospelkaus, K.-K. Ni, G. Quéméner, B. Neyenhuis, D. Wang, M. H. G. de Miranda, J. L. Bohn, J. Ye, and D. S. Jin, *Physical Review Letters* **104**, 030402(4), 2010.

S. Ospelkaus, K.-K. Ni, D. Wang, M. H. G. di Miranda, B. Neyenhuis, G. Quéméner, P. S. Julienne, J. L. Bohn, D. S. Jin, J. Ye, *Science* **327**, 853–857 (2010).

K.-K. Ni, S. Ospelkaus, D. Wang, G. Quéméner, B. Neyenhuis, M. H. G. di Miranda, J. L. Bohn, J. Ye & D. S. Jin, *Nature* **464**, 1324–1328 (2010).

Freeze Frame

The cold-molecule collaboration has developed a method for directly imaging ultracold ground-state KRb molecules. Their old method required the transfer of ultracold KRb molecules into a Feshbach state, which is sensitive to electric and magnetic fields. Thus researchers had to turn off the electric field and keep the magnetic field at a fixed value during the imaging process. However, the team recently began to probe the influence of changing electric and magnetic fields on the behavior of ultralow-temperature KRb molecules. Consequently, the researchers wanted to directly image ultralow-temperature KRb molecules in the ground state. However, the complex energy-level structure of molecules made the task of directly imaging molecules much more challenging than for atoms.

A collaboration team led by research associate Dajun Wang met this challenge. To do so, Wang had to find a molecular transition sensitive to a particular frequency of laser light. Then, he had to conduct experiments to determine how the molecules and photons interacted, including determining the laser intensity to use. The laser had to be intense enough so that most of the molecules in a ultracold molecular gas would absorb at least one photon. Then by counting the photons missing from the laser beam, the team could determine the number of molecules in the cloud.

But, the laser couldn't shine too brightly or it would create noise due to the extra photons, and the molecular signal would get lost. It took Wang months to solve these two problems. He had help from graduate students Brian Neyenhuis and Marcio de Miranda, former graduate student Kang-Kuen Ni, former research associate Silke Ospelkaus, and Fellows Deborah Jin and Jun Ye.

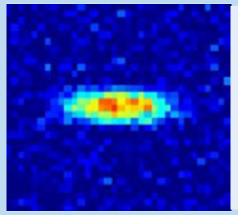


Image of 39,000 ultralow-temperature KRb molecules in their ground state taken 2 ms after the molecular cloud began to expand after its trap was turned off.
Credit: Dajun Wang

Finally, the team found the right combination of frequency and intensity to get direct images of the ground-state molecules. To image the molecules, Wang shined a 658 nm laser at a cloud of KRb molecules in their ground state. Molecules absorbed photons from this pulse, creating a shadow image. Then to reduce background noise, Wang shined a second pulse of the same wavelength on the same apparatus without any molecules. By subtracting shadow image created by the first pulse from the light image, Wang got a good picture of the ground-state molecules.

Next, Wang and his team did experiments to see what they could learn with the new technique. They found that if they aimed their laser pulses at an ultracold molecule cloud and turned off the trap (which lets the cloud expand), they could determine the momentum and position distributions of molecules in the original cloud. One of a series of pictures taken during the cloud's expansion (after 2 ms) is shown here.

The experiments included the imaging of molecules under an arbitrary combination of electric and magnetic fields. Thus, the team achieved what it set out to do. From now on, direct imaging should be a powerful tool for studying molecular quantum gases.

Reference:

D. Wang, B. Neyenhuis, M. H. G. de Miranda, K.-K. Ni, S. Ospelkaus, D. S. Jin, and J. Ye, *Physical Review Letters*, submitted.

Good Vibrations

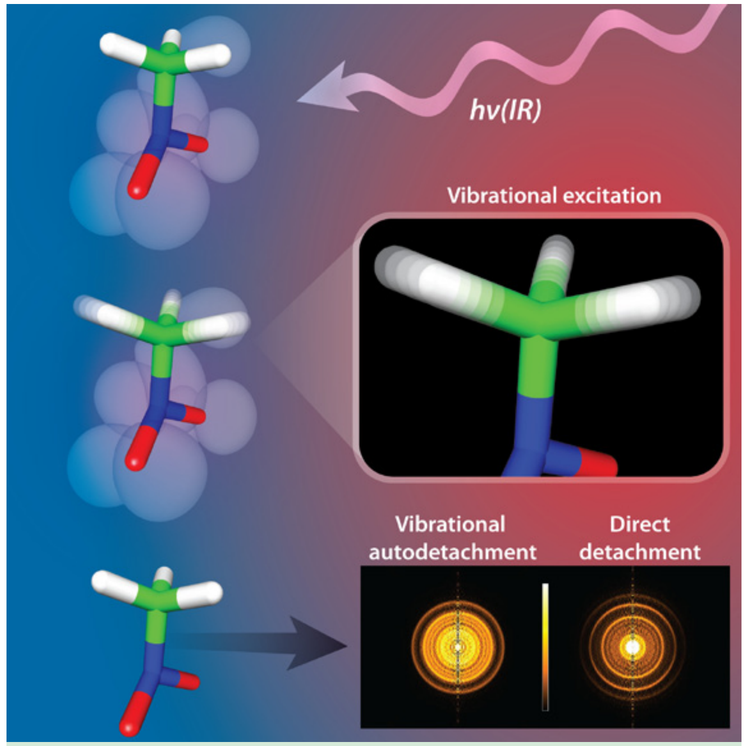
Mathias Weber and his team recently did the following experiment: They excited the methyl group (CH$_3$) on one end of nitromethane anion (CH$_3$NO$_2^-$) with an infrared (IR) laser. The laser got the methyl group vibrating with enough energy to get the nitro group (NO$_2$) at the other end of the molecule wagging hard enough to spit out its extra electron. The figure here, which appeared on the April 1, 2010, cover of the *Journal of Physical Chemistry A*, shows an artist's conception of the process from start to finish. The figure includes two photoelectron spectroscopic images that clearly distinguish between the loss of the extra electron due to nitro-group vibrations versus an ordinary chemical reaction.

