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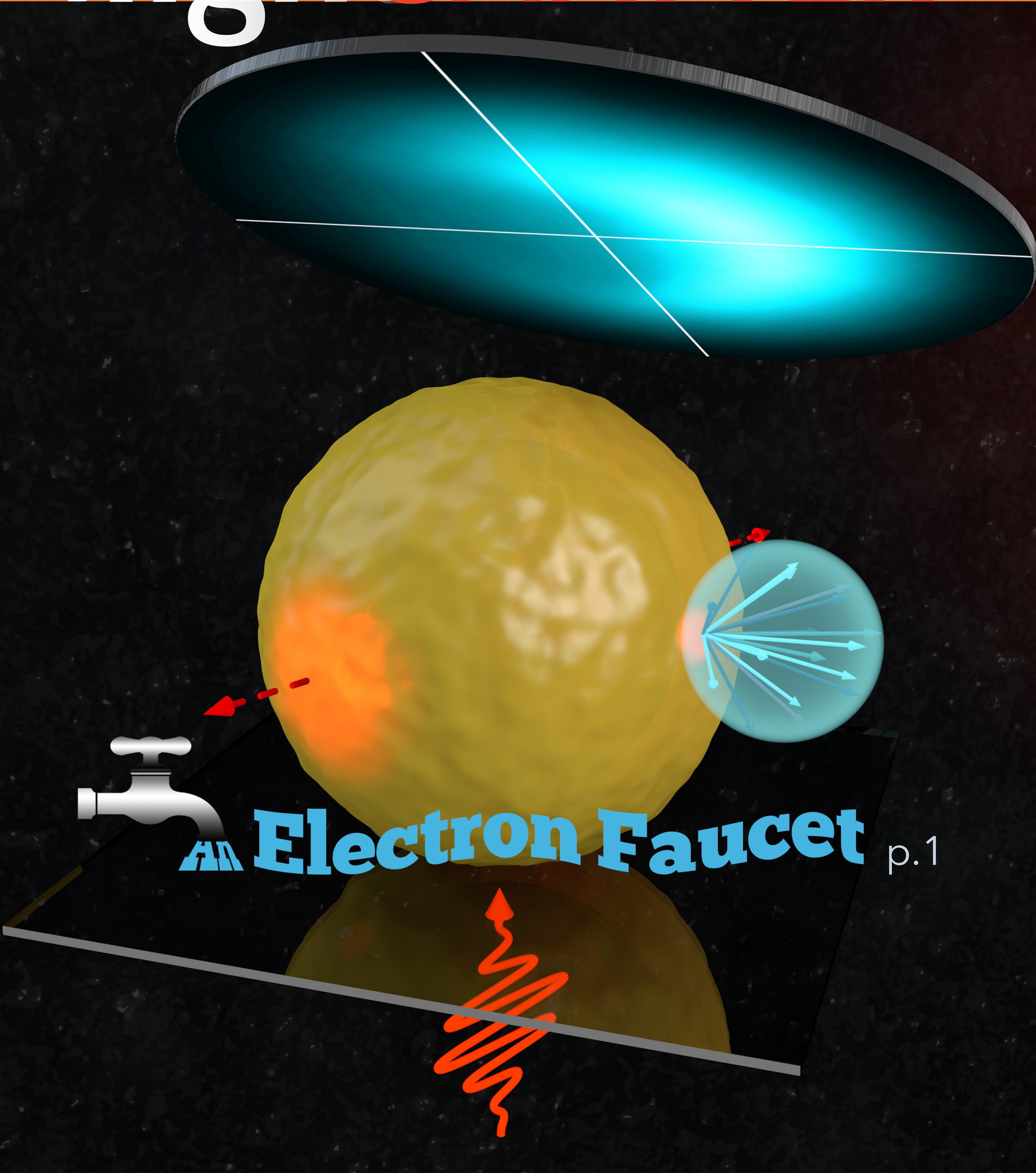
JILA light&MATTER



An Electron Faucet p. 1

Jin Fest: A Celebration of Deborah Jin's Scientific Career **was held in Boulder, Colorado on September 7 and 8, 2018. Colleagues gathered to present and discuss Deborah Jin's scientific work and related science, and to socialize.**

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Please check out this issue of *JILA Light & Matter* online at https://jila.colorado.edu/publications/jila/light-matter.

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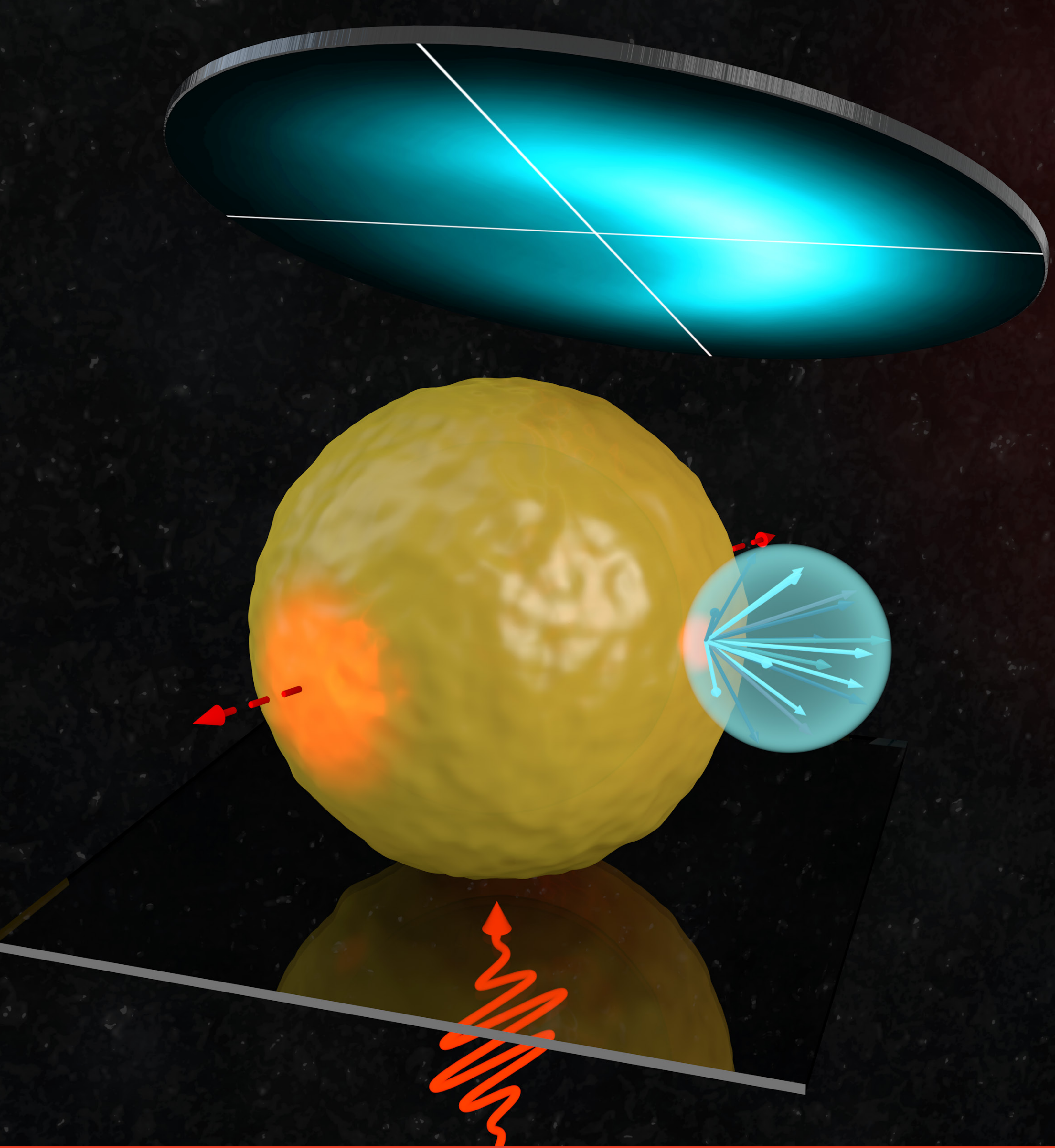
Stories

