No Small Undertaking

OU researcher wages second revolution in quantum physics to create a new breed of applied technology.

By Chip Minty

Photos by Hugh Scott

In the devastating aftermath of World War I, European economies struggled to overcome severe recessions, rampant joblessness and inflation.

Against this tumultuous backdrop, scientific upheaval was being sewn by a small core of European physicists. The outcome would define the 20th century and set the stage for future breakthroughs still on the horizon today. The revolution was led by Niels Bohr of Denmark and the German-born Max Planck and Albert Einstein. All three won Nobel Prizes in physics for their work in quantum theory, a paradigm in physics that cast the laws of matter and energy into a mysterious world of speculation and debate.

The scientists' early descriptions of atoms and their behavior set the stage for research and philosophical conjecture that has lasted a century. Researchers have taken decades to define and understand quantum theory enough to advance beyond basic research, says Arne Schwettmann, University of Oklahoma assistant professor in the Homer L. Dodge Department of Physics and Astronomy.

Schwettmann is part of that effort, doing research in his laboratory on the third floor of Nielsen Hall. But despite all the work and intrigue surrounding quantum theory, the atomic clock is the only major technological application, so far.

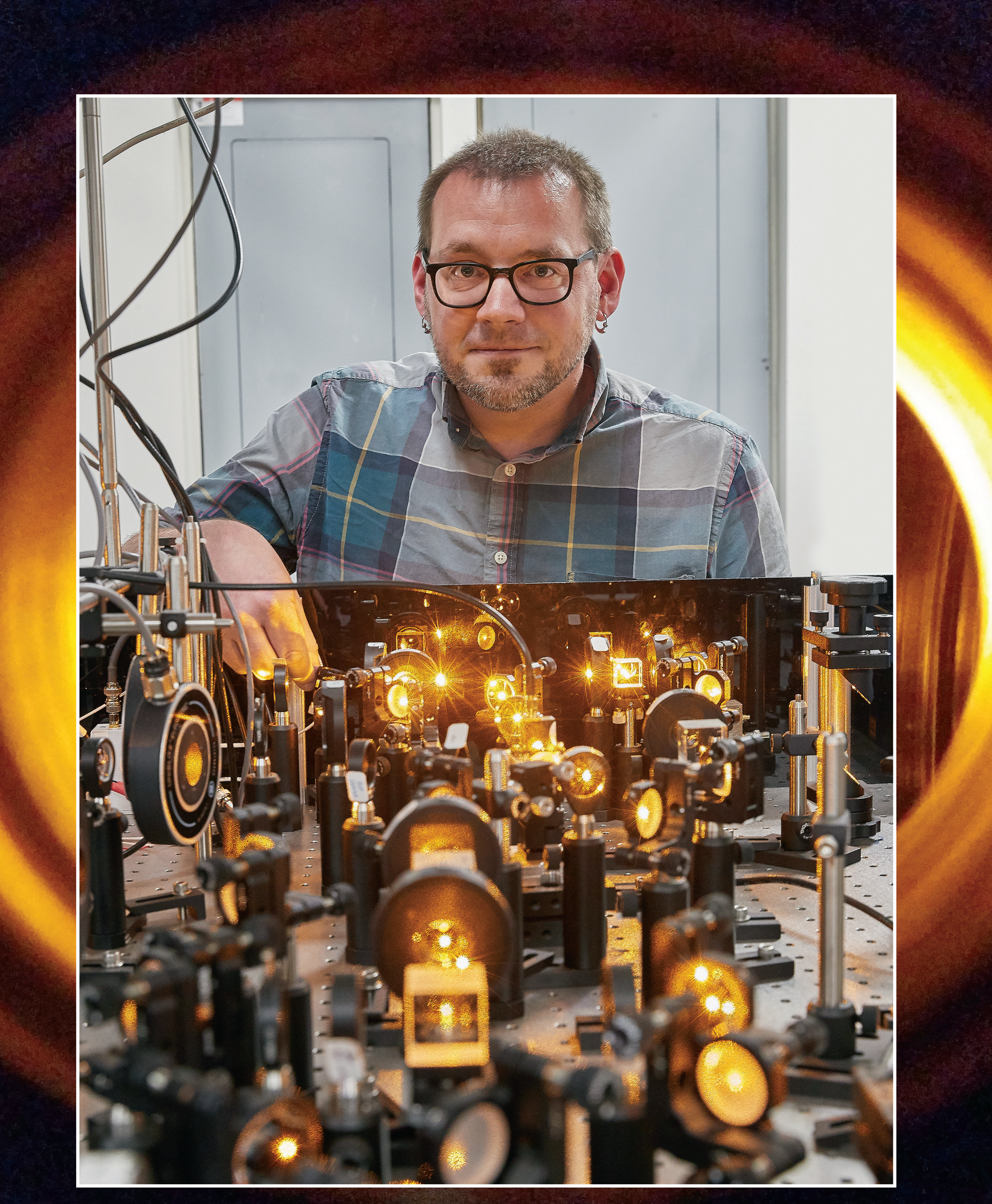
But that's about to change, Schwettmann says. He and his cadre of graduate students are part of a second revolution in physics that is bringing quantum theory out of the lab and into the mainstream where it could redefine the boundaries of applied technology. Some of the funding for his work is coming from a $500,000 Career Award Grant from the National Science Foundation.

