

JILA: LIGHT & MATTER

Summer 2010



Artist's concept of an extrasolar planet orbiting close to its host star. Although it is about the size of Jupiter, the planet is so hot that sizzling gases from its atmosphere are escaping into space. A strong stellar wind creates a cometlike tail on the planet.

Artwork Credit: NASA, ESA, and G. Bacon (STScI).

Science Credit: Jeff Linsky

Sizzling Planet Sports Cometlike Tail

A faint star that can easily be seen from Earth with binoculars has a Jupiter-like gas planet orbiting it once in just three days. That means the planet is close enough to its Sun-like star to get scorching hot, which affects both the planet and its atmosphere. The star is called HD209458, and its planet's moniker is HD209458b.

Recently Fellow Jeff Linsky, research associate Hao Yang, and their colleagues from CU's Center for Astrophysics and Space Astronomy learned a lot more about the planet and its star by analyzing data from the new Cosmic Origins Spectrograph (COS) aboard the Hubble Space Telescope. COS is a moderate-resolution ultraviolet spectrometer that was able to observe the planet both in front of the star and off to one side. When the planet was in front of the star, it obscured a portion of the starlight and made it easier to measure the absorption by ionized carbon and silicon gas in its bloated atmosphere.

The first thing Linsky and Yang noticed was that if the planet was really the size of Jupiter, it should cover only about 1.5% of the

star's surface instead of the 8% observed by COS. They quickly realized that the star was heating up the planet's atmosphere, causing it to expand to its bloated condition. The expansion of the atmosphere corresponded with a loss of mass from the planet. Plus, the atmosphere extended so far away from the planet that some of it was getting lost in space. This is the first exoplanet discovered to have an exosphere!

The most exciting discovery was that powerful stellar winds appear to be pushing the exosphere away from the planet, causing the planet to have a cometlike tail. The tail is aimed directly toward us Earthlings, so we don't see it directly. However, if we could see this interesting exoplanet up close and from a different angle, it would look a lot more like a comet than like a planet!

Reference:

Jeffrey L. Linsky, Hao Yang, Kevin France, Cynthia S. Froning, James C. Green, John T. Stocke, Steven N. Osterman, *The Astrophysical Journal* **717**, 1291–1299 (2010).



CURLING UP IN A NANOBATHTUB

In microscopic studies of single biological molecules or nanoparticles, it's useful to be able to precisely control the temperature around the sample. Until now, heating has required electric currents that warm up microscope stages, slides, and optics in addition to the specimen under study. Such methods are slow and hard to control, not to mention capable of accidentally altering the chemistry or structure of the sample. Now there is a better solution for keeping samples nice and warm: The nanobathtub.

Graduate student Erik Holstrom and Fellow David Nesbitt have come up with a way to precisely control the temperature of tiny "bathtubs" of water on a glass slide. The column-shaped bathtubs contain only 35 trillionths of a liter of water, which is easily warmed with gently focused laser light.

During studies of RNA folding, researchers use near-infrared laser light to heat water inside a nanobathtub containing a single RNA molecule.
Credit: K. Talbot/NIST

The heating laser is aimed at the samples from above and forms a spot size of about 20 micrometers. Its near-infrared light is the perfect wavelength for inducing the oxygen-hydrogen (OH) bonds in water to start vibrating. These vibrations are responsible for warming up the water in the nanobathtub. As the water warms, the researchers can monitor any changes in their sample with a fluorescence microscope. Such laser-induced-fluorescence-based microscopy techniques have been used extensively by the Nesbitt group to study single molecules of RNA.

What's new is that if a nanobathtub containing a single molecule of RNA is attached to the slide, the laser can warm the RNA molecule to exactly any temperature between 20 to 90 °C (68 to 194 °F). This capability means that researchers can now perform experiments that use sudden, controlled jumps in temperature to activate specific molecular processes and observe them in real time.