Features



Incident Infrared laser light (red) on a gold nanoshell (about 150 nm in diameter) coaxes electrons to stream (blue arrows) out of the surface; the electrons are then measured by a detector (cyan disc). A low-energy stream of electrons has many applications for electron imaging. The dashed red line represents an external electric field along the laser's polarization axis. The diffuse red glow on the sides of the shell represent the near-field enhancements due to plasmonic effects. Credit: Nesbitt Group and Steven Burrows / JILA.

Electron Faucet

Researchers from the Nesbitt Group discovered stable electron emission from nanoparticles

JILA researchers have created a laser-controlled "electron faucet", which emits a stable stream of low-energy electrons. These faucets have many applications for ultrafast switches and ultrafast electron imaging.

The electron faucet starts with gold, spherical nanoshells. "They are glass cores with a thin, gold layer over them," said Jacob Pettine, the graduate student on the project. These nanoshells are truly on the nanoscale, measuring less than 150 nanometers in diameter, which is "something like a thousandth of the size of a human hair," said Pettine.

These gold nanoshells source the electrons for Pettine's faucet. By showering the gold nanoshell with visible laser light, Pettine and Nesbitt are able to coax out an electron stream.

Electron emission is not inherently peculiar. The well-known photoelectric effect explained by Einstein describes emission of electrons when light shines on a material. Metals are particularly good materials for electron emission because they have large numbers of electrons not bound to atomic nuclei, and are therefore free to move throughout the metal. Collectively, these free electrons are called a "Fermi sea," evoking their ability to move freely in response to external forces.

When laser light strikes the surface of the metal nanoshell, it creates an electric field. Resisting change, the free electrons within the nanoshell fight the electric field by piling up against the incident surface. Within moments, however, the electric field of the laser light switches direction. In response, the free electrons barrel across the metal to accumulate on the opposite surface. This oscillation of electrons continues, creating volatile waves in the Fermi sea.

These electron waves slosh like coffee in a moving mug. And much like a walker's coffee, sometimes, electrons slosh out of their container. These "sloshed electrons" make up a metal's electron emission.

But when Pettine showered the gold nanoshells in laser light, he noticed something peculiar about their electron emission.

According to Pettine, it was peculiar that the electrons emerged in only one direction. Typically, electrons fly off in all directions, like water splashing off of a round stone.

Even more peculiar, Pettine and Nesbitt saw the direction of the electron flow change abruptly when they rotated the laser's polarization.

These peculiarities began to make sense once Pettine examined the gold nanoshells under a microscope. The nanoshells were not as spherical as expected.

"Bumpy," is how Pettine described the nanoshells. "And turns out that if you have just the right defect geometry [variation from a perfect sphere], you get really, really strong electric field enhancements in that region."

These defects, or nanocrevices, on the gold nanoshells can become "hot spots" because electric fields tend to build in curvier regions.

And the buildup of an electric field makes the crevice the easiest place for electrons to jump ship. Essentially, the crevice becomes a hot spot that emits electrons like a never-ending geyser.

But the geyser is more like a trickle, says Pettine, as the electrons have been coaxed out at low energy, rather than forcibly ripped away.

But the physics doesn't stop there. "By tuning our polarization, we can actually couple to a different defect, make it a hot spot, and kick electrons off in a different direction," said Pettine.

Changing the polarization, which is the axis of the laser's electric field, can activate different hotspots because the nanoshells' crevices materialize in random directions, and the crevices only resonate (make waves) for electric fields perpendicular to their geometry.

In the future, Pettine and Nesbitt would like to apply this technique to other nanoparticles, including nanostars, which Pettine describes as having a sea-urchin shape. Unlike the accidental crevices appearing in the gold nanoshells, the nanostars have pointy "spines" that provide large surface curvatures in many directions. By shining polarized laser light onto the nanostars, Pettine and Nesbitt hope they can gain more control over the direction of the electron emission.

A laser-controlled electron faucet with directional control has many applications in the field of electron imaging. Ultrafast laser pulses on the order of femtoseconds (10^{-15} seconds) could enable electron faucets that can switch from off, to on, and off again, on the order of femtoseconds. Such techniques could lead to improved electron imaging systems able to record dynamics on the speed at which molecules vibrate.

The work was funded by the Air Force Office of Scientific Research and the National Science Foundation.✺

J. Pettine, Grubisic, A., and Nesbitt, D.J., *The Journal of Physical Chemistry C*, **122** 14805–14813, (2018).

JILA Staff Feature

JILA staff members Dave Alchenberger, Gwen Dickinson, and Hans Green celebrated their 25th anniversary with JILA on Thursday, 7 June 2018. The anniversary celebration was annotated by fellow JILAns who have worked closely with the celebrated JILA staff.

JILA chair Tom Perkins began the event by succinctly describing how JILA staff members made research more enjoyable. "The staff lightens the load of the scientists," said Perkins; "[the staff] gives us the capability to realize our visions."

Before Alchenberger, Dickinson, and Green received their commemorative geodes, coworkers shared stories of appreciation for their work.

Dave Alchenberger

Dave Alchenberger's contribution to JILA was described by JILA Fellow Konrad Lehnert as "a big reason why I came to JILA in 2002."

Alchenberger maintains the JILA Keck lab and clean room. Currently, the Keck lab has two atomic force microscopes, an ellipsometer, a Fizeau interferometer, and two scanning electron microscopes capable of electron beam lithography, as well as a laser table for instruction on ultrafast laser technique.

Before JILA's expansion in 2012, the Keck lab was small compared to university standards, but "it had Dave, and Dave kept it humming," said Lehnert. Humming along so well, that Lehnert recalls students from across the University choosing JILA's clean room over their own department's.

Mark Carter, a JILA staff member who works closely with Dave Alchenberger, said Dave "taught me a lot of about what it means to be a leader."