Graduate student Chris Adams and former graduate student Holger Schneider (now a postdoc at the Paul Scherrer Institute in Switzerland) worked with Weber on this novel experiment. The experiment is a molecular analog of heat conduction, and molecular-level understanding of this kind of process is important because knowing the way in which energy flows through and gets redistributed in molecules is necessary for understanding and predicting chemical reactions.

Even before doing the experiment, the researchers suspected that the anion would end up emitting its extra electron. The other possible ways for getting rid of the excess energy were much less likely. For instance, the molecule could have fallen apart, but that route would have required more energy than the laser delivered to the molecule in the first place. The molecule could also have stopped vibrating by simply radiating its extra heat into the environment, in a process known as radiative cooling. However, radiative cooling occurs far more slowly than the vibrational detachment of the extra electron.

Consequently, the group opted to look for and study the vibrational detachment of the electron due to laser heating of the methyl end of the molecule. However, for heat to travel through nitromethane anion, the vibrations initiated by the laser in the methyl group had to couple into the nitro group. This end of the molecule is where the extra electron spends most of its time. Adams and his colleagues realized that it wouldn't take a lot of energy to dislodge this electron because it is quite weakly bound to the molecule. They also knew that if they excited their molecule in a specific way, they would be able to gather information about the processes that occur between the time when the molecule is excited by the laser and when it spits out the extra electron.

The researchers obtained enough information to model the processes they observed. They also began a new experiment in which they used an IR laser to "tickle" the methyl end of a similar, but larger, molecule, nitroethane (C$_2$H$_5$NO$_2$). This molecule also has a nitro group with a weakly bound electron at one end, but vibrations (from heating the other end) have farther to travel to get there. Eventually, these experiments will contribute to understanding heat transfer in molecular chains. This understanding could impact the design of molecular heat sinks for nanotechnology devices and the theory of combustion.

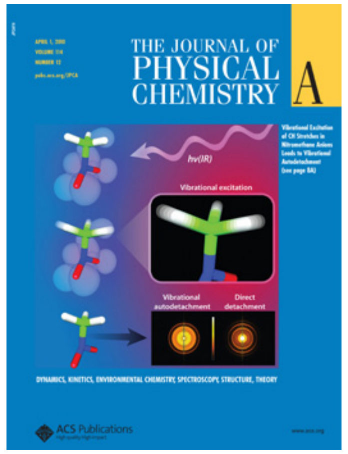


Artist's rendition of a process in which one end of a negative ion is heated with an infrared laser and the other end spits out an electron. First, the laser light is absorbed by a carbon (C) atom (green) linked to three hydrogen (H) atoms (white). Second, the three C–H bonds start vibrating furiously. Third, this vibration energy is passed along to the nitro group (a nitrogen (N) atom (blue) attached to two oxygen (O) atoms (red). Fourth, once the energy reaches the nitro group, the ion's extra electron (which hangs out with the nitro group) is ejected. Finally, the molecule calms down.

Credit: Greg Kuebler

Reference:
C. L. Adams, H. Schneider, and J. M. Weber, *Journal of Physical Chemistry A* **114**, 4017–4030 (2010).

Note: *the figure above was on the cover of the April 1, 2010, issue of J. Phys. Chem. A.*



THE JOURNAL OF PHYSICAL CHEMISTRY A

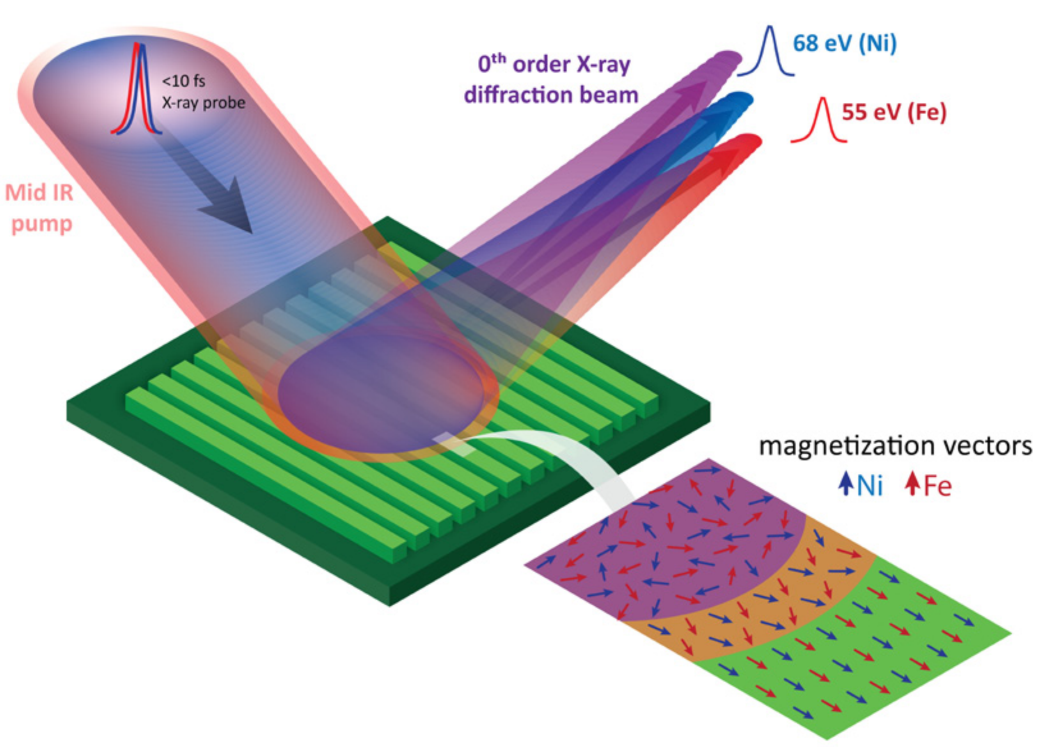
The Magnetic Heart of the Matter

Imagine being able to observe how a magnet works at the nanoscale level, both in space and in time. For instance, how fast does a nanoscale magnetic material switch its orientation? What if understanding magnetic switching might lead to the use of the spin of an electron rather than its charge to create new devices? A new method for investigating such possibilities is just beginning to be explored.

In 2009, an international research team from JILA, NIST-Boulder, and Germany used ultrafast bursts of X-rays to explore the speed with which the magnetic orientation of iron (Fe) and nickel (Ni) atoms in an 80% nickel–20% iron magnetic alloy could be destroyed by an intense infrared (IR) laser pulse. To watch this happen, the research team used a tightly focused and ultrafast (<<10 fs) tabletop X-ray strobe light to illuminate a slice of the alloy, then study the signals emitted from each element in the material, as shown in the figure.