Before attempting these new experiments, however, Holstrom and Nesbitt decided to compare observations of RNA folding

that occurred in the nanobathtubs with folding that took place when the entire slide and microscope stage were heated with an electric current. They found that the new bathtub-heating method worked just as well as the older method for studying single RNA molecules. In the process, they showed that the new laser-based method was able to heat the bath water with an accuracy of half a degree Celsius in less than 20 milliseconds!

This level of control is possible because all temperature changes that affect the RNA sample in the nanobathtub are controlled by the laser. The microscope stage, which remains at room temperature, no longer has any effect on the temperature of the sample.

Reference:

Erik D. Holmstrom and David J. Nesbitt, *The Journal of Physical Chemistry Letters* **1**, 2264–2268 (2010).

AN OCCURENCE AT THE SOLVENT BRIDGE

Solvents don't just dissolve other chemicals (called solutes) and then sit around with their hands in their pockets. Instead, they get involved in all sorts of different ways when dissolved molecules toss electrons around, i.e., they facilitate charge transfer events. In research, the hard part is figuring out exactly how and when solvent molecules get involved when an electron hops from one solute molecule to another. For example, in liquids (which do most of the dissolving), solvent molecules move constantly, making it very challenging to see what they're doing when charge transfer events occur.

The Lineberger group recently met this challenge using a simple prototype gas-phase system. In this system, a single solvent molecule of carbon dioxide (CO_2) interacts with an IBr^- molecule as it is broken apart by a laser pulse. A second, or probe, laser pulse is used to watch what happens as the IBr^- molecule falls apart. The group discovered the ways in which the CO_2 molecule affected the dissociation process. The experiments were

performed by research associate Lenny Sheps and graduate student Elisa Miller under the guidance of Fellow Carl Lineberger. The experimentalists collaborated with theorists Robert Parson, former graduate student Matt Thompson, Anne McCoy (the Ohio State University) and McCoy's student Samantha Horvath to unravel the role of CO_2 in the dissociation process.

When there was no solvent (CO_2) present, the laser pulse moved the IBr^- into a specific electronic state that then fell apart, producing only I and Br atoms. However, with a single CO_2 molecule present, things got very interesting. About a third of the time, the breakup still produced only I and Br atoms. The CO_2 molecule basically flew off into space. Then, a little less than two-thirds of the time, the breakup produced an $\text{I}(\text{CO}_2)$ complex and a Br atom. In this case, the CO_2 molecule kind of snuggled up to the I atom during the dissociation and just kept vibrating against it.

The most interesting chain of events occurred only about 3% of the time. In this case, right after the IBr^- was hit by the first laser pulse, the I, Br, and CO_2 began to separate, much like in the pathway that produced just a Br atom and an $\text{I}(\text{CO}_2)$ complex. However, in this case, the $\text{I}(\text{CO}_2)$ complex was hot (rapidly vibrating). After about 350 fs, it slammed against the Br atom, and the CO_2 formed a bridge between the I and Br atoms, which had been in the process of separating.

When the two atoms were about 7 Å apart (which is really far in the world of atoms and molecules), the extra electron on the iodine atom hopped right across the CO_2 bridge and into the Br atom, producing I and Br^- atoms. But, the CO_2 solvent molecule did more than just provide a physical bridge between the two atoms for the hopping electron. It also absorbed the energy