Gwen Dickinson

Gwen Dickinson, professional research assistant for the Toomre Group and Rey Group at JILA, was described as indispensable by Brad Hindman, a senior research associate in the Toomre Group. Hindman specifically noted her talent of making funding bureaucracy "disappear."

And from Paris, JILA Fellow Juri Toomre sent his appreciation for Dickinson's work to aid dozen of postdocs and students through funding and visa mazes. "I need a Gwen of mine own," is what they say when these researchers leave JILA.

And JILA Fellow Ana Maria Rey also expressed appreciation for Dickinson, recalling the first time Dickinson went above and beyond Rey's expectations by volunteering to edit a 50-page manuscript. "JILA is the place that is because of people like Gwen: a round of staff that care about JILAns," said Rey.

Upon receiving her award, Dickinson took a moment to thank JILA. "A horse can't be a champion without the right trainer… JILA trains you to your full potential," said Dickinson, recalling encouragement and support she has received from fellow JILAns over the past 25 years.

Hans Green

The story of Hans Green, a technical support staffer in the instrument shop at JILA, was detailed by the previous Instrument shop leader, now JILA retiree, Blaine Horner. Green began in the shop while still a student at the University of Colorado Boulder. "A history major," said Horner, whose hobbies (which included building bikes, rebuilding cars, and even building an airplane in his own garage) soon made it clear to Horner that Green was at home in the instrument shop.

Horner noted Green's social skills too. "He's not that gruff shop guy," said Horner, "it was always clear he was a customer favorite."

And the customer favoritism is well-earned, according to JILA graduate student Roman Chapurin. Chapurin knew Green's help was "selfless" after Green once stayed at JILA past 2 am to help Chapurin and his lab mate's assemble a vacuum chamber. "And then he biked home," said Chapurin.

Beth Kroger, administrative staff for JILA, recalled when Hans helped a high school student modify his wheelchair. "For racing!" said Kroger.

Upon accepting his award, Green admitted he was excited to come to work everyday. "JILA is a functional family," said Green, "not just a family, but a very functional family."

SHAKE IT TILL YOU MAKE IT

"Well, this isn't going to work."

That was recent JILA graduate Carrie Weidner's first thought when her advisor, JILA Fellow Dana Anderson, proposed the difficult experiment: to build an interferometer unlike any before—an interferometer of shaking atoms. But her grit paid off, as this compact and robust interferometer outperforms all others in filtering and distinguishing signal direction.

While the designs of most atom interferometers are symmetric and elegant, Weidner says the shaken-lattice experiment proposed by Anderson "is more like broken eggs."

Weidner's experiment begins with an optical lattice, which is a field of laser wells that looks similar to an egg carton. Into this laser egg carton Weidner drops tens of thousands of ultracold atoms. But rather than placing one atom per well, as one does with eggs, Weidner says the atoms exist in multiple wells at the same time, as if they were leaky, broken eggs.

But the leakage is intentional, says Weidner. This leakage allows the momentum, rather than the position, of the atoms to be well defined and quantized. And this is what sets Weidner's interferometer apart from others.

Interferometers measure acceleration, or forces, by splitting and recombining waves. Interferometers have many applications today in mapping ocean floors, studying atomic properties, and watching black hole collisions.

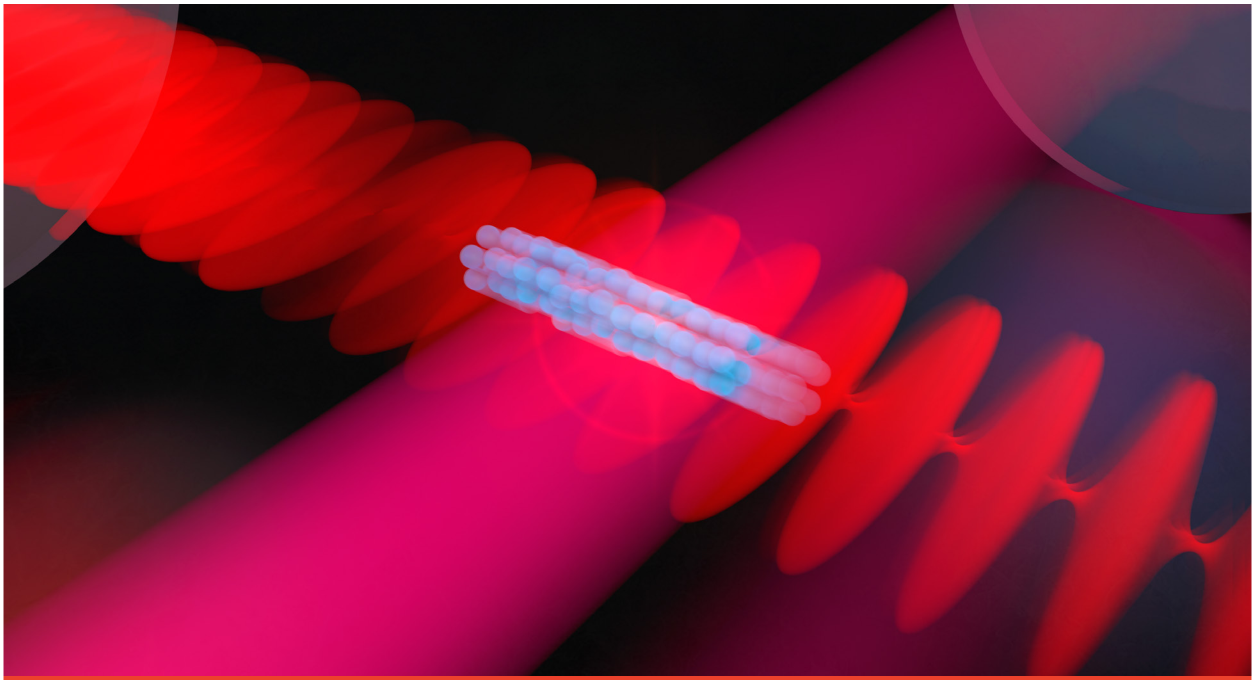
Originally interferometers split and recombined electromagnetic waves, specifically visible light. But atoms, which are also waves, can be interfered too. Weidner says atom interferometers, while more complicated, have benefits over light interferometers. "Atoms have mass, and so they aren't moving at the speed of light," explains Weidner. "Because [atoms] are slower and more massive, [atom interferometers] can actually be a lot more sensitive to certain quantities than light interferometers can be."

Unlike most atom interferometers, which split and recombine atoms' positions, Weidner's interferometer splits and recombines atoms' momentums. Shaking the optical lattice (which is not unlike shaking a carton of eggs) sends half of the atoms flying to the left, and half the atoms flying to the right. Later, the lattice is shaken such that the atoms recombine.

From this interference, Weidner can measure forces, or accelerations, applied to the system. And the longer the time between when the atoms split and recombine, the more sensitive this measurement. While Weidner has thus far only measured small forces that she purposefully applied, she predicts her experiment could be sensitive enough to measure seismological changes in the Earth. She even jokes that her experiment could one day sense a student skateboarding outside.