If atomic clocks are a small example of what is ahead, the world may be in for a wild ride. These clocks have redefined the world's standard of time, providing the precise synchronization that enables advanced communication systems, modern electrical power grids and international financial networks.

They also are the tools used to keep the Global Positioning Satellite (GPS) system aligned. Without atomic clocks, parents could not use GPS tracking to follow their teenagers, businesses could not track their delivery trucks and millions of drivers would be lost without the map apps on their smart phones. Through atomic clocks, GPS has dramatically changed society by improving the way people live, travel and communicate.

"Atomic clocks are the biggest success story for quantum physics so far," Schwettmann says, "because they're an applied technology that is marketed commercially."

OPPOSITE - Professor Arne Schwettmann works on the laser-cooling apparatus. Shutters, acousto-optic modulators, and other devices allow remote control of the laser beams via a nearby computer.



Within a decade or so, the second revolution will bring a new wave of technology that could rock the mainstream the way Einstein, Bohr and Planck rattled the scientific world a hundred years ago.

Although Schwettmann says applications still may be years away, he can already see signs of that technological tide. Among the first developments will be atomic sensors capable of measuring faint microwave and gravitational fields, opening new spheres of advancement and invention.

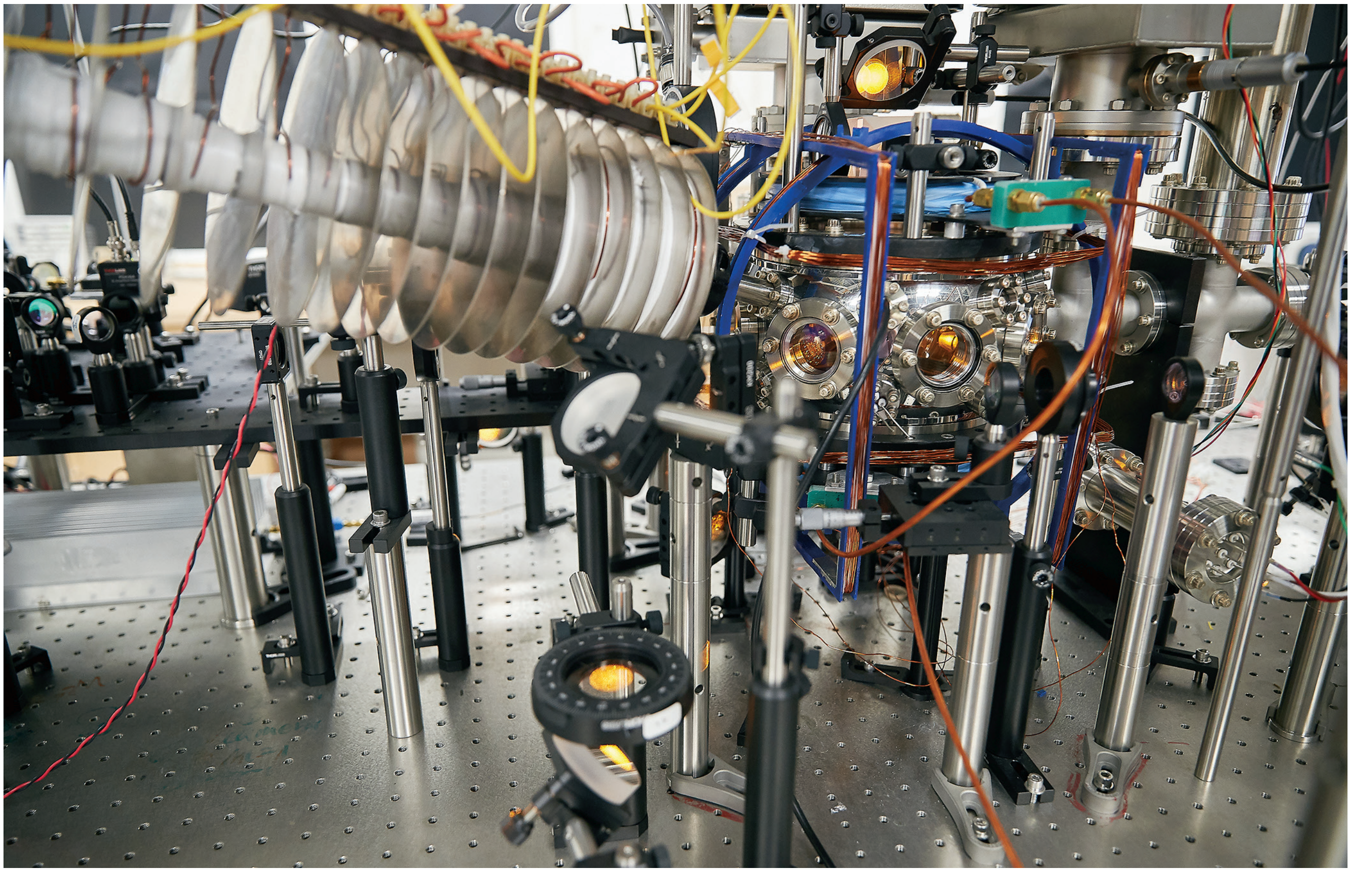
To get there, however, Schwettmann and others must further improve the experimental control of a particularly perplexing branch of quantum theory called atomic entanglement. Schwettmann, who earned his undergraduate degree from the University of Hannover in Germany and his Ph.D. from OU, stepped onto this path of discovery while doing post-doctoral work at the National Institute of Science and Technology (NIST).

