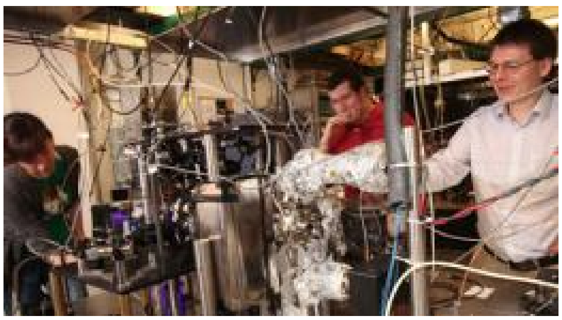
Chilled atoms are going to heat up scientific opportunities

July 20 2011, By Courtney Wickel



Chilling in Small Hall: Researchers (from left) Megan Ivory, Austin Ziltz and Seth Aubin make adjustments to their laser-cooled apparatus. The team must turn their attention to a computer monitor to track the transition of rubidium-87 atoms into the Bose-Einstein Condensate. Credit: Stephen Salpukas

A collection of atoms in the basement of Small Hall is a million times colder than outer space. It's one of the coldest spots in the universe, but it's not cold enough. Yet.

Seth Aubin has big plans for these tiny particles. A group led by Aubin, assistant professor of physics at William & Mary, is putting finishing touches on an apparatus that will chill atoms to near absolute zero. At such ultracold temperatures, the quantum nature of atoms takes over and they begin to follow an altogether different set of physical laws than atoms at room temperature -- laws that Isaac Newton never dreamed of.

Atoms normally move about according to classical Newtonian physics, Aubin explains, like apples falling from trees or billiard balls colliding on a pool table. However, under certain extreme conditions—in this case, cold—Newtonian laws don't hold and physical behavior can only be described by quantum mechanics. Under extreme temperature conditions, atoms begin "behaving less like billiard balls and more like waves," he says.

Aubin plans on exploiting the non-Newtonian properties of ultracold atoms to investigate fundamental questions in quantum physics. But, for Aubin's atoms to enter the quantum regime, they need to be cold enough. Specifically, atoms need to be on the order of a hundred nanokelvin—a hundred billionth of a degree Kelvin—before they start displaying the desired wavelike properties. To put that number in perspective, 0 degrees Kelvin is absolute zero; it is theoretically impossible for anything to be colder than absolute zero. Water freezes at 273 Kelvin. Outer space is about 3 Kelvin.

"They're pretty cold," says Aubin, describing the lab's current record temperature of four microkelvin. "But, unfortunately, that's not good enough for us. At these temperatures, the atoms still behave like billiard balls. If you can get down to a hundred nanokelvin, basically a thousand times colder than they are right now, those particles become quantum-like."

"At high temperatures the atoms all have different velocities," explains Aubin. "But, once you get cold enough, they all clump together. They say, 'that's it, we don't need to be different. We're all going to be the same.'" Aubin explains that atoms oscillating in phase are acting according to the laws of quantum mechanics.

Catching a wave

Because atoms are so small, Aubin uses laser-generated images to monitor the atoms throughout the cooling process. On the lab's computer monitor, a clump of about a hundred million atoms appears as a red globular blob. "It always starts off round," describes Aubin. "As you go colder, it gets smaller but it stays round. When they become completely quantum, they stop being round. They get very elongated. That oblongness is a characteristic of their wave nature. Instead of being a blob, you actually get a whole bunch of blobs that are evenly spaced—essentially, a wave."

It takes both science and engineering to make the transition from Newton to quantum. The first thing you notice in Aubin's research laboratory is the seemingly random disarray of mirrors and lenses scattered across two large optics tables. However, Aubin explains that the assembly of optics is anything but random: "Whenever my family or my friends come to visit, they'll say, 'Seth, your table's a big mess. Why don't you clean all this stuff up?' But, really, if any of this moves by between ten and a hundred microns, it won't work."

These mirrors and lenses concentrate and direct the lasers responsible for the initial cooling phase. Aubin concedes that it seems counterintuitive to use lasers as a cooling device. "It is true that if you shoot a laser at something, it will get hot," confirms Aubin. However, in terms of entropy, the thermodynamic measure of the order of a system, lasers are extremely cold.

"Laser light is made up of photons, the particles of light, and all the particles are identical," explains Aubin. With the same direction, polarization and wavelength, the photons of a laser oscillate in phase. "That's extremely ordered," says Aubin, "you couldn't get more ordered than that. So, lasers are actually extremely cold."

During the initial cooling phase, a few million rubidium-87 atoms are bombarded by six precisely oriented and tuned laser beams. An atom's temperature is proportional to its kinetic energy, which is a measure of its velocity: When an atom is bombarded by photons of just the right wavelength ("color"), it loses speed and therefore, it also loses energy and its temperature decreases.