This interferometer can measure not only the magnitude of accelerations, but the directionality, too. This is a difficult task for most interferometers due to their symmetry; however, the asymmetry inherent in the shaken lattice (originating from the first shake moving either left or right) lends itself for this use, says Weidner.

But this novel take on a century-old tool was not easily developed. Weidner can still recall the moment her advisor, Dana Anderson, proposed the idea. Skeptical at first, Weidner set out to simulate the experiment before building.



Tens of thousands of ultracold atoms (blue) sit within an optical lattice (red) like eggs in a laser carton. By shaking the optical lattice back and forth, the Anderson Group at JILA was able to split the atoms (half moved left, half moved right) and then recombine them, thus interfering their momentum. This interferometer is capable of measuring both magnitude and direction of applied forces. Credit: Anderson Group and Steven Burrows / JILA

It was clear what the experiment needed to do: shake an optical lattice such that half of the atoms move in one direction (at a very specific speed), and half the atoms move in the opposite direction (at the same, very specific speed). But how the lattice should shake—fast, slow, or to the beat of cha-cha-cha—was not easily solvable, said Weidner. Instead, Weidner decided to have the experiment teach itself how to shake.

"I taught the experiment to run itself," said Weidner. Specifically, she created a learning algorithm that would change shaking behavior based on experimental results. This learning algorithm eventually learned how to split the atoms apart and bring them back together.

"We would run the experiment with some random shaking function, and we would get a result… then the learning algorithm would look at it and be like, 'that's not what I want, try this shaking function'," said Weidner. "I almost coded myself out of a job, but I still had to lock the lasers," she joked.

Basing the interferometer on learning algorithms not only sped the research along, it also allows the experiment to be optimized for particular signals. This feature makes the experiment robust and portable, as the experiment could potentially filter forces in a noisy environment, such as on a bumpy airplane.

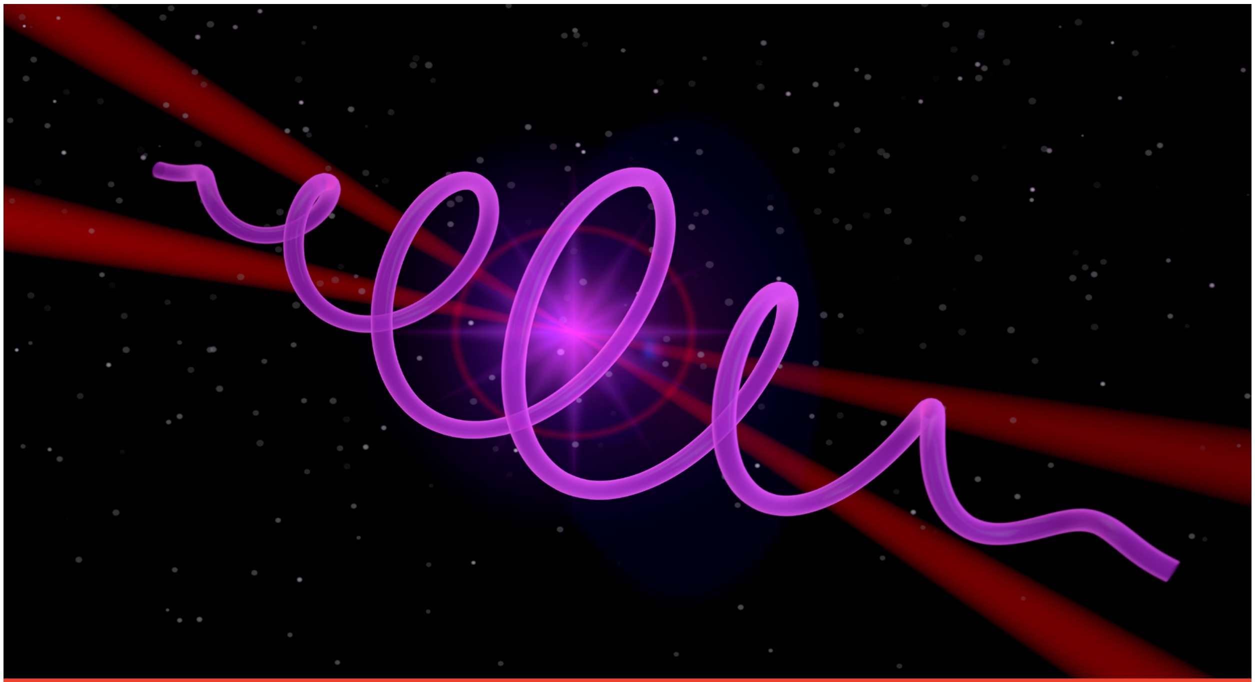
When it comes to learning algorithms, Weidner is now a firm believer. "I think the use of learning algorithms in quantum mechanical systems is really cool, and you're going to see a lot more of that in the future."

"My advice to any graduate student is, 'teach your experiment how to run itself.'"

C.A. Weidner and Anderson, D.Z., *Physical Review Letters* **120** 263201, (2018).

A Collaborative Mastery of X-rays

The hardest problems are never solved by one person. They are solved by teams; or in the case of science, collaborations. It took a collaboration of 17 researchers, including four JILA fellows and another six JILA affiliates, just a little over five years to achieve robust polarization control over isolated attosecond pulses of extreme-ultraviolet light.



It took a collaboration of 17 researchers, including four JILA fellows and another six JILA affiliates, just a little over five years to achieve robust polarization control over isolated attosecond pulses of extreme-ultraviolet light. Credit: Kapteyn-Murnane Group, Becker Group, and Steven Burrows / JILA.

In layman's terms, they smooshed oodles of energy into a temporally tiny, yet exquisitely controlled, burst of X-rays. In slang terms, they threw an X-ray sucker punch.

The complete accomplishment is indeed a mouthful. But the qualifiers detail the high degree of control the researchers now wield.

X-rays are an unruly electromagnetic wave that refuse to be controlled by typical optical tools. But the collaboration was not daunted by the formidable task. For years, JILA Fellows and their collaboration have been developing clever solutions for X-ray control.

The journey started more than twenty years ago, when JILA experimentalists first learned how to develop X-rays in a small laboratory setting. The technique, called high-harmonic generation, combines thousands of visible photons to generate just one high-energy X-ray photon.

"High harmonics have been around for a long time now," said Margaret Murnane, a JILA Fellow and experimentalist in the collaboration. "But until recently, most scientists didn't believe it possible to make circularly polarized high harmonics, not to mind attosecond bursts of circularly polarized high harmonics."

But according to Andreas Becker, a JILA Fellow and theorist in the collaboration, Murnane and JILA Fellow Henry Kapteyn were some of the best experimentalists for the task. ""[High harmonic generation] is the process that Margaret and Henry are absolute experts on," said Becker.