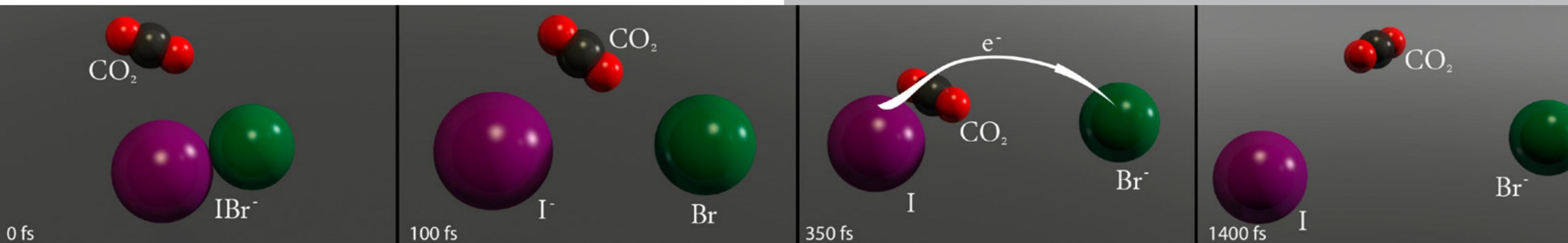
released when the electron combined with the Br atom. After the charge transfer was complete, the CO_2 molecule was left vibrating like crazy, which pushed it away from the two atoms.

This seminal experiment not only showed that a single solvent molecule can facilitate charge transfer, but also exactly how it can perform this feat. The Lineberger group is currently investigating charge transfer mediated by two solvent molecules.

Reference:

Leonid Sheps, Elisa M. Miller, Samantha Horvath, Matthew A. Thompson, Robert Parson, Anne B. McCoy, W. Carl Lineberger, *Science* **328**, 220–224 (2010).

On rare occasions, a single solvent molecule of carbon dioxide (CO_2 , black/red) will facilitate the transfer of an electron from a negative ion of iodine (I, purple) to an atom of bromine (Br, green). The CO_2 molecule not only provides a bridge between the two atoms for the electron to hop from one atom to another, but it also absorbs energy released when the electron combines with the Br atom to form Br^- .
Credit: Brad Baxley



CANNED HEAT

A while back, Fellow Eric Cornell started thinking about all the waste heat produced by the use of water to cool refineries and other industrial plants. In a few places, the waste hot water — at ~212°F — is used to heat commercial and apartment buildings. More often, though, such buildings are located too far from an industrial plant to make it cost effective to pipe the hot water to them. Instead, power plants and other facilities actually spend money to cool their hot water via cooling towers or ponds and then reuse the water — for more cooling.

What if there were an economical way to cool the waste water and get enough energy from it to make some electricity? All it might take, Cornell mused, would be to push 19th Century hot-air engine technology to its limit. Of course, this sounds like a very different kind of research project for JILA. Consequently, Cornell has teamed up with Mechanical Engineering Professor Gary Pawlas and his students to bring his dream into reality.

“The idea is not complicated,” Cornell explained. “We run hot water through a heat exchanger (like a car radiator), where it heats air confined in a box. This keeps the volume the same, which means that as the air gets hotter, the pressure goes up. Then we let the air blast out to spin a turbine and make electricity.”

Because turbine technology is well developed, the key to Cornell’s vision for a 21st Century hot-air engine is the blast of air. It has to be produced carefully, efficiently, cheaply — and sustainably. The prototype engine’s working fluid is air, its exhaust is air, and its heat source is hot water.



Prototype of the new hot-air engine under development in Eric Cornell’s lab at JILA. The engine is being designed to capture waste heat from refineries and other industrial plants to make electricity.

Credit: Greg Kuebler

In fact, everything is nontoxic in the prototype engine, which is currently under development in Lab C229 by teams of undergraduate mechanical engineering students. Each academic year, a new group works on improving the performance of the engine, which sits inside a steel drum hung from a steel frame.

Cornell’s new hot-air engine sports one major improvement over its 19th Century counterpart: a moveable heat exchanger. The moveable heat exchanger

The 2009–2010 team that worked on developing Eric Cornell’s new hot-air engine. (front row, l–r) Professor Gary Pawlas (Mechanical Engineering), Fellow Eric Cornell, Jesse Shapiro (Boulder High School). (back row, l–r) Mike Geocaris, Patrick Zimmer, Kris Schneider, Andrew Shewmaker, and Patrick Wessels (undergraduate students in CU’s Department of Mechanical Engineering).
Credit: Greg Kuebler



moves up and down, forcing air through the device up into an air valve at the top of the steel drum, where it rushes out. This design makes it easy to run the engine and test it at different pressures, identify leaks, and crank flow rates up on demand. It clearly will play a central role in maximizing the power of the air blast sent out of the engine into a turbine.