After earning his doctorate in 2012, he began working under NIST Fellow William Phillips, who won the 1997 Nobel Prize in physics for developing a method of cooling and trapping atoms with laser light. Phillips shared the award with two other scientists from the United States and France.

In 2014, Schwettmann returned to Norman to continue his work in quantum physics as an OU assistant professor, and for five years, he has been developing ways to control and manipulate atoms through laser light. At the end of the road is the mystifying phenomenon of entanglement, a theory so bizarre that the chorus of doubters included Einstein himself, Schwettmann says.

According to Schwettmann, entanglement occurs as atoms collide in their natural state of motion. Entanglement happens randomly and a pair of atoms may only be entangled for an instant until subsequent collisions jar them loose. While atoms are entangled, however, there is extraordinary physical change in the way they behave, he says.

"Before entanglement, if I measure the spin of one atom it



Detail of the vacuum system in which a sodium gas is cooled to ultracold temperatures. Mirrors guide six beams of yellow laser light into the vacuum chamber.

will not affect the spin of the other atom. Schwettmann says. "After entanglement, you can measure the spin of one of the atoms and it will affect the other."

While an interesting phenomenon, it may not be all that surprising. But here's where the theory gets weird. This entanglement effect can be seen even if the two entangled atoms are separated by vast physical distances, Schwettmann says.

"It's a quantum mechanical effect that has no classical analogue," he says. "It means that I could have an atom here on Earth and another one on the moon, and if they were entangled, the spin measurement I would do here on Earth would affect the spin of the atom on the moon."

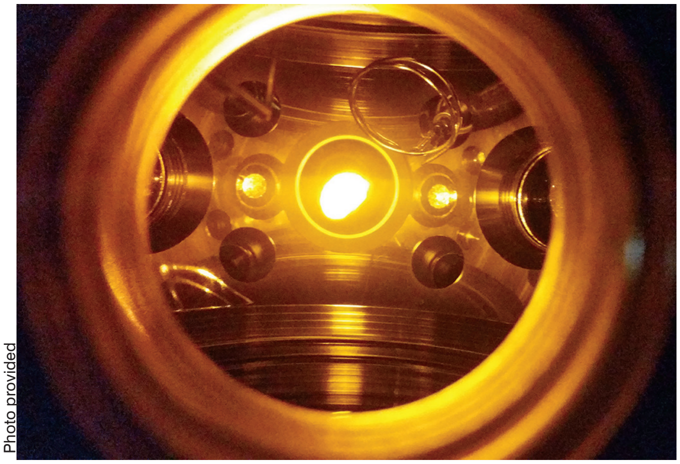


Photo provided

An ultracold cloud of sodium atoms in the center of the vacuum chamber is suspended by laser beams and magnetic fields. The size of the cloud is about 1 cm. Microwave and radiofrequency antennas, visible on the top left and top right, are then used to control spin-changing collisions and investigate the generation of entanglement.