For the past half-decade, a collaboration between the Kapteyn-Murnane group and former group members Oren Cohen, Charles Durfee, Carlos Hernandez-Garcia, Dan Hickstein and Ming-Chang Chen, has learned to control the polarization, emission angle, and pulse length of high-harmonic X-rays. Now they have combined all of their techniques to demonstrate ultimate control: generating a single attosecond pulse of circularly polarized X-ray light.

There are innumerable imaging applications for harnessed X-ray light, however, the high energy pulses generated by this collaboration are especially useful because they are very quick—as quick as an attosecond.

To say that an attosecond is fast is an enormous understatement. According to Becker, an attosecond is a hundred thousand times faster than the vibration of a molecule. In fact, attoseconds are more akin to the timescale at which electrons move. Therefore, attosecond X-ray pulses could advance the study of electron dynamics, such as charge migration, said Becker, and help probe spin dynamics in magnetic materials, added Murnane.

Applications of this technology are further broadened by polarization control. Controlling the polarization, which is the direction of the X-ray's electric field, means the experimentalists can produce linearly, circularly, or elliptically polarized X-rays. And the asymmetry of circularly polarized light is exactly what is needed to study chiral (a type of asymmetry) molecules, said Becker.

Murnane acknowledged that collaboration was essential for this technology development. "You can tackle a harder problem if you work with a team," said Murnane. "Within JILA, we work hard to work together, and the students absorb that outlook."

While the initial high harmonics and polarization control were developed in laboratories at JILA, the final experiments demonstrating isolated attosecond pulses were completed in Taiwan in the lab of Ming-Chang Chen, a former JILA graduate student of Murnane.

Through the long trek of development, experiment and theory took turns guiding, Becker said. "First the experiment took the lead, then the theory took the lead, and then it went back to the experiment—how cool is that? It's going back and forth all the time."

The most recent collaboration of 17 researchers included ten JILA affiliates, including four JILA Fellows (Andreas Becker, Agnieszka Jaroń-Becker, Henry C. Kapteyn and Margaret M. Murnane), two former JILA graduate students (Jennifer L. Ellis and Daniel D. Hickstein), one former JILA postdoctoral researcher (Carlos Hernández-García), two former JILA visiting fellows (Charles G. Durfee, and Luis Plaja), and one former JILA graduate student, Ming-Chang Chen, who is now a physics professor at the National Tsing Hua University in Taiwan.

P.-C. Huang, Hernández-García, C., Huang, J.-T., Huang, P.-Y., Lu, C.-H., Rego, L., Hickstein, D.D., Ellis, J.L., Jaron-Becker, A., Becker, A., Yang, S.-D., Durfee, C.G., Plaja, L., Kapteyn, H.C., Murnane, M.M., Kung, A.H., and Chen, M.-C., *Nature Photonics* **12** 349–354, (2018).

IN THE NEWS

JILA, CIRES, NOAA researchers honored with 2018 Governor's Awards

Two teams affiliated with CU Boulder have been recognized for their impact on the state of Colorado through research on tabletop lasers and the role of consumer products in air pollution.

CO-LABS announced this week that Margaret Murnane and Henry Kapteyn of JILA were one of three winners of its prestigious Governor's Awards for High-Impact Research. Brian McDonald of the Cooperative Institute for Research in Environmental Sciences (CIRES) also led a team that earned an honorable mention in this year's awards. CO-LABS is a consortium of Colorado-based federal research laboratories, research universities, state and local governments, economic development organizations, private businesses and nonprofit organizations.

Colorado Gov. John Hickenlooper said in a statement that this year's award winners "highlight the diversity and impact of the science and technology coming out of Colorado's research labs that make our state and the world a better place."

"We're thrilled that researchers from CU Boulder and several of our affiliated research institutes–CIRES and JILA–are receiving this honor," said Vice Chancellor for Research & Innovation Terri Fiez. "We believe that collaboration is key to achieving maximum impact, so it is fitting that these collaborations between the university and NOAA and NIST are being recognized for the impact they are having in Colorado and beyond."

Ultrafast lasers

Murnane, Kapteyn and their colleagues from JILA, a joint-institute of CU Boulder and the National Institute for Standards and Technology (NIST), earned a nod for their years of efforts to wrangle X-ray light.

The group debuted the world's first tabletop X-ray laser in 2007. Today, these devices can shoot out pulses of radiation at a millionth of a billionth of a second—fast enough for scientists to image molecules in the act of forming and breaking chemical bonds. In addition to peering at the workings of atoms, such lasers may also enable new types of semiconductors and medical technologies like CT scans.

To commercialize their inventions, Murnane and Kapteyn launched the company KMLabs in the 1990s. The husband and wife team also help to lead the STROBE National Science Foundation Science and Technology Center. Among other activities, STROBE supports undergraduate students at six universities, including CU Boulder, to "advance imaging science and technology and build the microscopes of the future."

"The quantum technologies and microscopes that the STROBE team and our group are developing are allowing us to understand how advanced materials work—the materials that will be used for next-generation energy-efficient and lightweight nanotechnologies," said Murnane and Kapteyn, both professors in the Department of Physics. "We are also passionate about growing high tech employment opportunities in Colorado."

Now in its tenth year, the Governor's Awards event brings together scientists, researchers, entrepreneurs, business leaders and government officials to celebrate exceptional work.

This year's honorees were formally recognized and celebrated on Thursday, October 4, 2018 from 5-9 p.m. at the Denver Museum of Nature & Science in Denver, Colorado.

This article is a repost of the 23 August 2018 CU Boulder Today article.

Sara Campbell named HHMI Fellow

Recent JILA graduate Dr. Sara Campbell was announced to be a 2018 HHMI Hanna Gray Fellows this morning.

The Howard Hughes Medical Institute (HHMI) announced their selection of 15 early career scientists as the 2018 HHMI Hanna Gray Fellows on 12 September 2018. The fellowship, named for Hanna Holborn Gray, the former chair of the HHMI trustees and former president of the University of Chicago, seeks to encourage talented early career scientists who have the potential to make significant contributions to science and become leaders in academic research.

The 15 new Fellows are all recent Ph.D. scientists continuing training as postdoctoral researchers in various fields including microscopy, parasites, biomaterials and nerve circuitry. As fellows, they will receive up to $1.4 million each in funding over the course of eight years, from early postdoctoral training through several years of a tenure-track faculty position.

Dr. Campbell earned her Ph.D. from JILA in 2017 by improving the Fermi-degenerate three-dimensional optical lattice clock in the lab of JILA Fellow Jun Ye. Campbell is now a postdoctoral researcher at the University of California Berkeley studying phase contrast electron microscopy with Dr. Holger Müller and Dr. Eva Nogales. For her fellowship, Campbell proposed using high-powered lasers to manipulate the electron beams used in microscopy to help make ultra-precise measurements of biological molecules and visualize their interactions at the atomic level.

Research proposals from all new Fellows can be find at HHMI.org

Jun Ye Stars in Feature Film

JILAn Jun Ye hit the big screen this summer as he debuted in the feature-length documentary, "The Most Unknown".