With respect to the prototype, things appear to be progressing well. However, for the new engine to have commercial value, it must be able to produce at least 1 megawatt (MW) of power. That means building the engine inside a poured-concrete structure the size of an Olympic swimming pool — and making sure every aspect of the engine is running at its maximum possible efficiency.

“The jury’s out on whether this engine will work the way we want it to,” Cornell said. “It will definitely make electricity, but we’re not sure yet whether we can do it cheaply enough to be useful. And, even if it does work, it’s not going to be a game changer.”

What it may do is make life a little more comfortable for us humans as the global economy switches from its reliance on carbon-based fuels to renewable energy resources. As Cornell explained, “It’s worth a shot.”

Window into the Sun

Senior research associate Brad Hindman of the Toomre group uses helioseismology to understand what’s happening under the surface of the Sun. Helioseismology is a lot like the ultrasound tests used to evaluate medical conditions. However, there’s a big difference: physicians already have a good idea of the basic structures they are probing with sound waves. Helioseismologists don’t. They study sound that travels below the Sun’s surface to learn about the structure and behavior of the Sun’s convection zone, which comprises the outer third of the Sun. However, if they misinterpret the nature of the sounds they analyze, then they are likely to miss the mark in determining what’s happening inside the Sun.

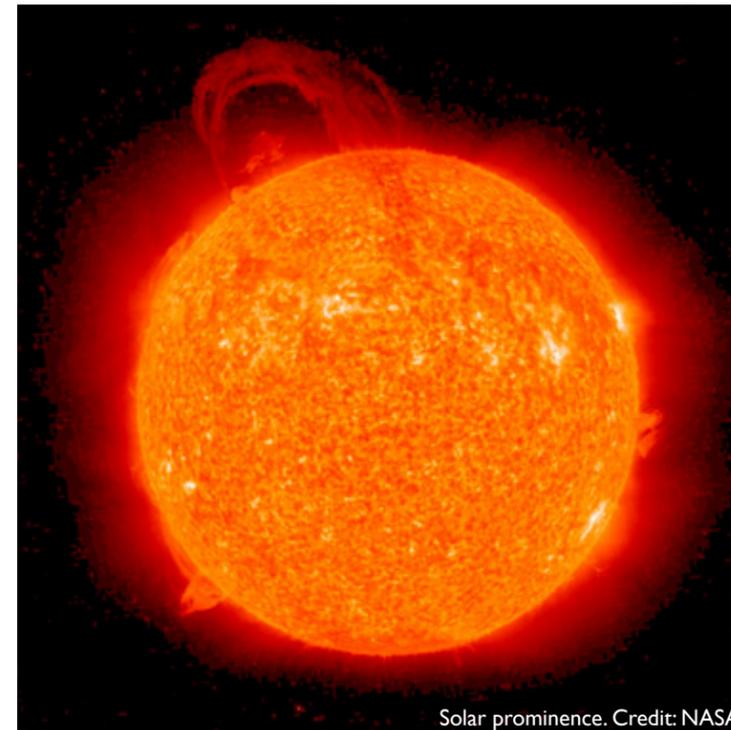
Thus far, solar physicists have identified two long-term wind patterns, or circulations, that exist within the convection zone. The first of these is a wind pattern directed along latitude lines (east-west) that varies in strength from equator to pole. This pattern results in an equator that rotates around the Sun in 25 days, while the poles rotate in 28 days. The second wind pattern follows longitude lines (north-south). Both of these circulations are crucial ingredients in the Sun’s magnetic cycles.