The emitted signals came from each element's "M edge," the place from which electrons excited by a laser move into empty valence bands. The M edges are unique for each element. Consequently, the researchers were able to use reflected X-ray beams from the M edges to determine what was happening to the magnetic orientation in the Fe and Ni atoms in response to illumination by an intense IR laser pulse. By studying the X-rays reflected from the different atoms, the international research team was able to "see" how fast the magnetic orientation in each element was destroyed by the IR light pulse. The team's first-ever ultrafast observations of element-specific magnetic behavior in an alloy were accomplished with a record-setting *time resolution of 55 fs*.

JILA team members were graduate student Chan La-O-Vorakiat, former graduate student Mark Siemens (now a research associate in the Cundiff group) as well as Fellows Margaret Murnane and Henry Kapteyn. The NIST Electromagnetics Division team members were Justin Shaw, Hans Nembach, and T. J. Silva. The University of Kaiserlautern team consisted of Stefan Mathias (now a Marie Curie Fellow in the Kapteyn/Murnane group) and Martin Aeschlimann, a former JILA Visiting Fellow. Patrik Grychtol, Roman Adam, and Claus M. Schneider of the Germany's Institute of Solid State Research rounded out the collaboration.



Reflection of a burst of X-ray photons (purple) off a compound consisting of nickel (Ni) and iron (Fe). Heating the sample with an intense IR laser light pulse causes both the Ni and Fe atoms to lose their magnetic orientations, as shown in the blow-up. The process is monitored for each element with reflected X-ray photons (shown in orange for Fe and blue for Ni) that contain information about the changes in magnetic orientation.

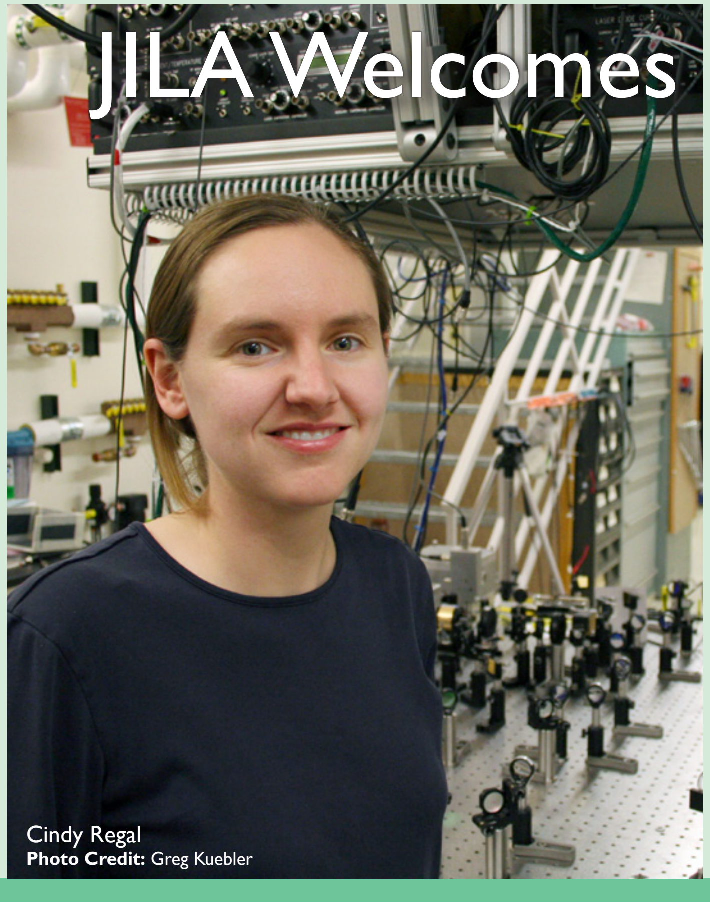
Credit: Greg Kuebler

The success of the collaboration's experiment could lead to improvements in the writing speed in information storage devices. It may also bring researchers one step closer to creating revolutionary new devices that are more energy efficient and smaller than today's electronics devices. It will definitely lead to additional experiments (with the table-top X-ray laser) aimed at understanding the magnetic behavior of such elements as Ni and Fe in magnetic compounds.

The collaboration's success has put it a step ahead of researchers who still use ultrafast lasers to explore magnetism. Ultrafast lasers can only generate a combined magnetic signal from all elements in a material. Other research groups use building-sized synchrotron facilities to produce bursts of X-rays to study magnetism and other material properties. However, these bursts are too slow (>100 fs) to probe the fastest electron motions.

Reference:
Chan La-O-Vorakiat, Mark Siemens, Margaret M. Murnane, and Henry Kapteyn; Stefan Mathias and Martin Aeschlimann; Patrick Grychtol, Roman Adam, and Claus Schneider; Justin M. Shaw, Hans Nembach, and T. J. Silva, *Physical Review Letters* **103**, 257402(4) (2009).

JILA Welcomes Fellow Cindy Regal


Cindy Regal
Photo Credit: Greg Kuebler

JILA welcomed Associate Fellow Cindy Regal in early January — about the time Instrument Shop staffers and Regal's students were putting the finishing touches on her new laboratory. When she arrived, the new Luce Assistant Professor of Physics at CU was also busy preparing to teach the junior electronics lab, which started a week later. Asked how she managed all this plus moving her family from California where she had been a postdoc in Jeff Kimball's lab at Caltech, Regal replied, "I try to be organized — and I am just quite busy."

Regal did her graduate work at JILA with Fellow Debbie Jin. She spent many long hours learning how to keep a cloud of fermions cold for long enough to allow them to interact strongly with each other. Eventually, she was able to get pairs of fermions dancing together and form a condensate. She received her Ph.D. in physics from the University of Colorado in 2006.

Her next adventure was as a postdoc in Fellow Konrad Lehnert's lab where she investigated techniques for cooling nanomechanical oscillators with microwaves, a process with many similarities to the laser cooling of atoms that is familiar in JILA. She designed chips with thin aluminum wires embedded in a microwave cavity that would allow for the detection of tiny fluctuations in the wires' motion. She and the Lehnert team also figured out how to cool these chips closer to the ground state. Her goal was to freeze out all the heat-driven motion from the oscillator, allowing her to see only quantum mechanical motion. She hoped to access and study individual phonons, or ultracold acoustic waves, which can be thought of as "sound photons."