"The Most Unknown" brings together nine scientists from across the globe, all of whom are using science to answer deep philosophical questions, such as how did life begin, and what is time? The scientists are brought together, ("blind-date style," as the New Yorker's review accurately describes it) to discuss how their work from various fields might overlap.

According to a New York Times review, "'The Most Unknown' works best as inspiration to delve deeper into these disciplines, and as a celebration of science."

The full 85-minute film was produced by Motherboard, Vice's media tech-culture channel, and directed by Emmy-nominated and Peabody Award-winning filmmaker Ian Cheney and advised by world-renowned filmmaker Werner Herzog. The film was made possible by a grant from Science Sandbox, a Simons Foundation initiative dedicated to engaging everyone with the process of science.

The film was first released on 18 May 2018 in select U.S. theatres. As of August, the film is streaming on Netflix.

A live screening with special guests was held at the University of Colorado Boulder on Monday, October 1st.

Watch the trailer at: https://youtu.be/VtUaZk3_Njk

"BEC's in Space" Now a Reality

JILA's favorite degenerate, the Bose-Einstein Condensate (BEC), has a new home: the International Space Station (ISS).

This new acheivement is "multi-mega-awesome," according to JILA Fellow Eric Cornell. BECs became a staple for measuring quantum phenomenon when they were experimentally realized in 1995 by JILA Fellows Eric Cornell and Carl Wieman at the University of Colorado Boulder, and by Wolfgang Ketterle at MIT.

Here on Earth, BEC experiments are plagued by the constant tug of gravity. To prevent a BEC from smashing into Earth, all Earth-bound BEC experiments must tightly confine the condensate, in either laser-based or magnetic traps.

But in a microgravity environment, like that of the ISS, the pull of gravity is lessened. This allows condensates to forgo typical confinement, resulting in longer lifetimes of up to 10 seconds (much longer than the fraction of a second that Earth-bound BEC's are stable). These long lifetimes will allow space BEC's to achieve much lower densities, and therefore much lower temperatures, than their Earth-bond counterparts.

To generate BEC's on the International Space Station, NASA's Jet Propulsion Laboratory launched CAL, a remotely operated Cold Atom Laboratory. At the heart of CAL is a vacuum chamber ("about the size of a stick of butter," says *Science*) and atom chip built by JILA Fellow Dana Anderson's company, ColdQuanta. Anderson's chip helps cool and trap the atoms, all necessary steps to generating a BEC.

Supplies to build the laboratory were launched this past May. CAL confirmed this July that BEC's of Rubidium-87 have been created, but they are still working to generate BEC's of both Potassium-39 and Potassium-41.

Lorraine Volsky, former SRO Director of JILA, passed away

Former JILAn Lorraine Volsky passed away on July 21, 2018. Lorraine worked at JILA from 1968 to 2013; leading the JILA Scientific Reports Office (now Science Communications Office) for the bulk of that time.

Lorraine Marie Halbower Volsky passed away early Saturday morning, July 21, 2018, at her Boulder residence, attended by family and friends. She was 88. Lorraine was born in Anthony, Kansas, where she grew up a hard-working farm girl with a keen interest in music and photography. She attended Kansas State University, where she earned her undergraduate degree in Journalism, as well as meeting and marrying her husband of 51 years, Dr. Theodore Volsky.

The Volskys settled in Boulder in the 60s, where Lorraine began her career at the University of Colorado as an editor at JILA - then known as the Joint Institute for Laboratory Astrophysics. For nearly 40 years, she helped physicists, astronauts, and research scientists remain readable, accurate, and relevant with her sharp eye and her ever-present red pencil. During that time, she and her husband rarely missed a CU football game, and were active participants in the World Affairs conference.

After retirement, Lorraine became a world traveler. Always curious, she visited more than 26 countries throughout Europe, South America, and Asia, often participating in local customs and adventurous activities including canoeing in the Yucatan, zip-lining through Costa Rica, and riding elephants in India, all the while creating extensive photo records of her experiences. Well known for her deep love and appreciation for music, dance, and theater, Lorraine also enjoyed sporty cars, good detective novels, and contributed generously to many charitable organizations, particularly those concerned with environment and animal welfare.

She will be missed by all who knew her, and especially by her daughters, Christine Northrup and Pam Vevea. No service is planned at this time. Those wishing to remember Lorraine in the spirit in which she lived are invited to contribute to the World Wildlife Fund, or their local philharmonic orchestra.

Rabin Paudel awarded Nepal Bidhya Bhusa

Recent JILA graduate Dr. Rabin Paudel was awarded the Nepal Bidhya Bhusan this September.

The Nepal Bidhya Bhusan is the highest academic award given by the Nepalese government.

This year, Nepalese president Bidhya Devi Bhandari gave 233 Bidhya Bhusan Padak (Medals) to Nepalese nationals who have demonstrated outstanding performance in Ph.D., Masters, of Bachelor's level academics, at local and foreign universities. The highest level of this award is reserved for those holding Ph.D. degrees.

Paudel earned his Ph.D. from the University of Colorado Boulder in 2017. His thesis work, which detailed the probing of strongly interacting Fermi gases, was advised by late JILA Fellow Deborah Jin. Paudel is now a senior optical engineer at Cymer LLC in San Diego, CA.

The Nepal Bidhya Bhushan ceremony took place in Kathmandu at Sital Niwas, the official presidential palace of Nepal, on International Literacy Day and Nepal's 39th National Education Day, the 8th of September 2018.

Sara Campbell Finalist for 2018 Laser Science Dissertation Award

Former JILA graduate student Dr. Sara Cambell has been named a finalist for the 2018 American Physical Society's Carl E. Anderson Division of Laser Science Dissertation Award for her doctoral work on the Fermi-degenerate three-dimensional optical lattice clock.

Campbell presented her thesis research during a special session at the Frontiers in Optics/Laser Science meeting September 16–20, 2018 in Washington, DC. This is the fifth year of the competition, and the pool of nominees was exceptionally strong. As a finalist, she also received a travel grant of $750 from the APS Division of Laser Science to attend.

Cindy Regal Named 2018 GRC Cruickshank Lecturer

JILA Fellow Cindy Regal has been named a 2018 Alexander M. Cruickshank Lecturer by the Gordon Research Conferences (GRC).

This prestigious title is given worldwide to scientists at the top of their fields in the physical, chemical, and biological sciences.

Regal presented her Cruickshank Lecture, entitled "Interferometers Harnessing Micromechanical Motion for Quantum Metrology and Information", on Sunday, 29 July 2018, after the introductory dinner of the Quantum Science GRC.

The 2018 GRC in Quantum Science was held at Stonehill College in Easton, MA, 29 July–3 August 2018. The 2018 GRC in Quantum Science is chaired by JILA Fellow and 2017 Cruickshank Lecturer Dr. Ana Maria Rey and Dr. Andrew Houck of Princeton University. The Quantum Science GRC brings together senior scientists, along with students and postdocs, to discuss the frontiers of quantum science and report experimental and theoretical advances.