The first wind pattern has been mapped out successfully by helioseismologists. The pattern of fast equator and slow poles persists throughout the convection zone. The second wind pattern has only been mapped inside the extreme upper portion of the convection zone where the winds flow away from the equator and toward the poles. However, solar physicists believe that there is also “return flow” toward the equator in the deeper layers of the Sun. Over the past few years, helioseismologists have looked for this return flow with sound waves. But, as it turns out, detecting and measuring these deep flows is challenging.

Hindman has recently demonstrated that many scientists have been barking up the wrong tree. They’ve been trying to measure a Doppler shift in the sound waves from the deep flows. However, they were assuming that the Doppler effect would manifest as a shift in the frequency of the sound waves. Many people would make the same mistake. After all, the Doppler effect is

often illustrated by the change in pitch that is experienced as a train passes by. This change in pitch is usually described as a change in the sound wave’s frequency. In the case of the Sun’s wind patterns, however, the Doppler effect causes a change in the phase and wavelength of the wave instead of the frequency, which is largely unaffected.

So, Hindman says that instead of trying to measure frequency or wavelength shifts in these sound waves, scientists should be focusing on measuring the sound waves’ spatial phase. A deep return flow will cause this phase to change as a function of latitude. This variation will be larger when the deep flow is faster. And, as with medical ultrasound tests, phase measurements should make it possible to deduce structures in the winds as they interact with the sound waves.



Solar prominence. Credit: NASA

The next step is clear. Hindman plans to analyze measurements from the Helioseismic and Magnetic Imager aboard the Solar Dynamics Observatory, launched in February of 2010. “We know we’re absolutely right that people have done these measurements incorrectly in the past,” he says. “All we need now is about eight years of new data to better understand the Sun’s deep flows.” (While waiting for the year 2018, Hindman and his collaborators will be testing their ideas on data sets from older instruments.)

Such an understanding will be critical for predicting space weather events such as the huge ejection of mass from the Sun in the picture above. Hindman wants to be able understand the solar dynamo well enough to predict the ejection of such giant clouds of charged particles, which not only wreak havoc on satellites and electricity distribution networks, but also could prove fatal to astronauts accidentally caught up in them. Mapping out the Sun’s internal winds is an important step toward developing an early warning system for solar eruptions.

Reference:

Douglas Gough and Bradley W. Hindman, *The Astrophysical Journal* 714, 960–970 (2010).

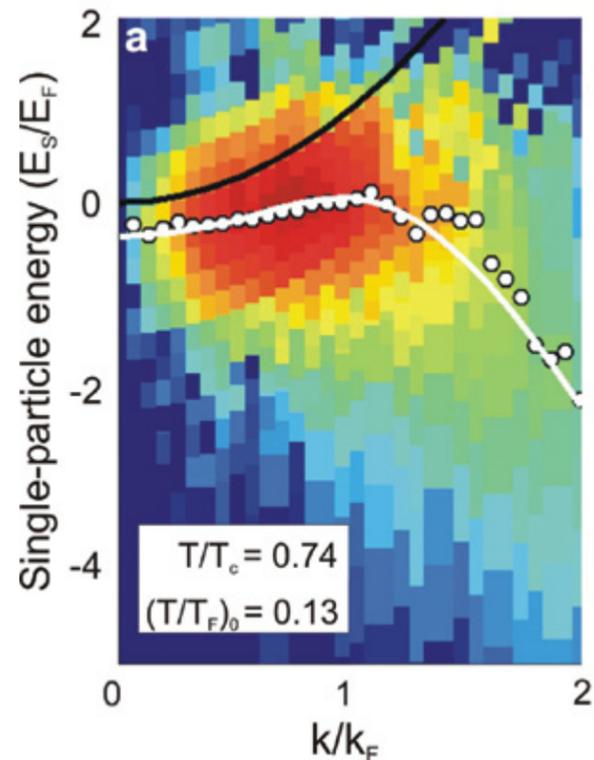
The Mysterious Fermi Gap

In 2008, the Deborah Jin Group introduced a new technique, known as atom photoemission spectroscopy, to study a strongly interacting ultracold gas cloud of potassium (^{40}K) atoms at the crossover point between Bose-Einstein condensation and superfluidity via the pairing of fermionic atoms (See *JILA Light & Matter*, Summer 2008). Near the crossover point, the physics of superfluidity in an atom gas system may be connected to that of high-temperature superconductivity.