In a second postdoc at Caltech, Regal further explored the idea of laser cooling nanomechanical oscillators while learning about quantum optics and quantum information with cold atoms. She studied atoms in scalable microcavities and whispering gallery-mode resonators as well as investigated ways to couple atoms controllably to these cavities. To pursue her interest in nanomechanics, she initiated a project to ask the question: Can a mechanical oscillator physically connected to a room temperature object be cooled to its quantum mechanical ground state? The team at Caltech found that with extremely tensioned silicon nitride and laser cooling the answer might indeed be yes. In a collaboration including her advisor Kimble and Jun Ye, who was visiting Caltech at the time, she also helped author an article on the prospects for cooling, trapping, and levitating tiny glass spheres. The ultimate physics envisioned in the latter projects are similar to how Dave Wineland's lab at NIST uses the motion of ions in quantum computing protocols. The nanomechanical systems, while unproven and in their infancy compared to trapped ions, could ultimately provide unique features in the quantum regime.

In Regal's future work, she seeks to engineer and explore new quantum systems using her knowledge of both cold atoms and nanomechanical oscillators, which she sees as potential "quantum resources." Both may be powerful in combination in hybrid cold-atom–nanomechanical systems.

Two different experiments are already underway in Regal's lab. They are designed to answer specific questions and give Regal's group the capability of experimenting with both cold atoms and nanomechanical systems. First, graduate student Adam Kaufman is developing a system for single neutral-atom trapping. His goal is to figure out how to "see" and study a single atom and perhaps even a few isolated atoms. His experiment is the starting point for work on controllable and efficient light-atom interfaces. Second, the mechanical resonators Regal used in both her prior JILA and Caltech research rely upon tension to produce high-frequency–high-quality factor mechanical oscillators. However, the mechanisms behind this phenomenon are only partially understood. To help solve this puzzle, graduate student Ben Yu and undergraduate student Ian Caldwell are investigating the material and tension dependence of quality factors for these unique "nanostrings."

Regal is married to former JILAn Scott Papp, who is currently an NRC postdoc in the Time and Frequency division at NIST. The couple has a one-year-old son, Nolan.

The Transformers: The JILA Laboratory

Fellow Cindy Regal arrived at JILA in January. But months before she arrived, she was in e-mail contact with dozens of people who were working to transform retired Fellow Alan Gallagher's 1960s-vintage space into a new lab dedicated to state-of-the art experiments in ultracold atoms and nanomechanical systems. Dave Errickson orchestrated crews of asbestos mitigators, flooring experts, electricians, plumbers, and CU facilities management staff to help Instrument Shop staffers Hans Green and Ariel Paul complete the transformation. Graduate student Adam Kaufman and undergraduate student Ian Caldwell arrived several months early to help make sure the new lab layout conformed to Regal's specifications.


Photo Credit: Hans Green

The first step in putting together Cindy Regal's new lab was emptying out the space vacated in early 2009 by retired Fellow Alan Gallagher. Soon afterwards, CU managed (and paid for) asbestos abatement and removal of the old floor tiles, leaving the bare floor seen here. A careful look at the back of the photo reveals an office (occupied by the Nesbitt group) before a wall was added to separate the two spaces.


Photo Credit: Hans Green

By October 2009, a new floor had been installed, the lab had a brand new coat of white paint on the walls (thanks again to CU). Building proctor Dave Errickson was hard at work arranging for electricians, plumbers, and CU facilities management staff to help with the "remodel."


Photo Credit: Ariel Paul

Hans Green and Ariel Paul installed green Unistrut below the lab's entire ceiling. Unistrut is used to attach electrical conduits, lights, and the aluminum frame for equipment shelves over the laser tables. Many of the benches, desks, and file cabinets on the main floor were leftovers that Regal decided to reuse.


Photo Credit: Hans Green

To the great relief of Adam Kaufman and Brian Lynch [head of the JILA (CU) supply office], the optics table is finally in place, resting on a hydraulic lift table prior to installation of its vibration-isolation legs.

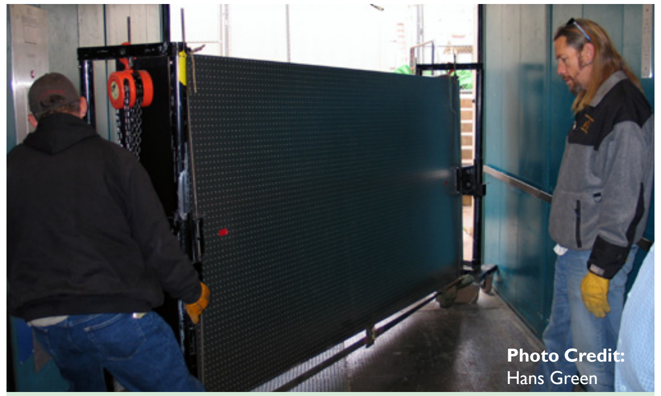


Photo Credit: Hans Green

CU's facilities management crew had a challenging time moving the new optics table. Eventually the crew managed to squeeze the table into JILA's freight elevator, which delivered the table to Regal's lab on the second floor of the B wing.

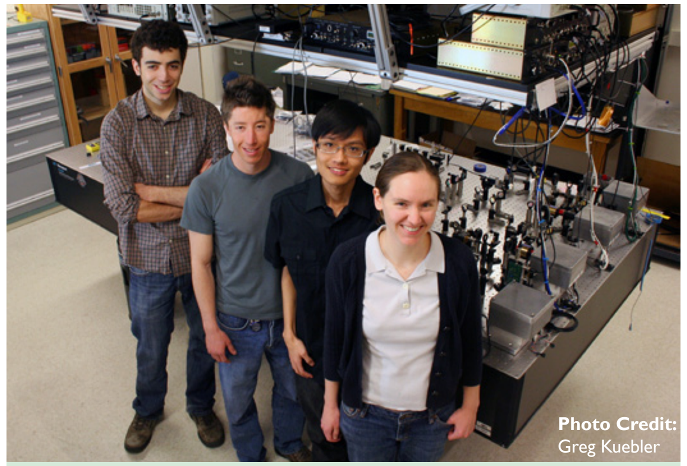


Photo Credit: Greg Kuebler

By March, Cindy Regal and her students (r–l) Ben Yu, Ian Caldwell, and Adam Kaufman have gotten the Regal lab up and running.