"That's the magic of quantum entanglement," Schwettmann says.

He attributes this phenomenon to "the wave function in quantum physics," which is technical jargon that is explained through mathematical and scientific principles, such as the quantum state, the superposition principle of quantum mechanics, Hilbert space, complex-valued probability amplitude, degrees of freedom and commuting observables.

That's the language of scientists on the front lines of discovery in an area of technology that may one day harness the secrets of the universe. Schwettmann sums everything up by calling it one of the most fascinating aspects of quantum mechanics.

"It's what Einstein called the 'spooky action at a distance,'" Schwettmann says. "He didn't want to believe in it, but now there have been many experiments that have proven that quantum entanglement is real."

But Schwettmann's lab is not focused on entanglement yet. There are other mountains he must climb first. While investigators have demonstrated that entanglement between atoms is real, they only see it occur in a random, uncontrolled way.

Schwettmann is working to place atoms in a state of sustained entanglement, and when they reach that point, they will have unlocked the door to a new wave of invention in quantum mechanics. That process started with a breakthrough discovery by his mentor at the National Institute of Science and Technology.

NIST Fellow Phillips and his colleagues demonstrated how the photons that make up laser light can be used to move atoms. For Schwettmann, those photons are now the workhorses in a delicate network of lasers, mirrors and prisms that take up most of his laboratory. A little like a Rube Goldberg cartoon, Schwettmann bounces several individual beams of light off dozens of mirrors and through prisms. At the end of their journey, the photons are shot into a vacuum chamber filled with a gaseous collection of 300 million sodium atoms.

Schwettmann uses the photons to bombard his sodium atoms from six sides, forcing them into a dense cluster. Through this bombardment, the spinning and motion of his atoms slows, and their temperature becomes colder and colder, and that's the key to entanglement, he says.

Before Schwettmann can control the atoms and create entanglement, the gas must be cooled to the lowest possible temperature, which is just above absolute freezing at minus 459.67 degrees Fahrenheit. At this temperature, atoms that comprise the gas cloud stop behaving like billiard balls and they become a quantum mechanical object called a "giant matter wave" or "Bose-Einstein condensate."

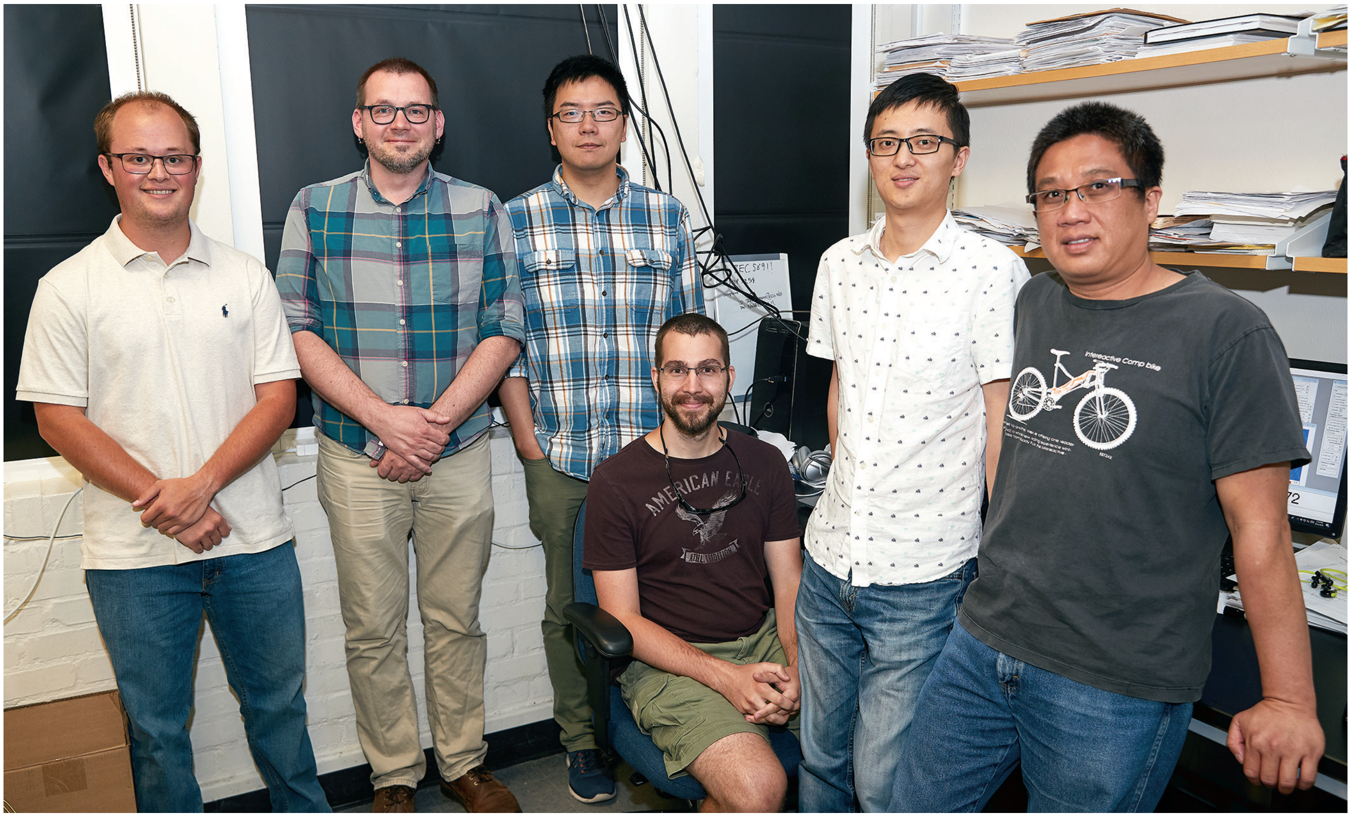
"You could think of it as superfluid, a new phase of matter like a liquid or solid, but different. Rather than behaving like individual atoms, they begin to behave like one wave, like a water wave or a sound wave. It's a collective phenomenon that undergoes changes together," he says.