In the 2008 experiment, the researchers discovered an energy gap in their superfluid gas. The atom gas was filled with atom pairs that were dancing in sync even though they didn't actually form molecules. The energy gap corresponded to the minimum energy required to break apart the pairs back into single atoms.

Here's a good way to think about the energy gap: If you put a tiny amount of energy into an ideal Fermi gas, you can excite a fermionic atom and make it move faster. If the system has an energy gap, however, then amounts of energy smaller than the gap cannot excite one of the atoms. You need energy equal to or larger than the gap to excite atoms. The gap exists because you have to put in enough energy to break apart a pair of fermions before you can excite either one of them.

That's why finding and measuring the gap was so exciting back in 2008. This experiment was conducted at a temperature,



Energy gap (right side of figure). Credit: J. Gaebler

known as T_c , which is the point at which a superfluid forms. The observation of a gap fit with conventional theory. This theory predicted that pairs of Fermi atoms would act in synchrony below T_c , creating an energy gap. The same theory predicted that above T_c , no atom pairs would form, and thus no energy gap would exist. Similar relationships were predicted to hold true for superconductivity in solid materials.

Interestingly, the prediction that the gap must disappear above T_c held true for all superconducting materials except high-temperature superconductors. In high-temperature superconductors, researchers do see a gap in the region above T_c . This anomaly recently piqued the curiosity of the Jin group and their theorist colleagues from Italy's Università di Camerino. They began to wonder what would happen to the gap in an ultracold atom gas at temperatures above T_c . After all, conventional theory predicts that pairing disappears along with the gap.

So, the Jin group team, led by graduate student John Gaebler, repeated its photoemission spectroscopy experiment with a gas of ^{40}K atoms above T_c and, sure enough, they observed a gap! Gaebler was assisted in this unexpected discovery by former graduate student Jayson Stewart and graduate student Tara Drake.

"We think our observation means that there are still pairs of atoms hanging together at the higher temperature, despite the fact there is no longer a superfluid," Gaebler said. He added that if he's correct, then what he and his colleagues observed is a very exotic state of matter. To further complicate the picture, other things you can measure in cold-atom gases turn out to be consistent with conventional theory. The Jin group's theorist colleagues in Italy are hard at work figuring out exactly what is going on here.

The new results raise the question of what is similar about high-temperature superconductors and strongly interacting superfluid Fermi gases. For starters, the new results from the Jin group clearly demonstrate the existence of an energy gap in strongly interacting Fermi gases both below and above T_c ; the same is true of high-temperature superconductors.

So, Gaebler is back at work refining his measurements, evaluating other techniques for exploring the gap, and understanding the effects of laser trapping on his results. Ultimately, he wants to not only observe, but also understand the transition from pairing to nonpairing in an ultracold gas of ^{40}K atoms. This understanding will increase our knowledge of how such behavior relates to what happens in high-temperature superconductivity.

References:

J. P. Gaebler, J. T. Stewart, T. E. Drake, D. S. Jin, A. Perali, P. Pieri, and G. C. Strinati, *Nature Physics* **6**, 569–573 (2010).

THEM'S THE BRAKES



Ryan Wilson and John Bohn are looking for an experimentalist interested in putting the brakes on a superfluid BEC. Credit: Brad Baxley

The Bohn group has just come up with an exciting, really complicated experiment for someone else to do. This is something theorists like graduate student Ryan Wilson, former research associate Shai Ronen, and Fellow John Bohn get a kick out of. In this case, they're recommending an experiment to measure how fast a tiny blue laser would have to move through a dipolar Bose-Einstein condensate (BEC) to create ripples. Energy lost to the ripples would create a drag force on the laser, signaling the onset of friction inside what would otherwise be a frictionless superfluid. And, of course, friction means putting the brakes on the superfluid — literally.