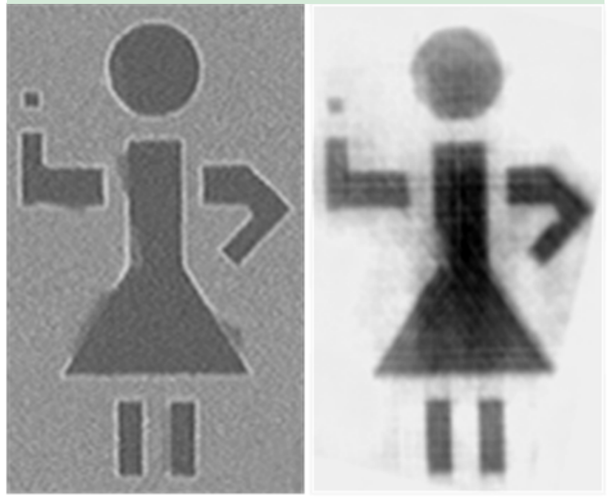
Close Encounters of the Third Dimension

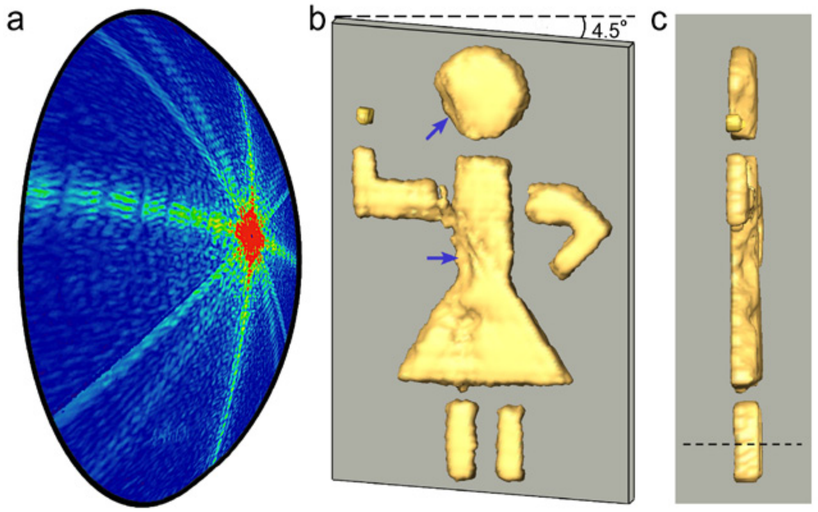
When Richard Sandberg and his colleagues in the Kapteyn/Murnane group developed a lensless X-ray microscope in 2007 (see *JILA Light & Matter*, Winter 2008), they were delighted with their ability to obtain a stick-figure image (below) that was comparable in resolution to one from a scanning-electron microscope. However, they didn't know yet that this was not all they had accomplished. Their collaborators on this work, Professor John Miao and undergraduate Kevin Raines at UCLA's California NanoSystems Institute, took the Kapteyn/Murnane group's experimental data and performed a *three-dimensional (3D)* image reconstruction of the stick figure.

This accomplishment was truly remarkable. Most schemes to determine something's 3D structure, such as crystallography and tomography, involve multiple measurements at various sample orientations. Determining an object's 3D structure from just one exposure to a single-wavelength X-ray, recorded on a *two-dimensional* image detector nearly identical to the ones in a digital camera was — well — unheard of. So when the UCLA researchers came up with a workable approach to doing just that, they had to invent a brand new name for their computer-enhanced imaging technique: ankylography, which means "curved writing."

The development of ankylography was a direct result of the Kapteyn/Murnane group's experimental work. To obtain very high resolution of their stick-girl image, the researchers had to capture light from the object deflected to very large angles. The process is similar to how the lens on a microscope must be adjusted very close to the microscope slide at the highest magnification.

Comparison of image reconstructions of a 7 µm stick girl figure with X-ray and scanning-electron microscopes. **(left)** Scanning-electron microscope image. **(right)** X-ray microscope image.
Credit: Richard Sandberg





Researchers at UCLA took single-wavelength X-ray data from the Kapteyn/Murnane group and performed a 3D image reconstruction of the stick figure, as shown in **b** and **c**.
Credit: Kapteyn/Murnane group

What the UCLA researchers realized was that the light recorded on the image detector was *simultaneously* seeing the object from many different directions. This process was actually a version of the stereoscopic vision that people have when they see with two eyes. The figure above is evidence of their success in determining the depth of an object. Panels b and c are 3D views of the stick girl from the front and side, respectively. Panel a is a picture of an Ewald sphere, a two-dimensional geometric construct used to show the relationship between the wavelengths of incident and diffracted X-ray beams as well as the diffraction angle for each reflection.

Miao and his colleagues showed that their new method not only works for the little stick girl, but also for computer-generated data simulating 3D reconstructions of a piece of sodium silicate glass and a single poliovirus. Kapteyn believes that with further development, ankylography could have applications in both the physical and life sciences, making it possible in the future to take 3D "snapshots" with nanometer resolution using an X-ray flash of only a few femtoseconds. Superman would be envious!

References:

Kevin S. Raines, Sara Salha, Richard L. Sandberg, Huaidong Jiang, Jose A. Rodriguez, Benjamin P. Fahimian, Henry C. Kapteyn, Jincheng Du, & Jianwei Miao, *Nature* **463**, 214–217 (2010).

Richard L. Sandberg, Changyong Song, Przemyslaw W. Wachulak, Daisy A. Raymondson, Ariel Paul, Bagrat Amirbekian, Edwin Lee, Anne E. Sakdinawat, Chan La-O-Vorakiat, Mario C. Marconi, Carmen S. Menoni, Margaret M. Murnane, Jorge J. Rocca, Henry C. Kapteyn, and Jianwei Miao, *Proceedings of the National Academy of Sciences* **105**, 24–27 (2008).