"Collisions don't happen randomly anymore, but the gas begins to behave like a single object, with the collisions occurring in a controllable and predictable way."

At that temperature, he says the atoms can be radiated with microwaves to cause sustained entanglement.

"My interest is in demonstrating that entanglement can create an enhanced sensitivity," Schwettmann says. "The label for this is 'quantum enhancement,' and the idea is you can enhance the sensitivity when you use entangled atoms as sensors.

"Quantum-enhanced sensing is one of the major motiva-



Schwettmann's team includes, from left: undergraduate Cameron Cinnamon, Schwettmann and graduate students, Shan Zhong, Isaiah Morgenstern, Qimin Zhang and Hio Giap Ooi.

tions in atomic physics at the moment," he says. "The next big success story for atomic physics will be quantum-enhanced sensors."

Perhaps, a decade from now, searchers will be harnessing the sensitivity of Bose-Einstein condensate to scan for shipwrecks or crashed planes on the ocean floor. The faint but unique magnetic fields of wrecks would stand out and could be detected by these high-sensitivity instruments, Schwettmann says. For example, this type of tool may have been invaluable to searchers combing the depths of the Indian Ocean for Malaysia Airlines Flight 370, which disappeared in 2014 with 239 people on board.

In the future, geologists searching for oil and natural gas may be able to map the earth's subsurface using atomic-enhanced sensors capable of distinguishing minute changes in gravitational fields from one location to the next, Schwettmann says.

"It can be used to map the density changes in the Earth by sensing the changes in the gravitational field on the surface. Companies could determine if there is a reservoir underground without having to do seismic measurements. You can just map the gravitational field on the surface, and you can deduce what's underground because you have a very precise and high-resolution measurement of the gravitational field," he says.

OU physics department chair Phillip Gutierrez calls Schwettmann's work cutting edge.

"If you think of 300 million atoms behaving as a single particle, it's fairly amazing," he says. "The interesting thing is, it can be used for applications."

As impressive as Schwettmann's work is, Gutierrez says it is only one part of the broad tapestry of advanced science being conducted by OU's department of physics. His team of 26 faculty researchers are delving into areas such as astronomy and astrophysics, high energy particle physics, atomic and molecular particle physics, and condensed-matter physics.

Together, they represent the core of modern scientific investigation in physics, he says. "Everyone in our department has research on the cutting edge."

Gutierrez says Schwettmann is up for tenure this year, and he will soon be moving into high-technology lab space in Lin Hall, the new, adjacent physics building, where his delicate research will be protected from the interference of vibration, radio waves and power surges.

Whether Schwettmann is on the cutting edge or in a revolution, one thing is certain. The 42-year-old native of Germany is happy to be in Norman, and he's glad to be a Sooner.

"I love it here. I love being here. I love Norman," Schwettmann says. "It was an honor to come back and it is an honor to be here as a professor."

Chip Minty is a Norman-based writer and the principal of Minty Communications, LLC.