Past Alexander M. Cruickshank Lecturers include Nobel Laureates Eric Cornell of JILA and Dave Wineland of NIST Boulder. Other past winners with ties to JILA include Ana Maria Rey (JILA Fellow), Immanuel Bloch (Ludwig-Maximilians University and Max Planck Institute of Quantum Optics), Mikhail Lukin (Max Planck Institute of Quantum Optics and Harvard University), and 1997 Nobel Laureate Claude Cohen-Tannoudji (University of Paris).

The Alexander M. Cruickshank lectures were established by the GRC Board of Trustees to honor former director Dr. Cruickshank. These lectures, presented at Gordon Conferences, keep with the GRC tradition of presenting research at the frontiers of Science.

Jan Hall donates medal to CU

John "Jan" Hall, 2005 winner of the Nobel Prize in physics for his work in harnessing light to make ultra-precise measurements, has donated his Nobel medal and accompanying original artwork to the university to inspire current and prospective students.

Hall, a fellow and senior research associate at JILA—a joint institute on campus between CU Boulder and the National Institute of Standards and Technology—presented his Nobel medal in a May 8 reception at the Heritage Center in Old Main.

During the ceremony, Jan and Lindy Hall talked about their hope that students can view the symbols of achievement and "dream the big dream of advancement and success."

"There could never be enough time or opportunity to deliver an individual message of hope, inspiration and encouragement to each individual," Lindy Hall said at the reception. "Let the memorabilia begin that process and lead to ambitious goal-setting and remarkable outcomes."

Jan Hall is one of five CU Boulder faculty members to win a Nobel Prize.

Hall's Nobel Prize along with those from all of CU's Nobel laureates will have an impressive impact when displayed in three locations on campus: the Heritage Center, the new Center for Academic Success and Excellence (CASE) and in the existing exhibit in the Duane Physics Building.

In celebration of receiving Hall's Nobel Prize gold medal and diploma, the Heritage Center is planning a dedicated gallery to honor all five of the Nobel laureates. Previously, the museum received the replica medal and original diploma in chemistry from Tom Cech, the first CU Nobel Prize laureate. Exhibit panels will educate visitors about the creator of the prize, Alfred Nobel, and explain the history and the ceremonial traditions of receiving the Nobel Prize. Each of CU's laureates will be featured with visual descriptions of their work and interactive video. A unique aspect of the display will be the panels dedicated to the Peace Prize listing CU faculty, staff and alumni who have participated in these significant humanitarian ventures.

The CASE building will become the gateway to CU Boulder with thousands of visitors, students, alumni and prospective students expected to pass through the doors each year. A display highlighting CU Boulder's academic strengths and excellence will be installed with a panel dedicated to CU's Nobel laureates.

These displays will showcase the ground-breaking scientific achievements conducted by all five Nobel laureates at CU Boulder.

This article is a repost of the 28 June 2018 CU Boulder Today article.

JILA Graduate Students Julia Cline and William Cairncross swept the student poster awards at DAMOP 2018.

The Topical Group on Precision Measurement and Fundamental Constants (GPMFC) hosts a student poster competition at the annual meeting for Division for Atomic, Molecular & Optical Physics (DAMOP).

The competition has two categories: (1) Atomic Clocks and Sensors and (2) Fundamental Constants, EDM's and CP Violation. Students submitting DAMOP poster abstracts on precision measurements can participate in the GPFMC Student Poster competition. From submitted abstracts, four finalists are chosen in each category.

Julia Cline, a graduate student in the Thompson group, won the Atomic Clocks and Sensors category with her poster entitled, "Superradiant Lasing on the Millihertz Clock Transition".

William Cairncross, a graudate student in the Cornell and Ye group, won the Fundamental Constants, EDM's and CP Violation category with his poster entitled, "Towards an Order of Magntiude Improved Senstivitiy to the Electron's EDM with Trapped HfF+".

The winners in each category received a $500 cash prize and were recognized at the DAMOP 2018 banquet.

Ralph Jimenez Receives Arthur S. Flemming Award for Outstanding Public Service

JILA Fellow and NIST Physicist Ralph Jimenez received the 2017 Arthur S. Flemming Award for outstanding public service as a Federal employee. Jimenez was one of 12 honorees from across all parts of the Federal government to receive the Flemming Award this cycle. Jimenez was a winner in the Applied Science and Engineering category for his pioneering research on combining microfluidics, ultrafast lasers, biochemistry and molecular biology to dramatically accelerate the creation and characterization of specialized biomolecules to serve as sensors within living cells.

"I'm honored to join a very distinguished group of JILA/NIST colleagues who have won this award, including Tom Perkins, Jun Ye, Debbie Jin and David Nesbitt," said Jimenez.

The Flemming Award program, established in 1948, is administered by the George Washington University's Trachtenberg School of Public Policy and Public Administration to recognize outstanding accomplishments by Federal government employees within the first 15 years of their service. Awards are presented in the categories of Applied Science and Engineering (Jimenez's category), Basic Science, Social Science, Clinical Trials, Legal Achievement, and Leadership and Management.

JILA Flemming Award winners have included David Nesbitt (1991), Debbie Jin (2003), Jun Ye (2005), and Tom Perkins (2013), as well as former JILAns Lewis Branscomb, Pete Bender, David Hummer, and Steve Leone. Other well-known Flemming winners have included astronaut Neil Armstrong, Francis Collins (NIH Director and Human Genome Project leader), Anthony Fauci (Director of the National Institute of Allergy and Infectious Disease and pioneer in characterizing HIV), and NIST Nobel Physics Laureate Bill Phillips, among many other prominent winners.

Jimenez officially received the award in a ceremony at George Washington University in Washington, DC on June 4, 2018.

John Robinson wins IFCS Student Paper Competition

JILA graduate student John Robinson won the Student Paper Competition at the 2018 IEEE International Frequency Control Symposium (IFCS).

Finalists for the Student Paper Competition were selected by abstracts, and final judgements were based on poster presentations.

The competition was divided into six groups. Robinson was competing in the Optical Frequency Standards and Applications group. Robinson's winning poster, entitled "Thermal Noise Limited Optical Cavity at 4 Kelvin: Paving the Way for the Next Generation Optical Clock", was awarded for "advancing the state of the art in cryogenic cavity performance."

"This has been a wonderful team effort and I'm deeply indebted to each and every one of you. I hope to continue this great fun and joy of working in the lab. It truly is the best thing in the world," said Robinson to his labmates upon winning the prize. Robinson, currently a fourth year graduate student, works in the Ye lab at JILA.

The 2018 IEEE IFCS was held 21–24 May in Olympic Valley, CA.

JILA Fellow Jun Ye was also in attendance, and was awarded the I. I. Rabi Award "For the development of stable, reproducible, and accurate atomic clocks based on optical lattices, and the use of those clocks to probe fundamental atomic interactions and quantum many-body systems."