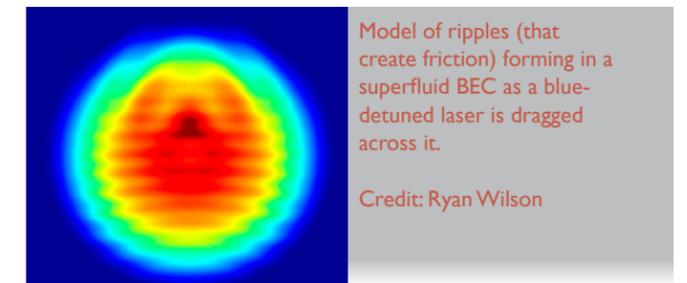
And that's not all, according to Wilson and his colleagues: Such an experiment could also demonstrate the presence of a roton. A roton is the quantum of energy that may represent the link between superfluid helium and a yet-to-be-observed "supersolid" phase of helium. In helium, it is also the excitation, or quasi particle, that determines the fluid velocity at which friction sets in. The analog of the roton in a dipolar BEC has been often discussed, but never seen.

Wilson hopes this situation will change soon, once his new theoretical analysis becomes widely known. He believes that dipolar BECs provide an amazing opportunity to explore the relationship between roton behavior and superfluidity. This is the reason he decided to model an experiment with a dipolar BEC similar to an actual experiment done 15 years ago at MIT on a BEC of sodium atoms. This experiment, unfortunately, was somewhat inconclusive.

In the new model, a blue laser beam sweeps through a dipolar BEC of chromium (Cr) atoms at constant speed. As this speed reaches a critical velocity, it excites roton modes, friction develops, and the condensate begins to slosh. The onset of sloshing is linked to a critical velocity, which, in turn, depends on the density of the Cr atoms making up the BEC and their dipole moment. According to the model, the critical velocity is somewhat smaller than expected from studies of denser materials. However, Wilson and his colleagues believe this finding is related to the role that the roton plays in the mechanical stability of a dipolar BEC.

Wilson and his colleagues hope that their proposed experiment will soon come into reality. They'd like to see an unequivocal measurement of the critical velocity in a dipolar BEC and find out whether dipolar BECs are similar to superfluid helium. Plus, they'd like to prove there's actually a roton hiding somewhere in a BEC of Cr atoms. Of course, the theorists already think the roton is real.

Finding a roton would offer clues to the behavior of systems in which the frequency of waves decreases as the wavelengths get shorter. It also may shed light on what occurs when a collection of atoms is trying to be a solid rather than a liquid. For instance, the spectrum of the roton in liquid helium correlates with the clustering of helium atoms, a first step in the formation of a solid structure.



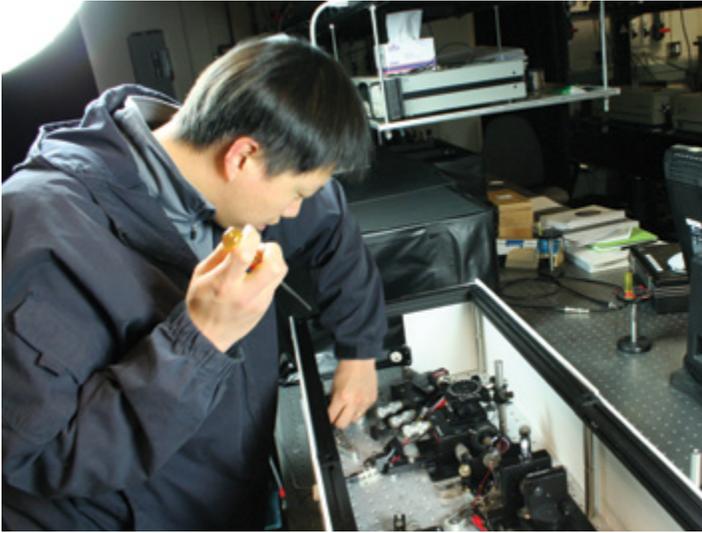
"The roton is really an oddball phenomenon," says Bohn. "If you drag a stick (i.e., laser) slowly enough through a BEC, there's no friction. But once you determine the critical velocity for introducing friction, you can measure the underlying structure of the fluid and how it uses energy. Plus, it should be really handy to be able to turn friction on and off in a laboratory system."