Sculpting a Star System: The Outer Planets

Fellow Phil Armitage and colleagues from the Université de Bordeaux and Google, Inc. are key players in the quest to understand the secrets of planet formation. Current theory posits that there are three zones of planet formation around a star (as shown in the figure). In Zone One, the hot innermost zone, small rocky planets form over a period of hundreds of millions of years. The planets form too slowly to accrete gas from the original planetary disk. Zone One is the terrestrial, or habitable, zone.

Zone Two is the region where giant gas planets like Jupiter and Saturn and ice giants like Uranus and Nepture form. The giant planets form quickly and are often closely packed. The close packing can make them violently unstable. Interactions (and collisions) of these planets not only influence the evolution of planets in Zones One and Two, but also the planetoids and debris found in Zone Three.

Zone Three comprises the solar system's Kuiper Belt and Epsilon Eridani's comet belt. These zones are filled with debris that didn't have time to build large objects (i.e., planets) or whose planet-building was thwarted by the giant planets in Zone Two. In today's solar system, the Kuiper Belt contains 10 known dwarf planets, including Pluto, plus millions of smaller objects. The original Kuiper Belt is thought to have been hundreds of times more massive than it is today. Most of the Kuiper Belt's mass was ejected from the solar system via collisions and other interactions with the giant planets.

Armitage and his colleagues examined the impact of collisions and interactions involving the giant planets in Zone Two. They found that a collision could move giant planets inward toward their star or eject them entirely from the star system. They concluded that the ultimate fate of an entire planetary system appeared to depend on interactions of the closely packed giant planets, whose gravitational influence dominated everything else. These planets were also affected by the primordial Kuiper disk, which helped to separate them and stabilize (and possibly recircularize) their orbits after an early period of instability and collisions. According to Armitage, the unstable period of collisions in Zone Two is responsible for what happens to a planetary system's outer planets. If things are relatively calm, the giant planets will interact with the outer debris disk, gradually widening the space between them and settling into near circular orbits.

In other star systems, collisions can send giant planets spiraling into their star or rocketing out of the star system. They can cause planets to have wildly eccentric orbits, setting the stage for additional crashes. There are many possible outcomes to this early and often violent period, in which ~50% of the giant planets that end up in close orbits around their star will have had at least one collision.

The violent interactions inside Zone Two also affect the terrestrial planets, which grow slowly via collisions with other rocky bodies. If the outer planets are relatively well-behaved, as was likely in the early solar system, then the inner planets are free to evolve, possibly into habitable planets. In contrast, violent collisions in Zone Two can not only eject the giant planets there, but also scour Zone One, ejecting part or all of its rocky material.

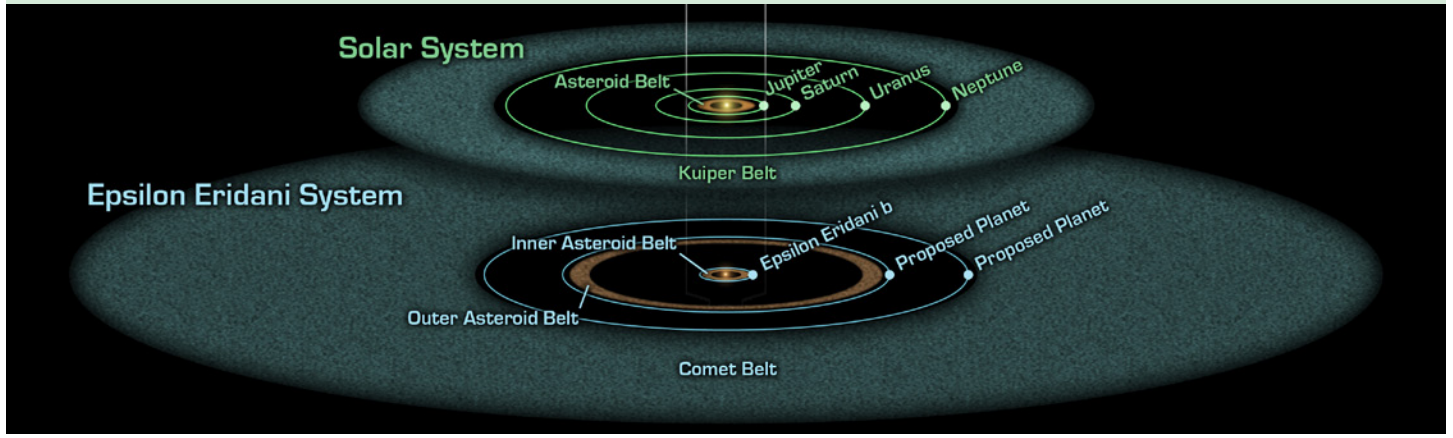
With their new understanding of the effect of the interaction of giant planets on a planetary system, Armitage has now turned his attention to Zone One, looking for clues to the formation of habitable planets. He knows that all terrestrial planets form from collisions of smaller bodies. In fact, he says that our moon was likely created in the last large collision with a body the size of Mars that formed the Earth. This suggestion raises the question whether there might have been a fifth terrestrial planet, which formed in the region now occupied by the asteroid belt.

Armitage says there might even have been a fifth giant planet that was ejected early from the Solar System. Perhaps, it's lurking beyond the Kuiper Belt, where it influences the wildly eccentric orbit of Sedna, a dwarf planet discovered in 2003. However, whether there were once more planets in our solar system is still a mystery to be solved. There is still much to be learned about the planet we call home and others like it.

Reference:

Sean N. Raymond, Philip J. Armitage, and Noel Gorelick, *The Astrophysical Journal* **711**, 772–795 (2010).