"We can slow atoms down from room temperature to essentially zero in a matter of milliseconds," Aubin said. "It's a very massive deceleration. And a massive cooling."

When atoms become quantum-like, they are said to exist in a state known as the Bose-Einstein Condensate, or BEC. After laser cooling, temperatures typically range between ten and a hundred microkelvin, but, these atoms still haven't reached BEC. Further cooling the atoms—from microkelvins to nanokelvins—requires some additional electromagnetic hoop-jumping.

As spring began, Aubin and his lab were trying to get the atoms the rest of the way from cold to ultracold—and into a Bose- Einstein Condensate—via a second phase of cooling. Going from one millionth of a degree to one billionth of a degree isn't trivial.

"When I got into this business, I thought, 'You know, a hundred microkelvin, a hundred nanokelvin—same difference. You're just adding a few zeros. You're already pretty close to absolute zero. What difference does it make?,'" Aubin said. "Actually, it makes a huge difference."

Bottling atoms

This second phase of cooling involves moving the atoms into a magnetic bottle. "In the magnetic bottle the atoms are literally suspended in space" explains Aubin. "The atoms are sort of trapped, confined by a magnetic force." Inside the magnetic bottle the atoms will collect on an aluminum nitride chip. This chip, about the size of a microchip, serves as the site for the second cooling phase, in which the atoms are shot by a stream of RF—radio waves.

The chip generates a magnetic trap, shaped like a well. The most energetic (and therefore warmest) atoms jostle about at the top of the well while the cooler atoms sit nearly motionless at the bottom. A shot of RF removes the warmest atoms.

"It's just like when you blow the steam off your coffee to let it cool down, you blow away the hottest coffee molecules," explains Austin Ziltz, a graduate student working in Aubin's lab. "By adding some RF, you can make the hottest atoms flip out of the trap. Get rid of the hottest ones and the collection will go to a colder average temperature."

As the lab makes the progression from cold to ultracold, they're performing a number of measurements and experiments.

"We're characterizing the system with physics. We're measuring the temperature; we're measuring the density of the atoms. We have lots of 'little experiments.' We're gearing up to do a nonlinear optics experiment, we also have magnetometry, measuring magnetic fields," says Aubin. "These experiments are not the main focus; they're little things that will help us massage the system into proper working conditions so we can finely tune the machine."

Aubin has a menu of experiments planned once the lab achieves a BEC and he and his colleagues can investigate the quantum-wave behavior of atoms. High on the list is an atomic laser.

"Atomic lasers don't sound that incredible, but they can be quite useful. Just like how the photons in a laser all have the same wavelength, the same polarization, the same direction—atoms do the same thing when they're in BEC," explains Aubin. "A BEC is like a laser for atoms." Atomic lasers are more powerful than traditional lasers made of light. Because atoms have mass, atomic lasers are characterized by much shorter wavelengths.

He points out the atomic laser will advance theoretical study as well as address practical problems in the field of physics. Aubin is interested in creating an atomic-laser interferometer to investigate the Casimir-Polder force, a force that causes attraction between a surface and an atom at the atomic scale. This force is too small for us to notice in our everyday life; however, once you get down into the microenvironment of individual atoms, surface forces are more powerful than gravity. The Casimir-Polder force is especially problematic in nanotechnology applications.

"When you make these micromechanical devices, the surface force dominates," explains Aubin. "It's the biggest force around. In fact, often these micromechanical devices will stick together, and then they don't work. Understanding and characterizing this force is a big deal."

Simulating components

An atomic laser also provides new ways to simulate solid-state systems. A resistor, transistor, superconductor, microchip or any solid-state system consists of solid crystals through which electrons flow. The crystals have inherent impurities that affect the flow of electrons. Aubin plans on using light lasers to create perfect crystal lattices through which BEC atoms, simulating electrons, will flow.

"By using atoms instead of electrons, the atoms are easier to see, and they're much easier to manipulate," explains Megan Ivory, a Ph.D. student working on the cold atom project. And, she adds, using lattices made of light allows control of the system quality.

“It won’t make a new device for you,” stresses Aubin. “If you want a single-electron transistor, or a one-dimensional quantum wire, you need something that’s based on electrons, but what this simulation can do is provide you with a much better understanding of what’s going on. You can test all your theories. From a theoretical standpoint, it will help us understand how real quantum-scale electronics work.”

Atom interferometry and experimental solid-state simulation are just two of the exciting things that will be done at William & Mary with ultracold atoms. But first, the atoms need to enter the Bose-Einstein Condensate. Aubin expects that his lab will achieve BEC before the beginning of the 2011 fall semester. “The idea is that if everything goes well, we should have the BEC sometime this summer” says Aubin. “And, it could be sooner if things go our way, ‘Knock on optics table.’

Provided by The College of William & Mary