Bohn and Wilson see at least a thousand device applications for their new superfluid BEC brakes. All they have to do is convince someone to do the difficult experiments needed to refine the control of quantum friction.

Reference:

Ryan M. Wilson, Shai Ronen, and John L. Bohn, *Physical Review Letters* **104**, 094501/1–4 (2010).

GONE OVER TO THE DARK SIDE, IT HAS



When former graduate student Mingming Feng started his thesis project, his goal was to build and characterize a mode-locked quantum dot diode laser in Kevin Silverman's lab at the National Institute of Standards and Technology (NIST). Feng chose this lab (after consultation with his advisor Steve Cundiff) because Silverman not only does a lot of work on diode laser development, but also collaborates regularly with Cundiff. As an added plus, Silverman's lab was near the lab of NIST's Richard Mirin, who is a world-class fabricator of semiconductor structures, including quantum dots.

As Feng began building his new laser, it never occurred to him that he was about to make a startling discovery. He expected

his laser would produce the trains of bright pulses typical of a mode-locked laser linked to an external optical cavity; his job would be to tweak the new laser to make the pulses as bright and stable as possible and see if it offered advantages over other diode lasers.

However, when it lased, the new quantum-dot diode laser emitted a train of dark pulses. Instead of the expected bright pulses, i.e., increases in the laser intensity, the dark pulses were actually intensity dips occurring on a background of continuous-wave lasing. Feng couldn't believe his eyes. He kept going back to take new data to see if the dark pulses were real, or just some kind of crazy artifact.

The dark pulses turned out to be quite real. In fact, an examination of the master equation for mode-locked lasers revealed that a dark pulse train is a perfectly good solution for this equation. In theory at least, the possibility of a dark pulse laser had been there all the time. It was simply so counterintuitive that no one had noticed what had been sitting there in plain sight — until Feng garnered irrefutable experimental evidence that his laser had indeed gone over to the dark side.

This evidence included studies of the stability of the dark pulses using simulations. These studies were consistent with what was observed in the laboratory.

All in all, it was an exciting discovery for Feng and his colleagues. However, the dark pulse laser doesn't appear to have much of a future either as a research tool or a practical device. Nobody, including Feng, has any idea of what to actually do with it.

Reference:

Mingming Feng, Kevin L. Silverman, Richard P. Mirin, and Steven T. Cundiff, *Optics Express* **18**, 13385–13395 (2010).

Kudos to...

Stefan Mathias for being awarded a prestigious Marie Curie Postdoctoral Fellowship.

Kang-Kuen Ni for winning the American Physical Society's DAMOP Thesis Prize. Ni was cited for the first experimental realization of an ultracold, near quantum degenerate gas of polar molecules — work that opens new research directions in ultralow-energy chemical reactions, quantum-phase transitions, and quantum information science.

Rosalba Perna for winning the 2010 SIGRAV Prize from the Italian Society of General Relativity and Gravitational Physics. One of the most prestigious Italian prizes in astrophysics, the prize is given biannually to an Italian astrophysicist under age 40 who has distinguished himself or herself for work related to gravity. Perna was honored for her work on neutron stars, black holes, and gravitational lensing. She will deliver an invited plenary talk at the October SIGRAV 2010 conference where she will receive the prize.

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