Artist's conception comparing the Epsilon Eridani star system to our own solar system. Both systems have asteroids (**brown**), comets (**blue**) and planets (white dots). This star system is located 10 light years away from Earth in the constellation Eridanus. Its central star is a younger and fainter version of our Sun. At about 800 million years old, it is about the age of our Sun when life first arose on Earth.
Credit: NASA/JPL-Caltech

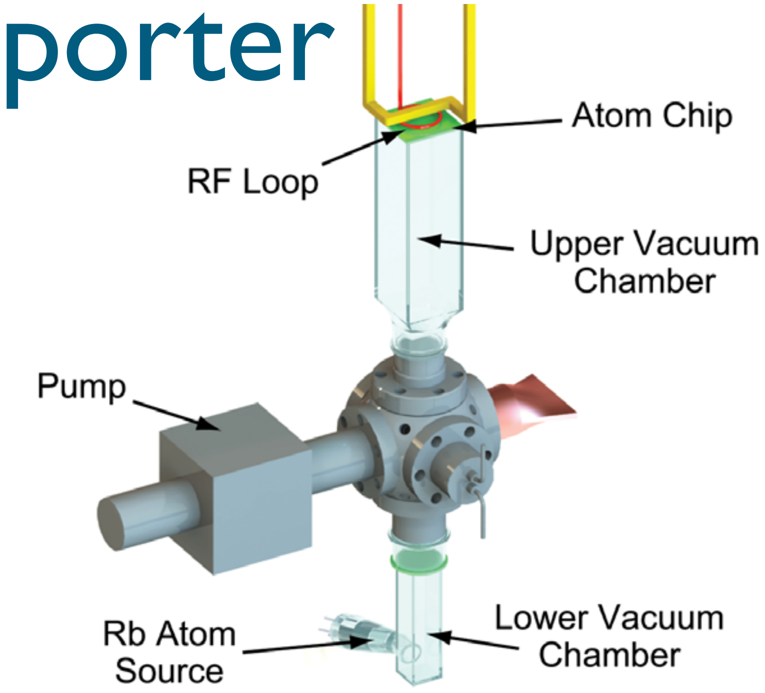


The BEC Transporter

The Dana Z. Anderson group has developed a microchip-based system that not only rapidly produces Bose-Einstein condensates (BECs), but also is compact and transportable. The complete working system easily fits on an average-sized rolling cart. This technology opens the door to using ultracold matter in gravity sensors, atomic clocks, inertial sensors, as well as in electric- and magnetic-field sensing. Research associate Dan Farkas demonstrated the new system at the American Physical Society's March 2010 meeting, held in Portland, Oregon, March 15–19.

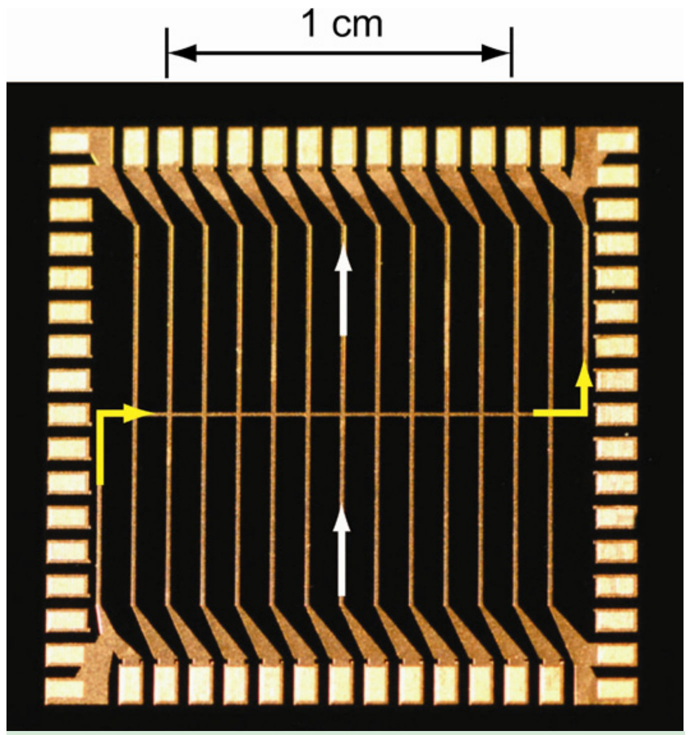
To perfect the new compact BEC transporter, Farkas worked closely with Fellow Dana Z. Anderson, graduate students Kai Hudek, Evan Salim, and Stephen Segal, and Matthew Squires, who received his Ph.D. from CU in 2008. The Anderson group has been working on different aspects of this new technology for more than a decade.

Key components of the new system include the two-chamber vacuum cell and an innovative atom-chip design. The new vacuum cell took the Anderson group more than a decade to perfect. Researchers built and tested more than 70 different prototypes before coming up with a design that provides the ultrahigh vacuum quality needed in the new portable system. The new vacuum cell is 10–20 times smaller than its conventional counterparts. It also serves as the platform for the atom chip where the BECs are made. Plus, the cell is now standardized, making it a good candidate for commercialization.



A color schematic of the Anderson group's new two-chamber vacuum cell and its placement with respect to the atom chip and other system components.
Credit: Evan Salim

The atom chip was developed in 5-year collaboration between Anderson and Victor Bright of CU's Department of Mechanical Engineering, Teledyne Technologies, Inc., the Sarnoff Corporation, and Vescent Photonics. Although the collaboration's microchip was not the first to incorporate a BEC, it makes a BEC faster than any comparable technology in the world. It can transform "hot" atoms at room temperature into a BEC in 3 seconds, about 10 times faster than traditional BEC apparatus. Such speed is important for such applications as atomic clocks or gyroscopes in which waiting a minute between measurements is problematic. For instance, the ability to rapidly read the state of the ultracold atoms will increase atomic clock stability, and faster transitions to BEC will allow more rapid measurements of acceleration and rotation. For these reasons, atomic clocks and gyroscopes employing BEC-on-a-chip systems are likely to be part of high-tech navigation systems on ships and airplanes in the future.



The vacuum side of an atom microchip.
Credit: Evan Salim

Additional advantages of the portable microchip-based system are its lower power usage and design flexibility. With an electrical power consumption of ~525 watts, the system can run on batteries, if necessary. Its system design can also easily be tailored to a variety of specific uses, primarily by incorporating atom chips with different wire configurations.

Reference:

Daniel M. Farkas, Kai M. Hudek, Evan A. Salim, Stephen R. Segal, Matthew B. Squires, and Dana Z. Anderson, *Applied Physics Letters* **96**, 093102 (2010).

The Business of Science

Fellow Dana Z. Anderson had a dream of making miniaturized ultracold-atom technology readily available to laboratory researchers wanting to jump start new experiments with ultracold atoms. He also wanted to develop a simplified version of ultracold-atom technology for use in undergraduate labs to teach the principles of laser cooling. Anderson and three colleagues brought these dreams into reality in 2007 when they founded ColdQuanta, Inc.

In addition to Anderson, who is the firm's Chief Technology Officer, ColdQuanta's founders include Rainer Kunz, who serves as President and Chief Executive Officer of the company, and two Scientific Advisors, Nobel Laureate Theodor Hänsch of the Max Planck Institute of Quantum Optics in Garching, Germany and Jakob Reichel of the Laboratoire Kastler Brossel in Paris. In 2001, Reichel and Hänsch worked together to obtain the first Bose-Einstein condensate (BEC) on a microchip.

ColdQuanta currently sells a magneto-optical trap, or MOT, consisting of an ultrahigh vacuum cell, a rubidium source, and an ion pump, for use in undergraduate teaching labs. The company also sells the more complex two-chambered ultrahigh-vacuum systems used in miniaturized ultracold-atom technology. Both products were originally developed on the CU campus before being commercialized by ColdQuanta. The company also designs and sells custom silicon-atom microchips to go with its ultrahigh vacuum cell. And, it will soon offer the magnetic field coils and associated electronics used in BEC-on-a-chip systems.

For more information, please see:

http://www.coldquanta.com/

ALUMNI PROFILE

Sacha Brun, Service d'Astrophysique, CEA/Saclay

Sacha Brun explaining the principles of astrophysical fluid dynamics.
Photo Credit: L. Godard

Former JILA postdoc Sacha Brun is currently a tenured professor at the Service d'Astrophysique, a division of France's Commisariat à l'Energie Atomique (CEA) in Saclay, a small town 18.8 km southwest of Paris. Brun was recently appointed director of a laboratory that studies the dynamics of stars and their environments. He is putting together a research group with funding from a 5-year European Research Council Starting Grant. The grant was awarded for his STARS2 (Simulations of Turbulent, Active and Rotating Suns and Stars) project.

The project's scientific goal is to understand the interactions between convection, turbulence, shear, rotation, and magnetic fields in the Sun and other stars. The means to achieving this goal is the development of three-dimensional stellar models that run on massively parallel supercomputers. As part of this effort, Brun and a colleague recently completed an analysis of the interplay between rotation and convection in the envelope of a red giant star and found major temperature variations. To model the star, the researchers used the Anelastic Spherical Harmonics (ASH) code originally developed at JILA in Fellow Juri Toomre's group.

Brun's new project is near and dear to the heart of Toomre, who was Brun's postdoctoral advisor from January of 1999 through December of 2002. Brun came to Boulder on the recommendation of his thesis advisor, Jean-Paul Zahn of the Observatoire Paris. Brun brought with him the idea of using the code Toomre was developing to understand the Sun's rotation and convection patterns to study other stars. The two have collaborated on modeling both the Sun and different stars ever since. As Brun remarked during one of his many visits to JILA, "Juri likes to come to France, and I like to come to Boulder." Brun says the visits are always a mixture of science, paper writing, spirited discussions, analyses, and brain storming.

Currently, there's a memorandum of understanding between Brun and Toomre's groups that supports an exchange program between Boulder and Saclay for researchers, graduate students, and postdocs. Brun estimates he spends 1–2 months a year (in two-week chunks) in Boulder working in the JILA Laboratory for Computational Dynamics (LCD). Every other year, Toomre travels to Paris for a month.

Brun spent two weeks in Boulder in May 2009, working with Toomre's group to develop a new architecture for the ASH code and make it run more efficiently on supercomputers. Recalling his years as a JILA postdoc, he said, "I used to love it when Juri came into my office (on the 6th floor of the tower) and say, 'Let's have tea,' and he'd bring me a pear to eat." Toomre would often add, "Let's go to the 10th floor to see the sky and discuss fluid dynamics." Brun said he was very lucky to have such a kind person as his mentor.

Maybe that's why he proposed (and got the funding for) a June conference on Astrophysical Dynamics to be held in Nice, France, in honor of Toomre's 70th birthday (see page 12 for details).

June Symposium To Honor Juri Toomre's 70th Birthday

IAU Symposium 271, ***Astrophysical Dynamics: From Stars to Galaxies***, will be held in Nice, France, from June 21–25. The symposium will celebrate Professor Juri Toomre's 70th birthday and his many contributions to the field of astrophysical dynamics. It features leading experts who will review our current understanding of stars, galaxies, and their dynamics. Speakers will emphasize the commonalities between various fields and identify specific projects or astrophysical problems that could lead to cross-fertilization between different communities. They will also preview current challenges that may be amenable to observational and modeling techniques from other research fields.

Conference co-chairs are former JILANs Drs. Allan Sacha Brun (CEA/Saclay) and Nic Brummell (University of California, Santa Cruz). Invited speakers include Keith Moffat (retired), Juri Toomre's thesis advisor at Cambridge University; Alar Toomre (MIT), Juri's brother; and Former JILA Fellow Ellen Zweibel (University of Wisconsin). Most importantly, Juri Toomre gets the last word — literally — on the final day of the symposium.

For more information, please see:

http://irfu.cea.fr/Projets/IAUSymp271/

Kudos to...

Henry Kapteyn and **Margaret Murnane** for winning the 2010 Arthur L. Schawlow Prize in Laser Science for their pioneering work in the area of the ultrafast laser science, including development of ultrafast optical and coherent soft X-ray sources. The prize consists of $10,000 and a certificate citing their contributions.

Henry Kapteyn and **Margaret Murnane** for winning the R. W. Wood Prize of the Optical Society of America. The prize recognizes outstanding scientific achievement in the field of optics.

Art Phelps for winning first prize, along with Z Lj Petrović, for the most highly cited paper in the past 10 years from the journal *Plasma Sources Science and Technology*. His paper was titled "Cold-cathode discharges and breakdown in argon: surface and gas phase production of secondary electrons."

Juri Toomre for winning the 2010 Hazel Barnes prize, the largest and most prestigious single faculty award funded by the University of Colorado at Boulder. The $20,000 prize was established in honor of Philosophy Professor Emerita Hazel Barnes to recognize "the enriching interrelationship between teaching and research."

Carl Wieman for being nominated by President Barack Obama to be Associate Director for Science at the White House Office of Science and Technology Policy.

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The editors do their best to track down recently published or upcoming journal articles and great research photos and graphics. If you have an image or a recent paper you'd like to see featured in the newsletter, contact us at sro@jila.colorado.edu.

Please check out this issue of *JILA Light & Matter: Spring 2010* online at http://jila.colorado.edu/research/ where you can find supplemental multimedia that may be associated with the articles.

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