Ben Saarel named Outstanding Graduate and PAC-12 Scholar-Athlete of the Year

It was a busy week for recent CU Boulder graduate Benjamin (Ben) Saarel.

Saarel, who for the past two years has worked as an undergraduate researcher in JILA Fellow Heather Lewandowski's lab, graduated summa cum laude on 10 May 2018, earning his B.S. in Engineering Physics, and a minor in Computer Science. But that's not all.

Saarel was named the Outstanding Graduate in Engineering Physics at his graduation. But that's not all.

Saarel, an avid runner, competed in the PAC-12 Championships, in Palo Alto, CA, on 13 May 2018. Saarel earned first place in the 5000-meter run, clocking in at 14:11.23. But that's still not all!

That same weekend, Saarl was named the PAC-12 Men's Track and Field Scholar-Athlete of the Year. According to the PAC-12 website, eligible students must be resident seniors with a cumulative GPA of 3.0 or higher, on track to receive a degree, and have participated in at least 50 percent of scheduled contests. The Scholar-Athletes of the Year in each sport will receive a commemorative award.

Twisting Atoms to Push Quantum Limits

The chaos within a black hole scrambles information. Gravity tugs on time in tiny, discrete steps. A phantom-like presence pervades our universe, yet evades detection. These intangible phenomena may seem like mere conjectures of science fiction, but in reality, experimental comprehension is not far, in neither time nor space.

Astronomical advances in quantum simulators and quantum sensors will likely be made within the decade, and the leading experiments for black holes, gravitons, and dark matter will be not in space, but in basements—sitting on tables, in a black room lit only by lasers.

These experiments, generally called quantum precision measurements, are leading the forefront of our fundamental understanding of the universe. These experiments use QIST (Quantum Information Science and Technology) phenomena to study and harness the quantum behavior of atoms, ions, and molecules, yet can fit within a food truck. Their power lies in their precision, or more colloquially, their sensitivity. Current quantum precision experiments, such as JILA's atomic clock, have sensitivities of nearly 10^{-19}[1], and with only a little more[2], this clock will be capable of detecting gravitational waves caused by colliding black holes, or measuring gravity's influence on time. There's only one problem: we've already hit the limit of quantum precision.

The limit of quantum precision is defined by the Standard Quantum Limit, or SQL for short. Inherent to quantum measurements, SQL defines the inevitable quantum noise that arises from wave function collapse. This noise is not unlike the noise in a coin toss experiment, where more throws better estimate equal outcomes of heads and tails.

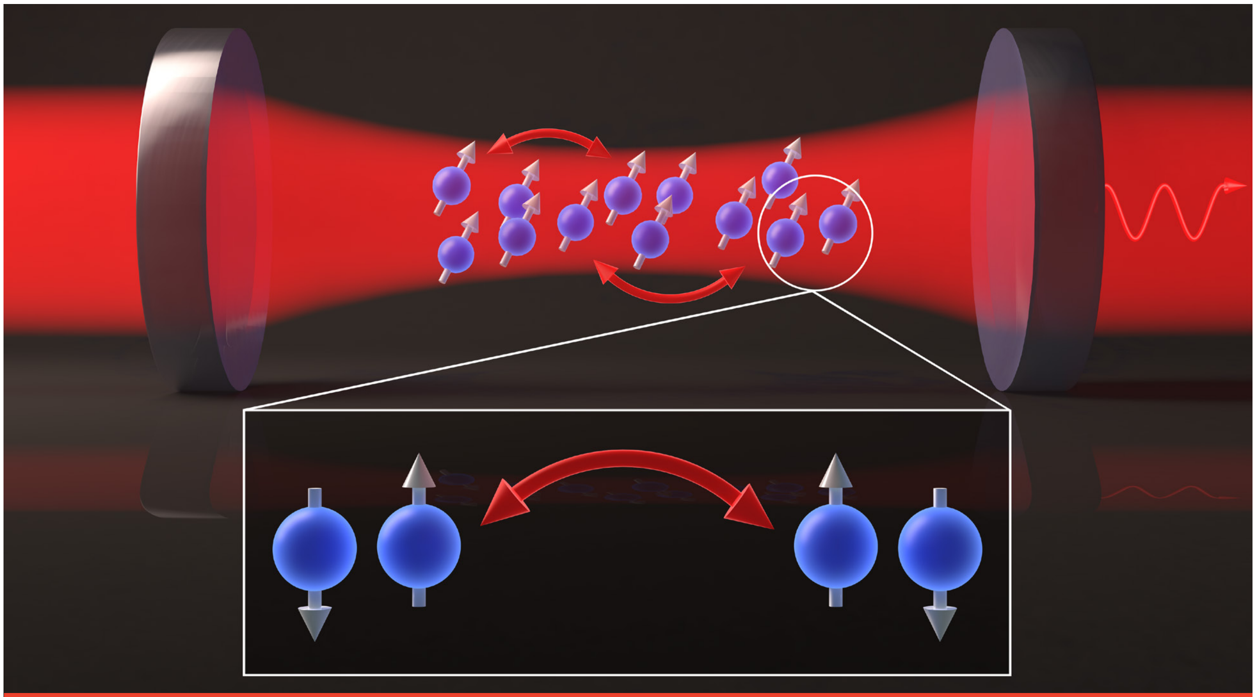
But according to JILA Fellows Ana Maria Rey and James Thompson, unordinary quantum experiments could access precisions beyond the standard limit. Quantum noise can be evaded, Thompson explained, by harnessing quantum entanglement. "When two atoms are entangled, the quantum noise of one atom cancels the quantum noise of another atom."

Atoms can become entangled by undergoing a coherent interaction called spin exchange. "The physics [behind spin exchange] is very easy," explained Rey, as she described two atoms exchanging a photon to swap energy quantified by spin. When the atoms swap spins, they become entangled, meaning measuring the spin of one atom gives immediate information about the spin of the second atom. If two coins could be entangled, for example, then one coin landing heads would force the second coin to land tails.

The physics of spin exchange may be easy to understand, but the physical feat is anything but easy for the atoms. Two atoms may be many centimeters apart when they exchange spins. For these tiny atoms, that is the spatial equivalent of two humans discussing a coin toss while one is in Europe, and the other is on the far side of the sun.

To spur long-distance relationships between two atoms, researchers in the Thompson lab placed tens of thousands of Strontium atoms between two mirrors. The scene then plays out like an apathetic game of catch: Bored of standing around, a random atom tosses a photon into the void. The mirrors then bounce that photon back and forth,

1. With a current precision of 2.5 x 10^{-19}, the atomic clock loses less than a second within the age of the universe.
2. About two orders of magnitude more precision.



The cavity mode mediates spin-exchange interactions in which one atom emits a photon into the cavity that is then absorbed by another atom, driving anti-correlated spin flips. Credit: Rey Group, Thompson Group, and Steven Burrows / JILA

back and forth, beating on, borne back ceaselessly into the – boom! A second atom steps up and catches the photon. And just like that, the two atoms, tosser and catcher, swap spins.

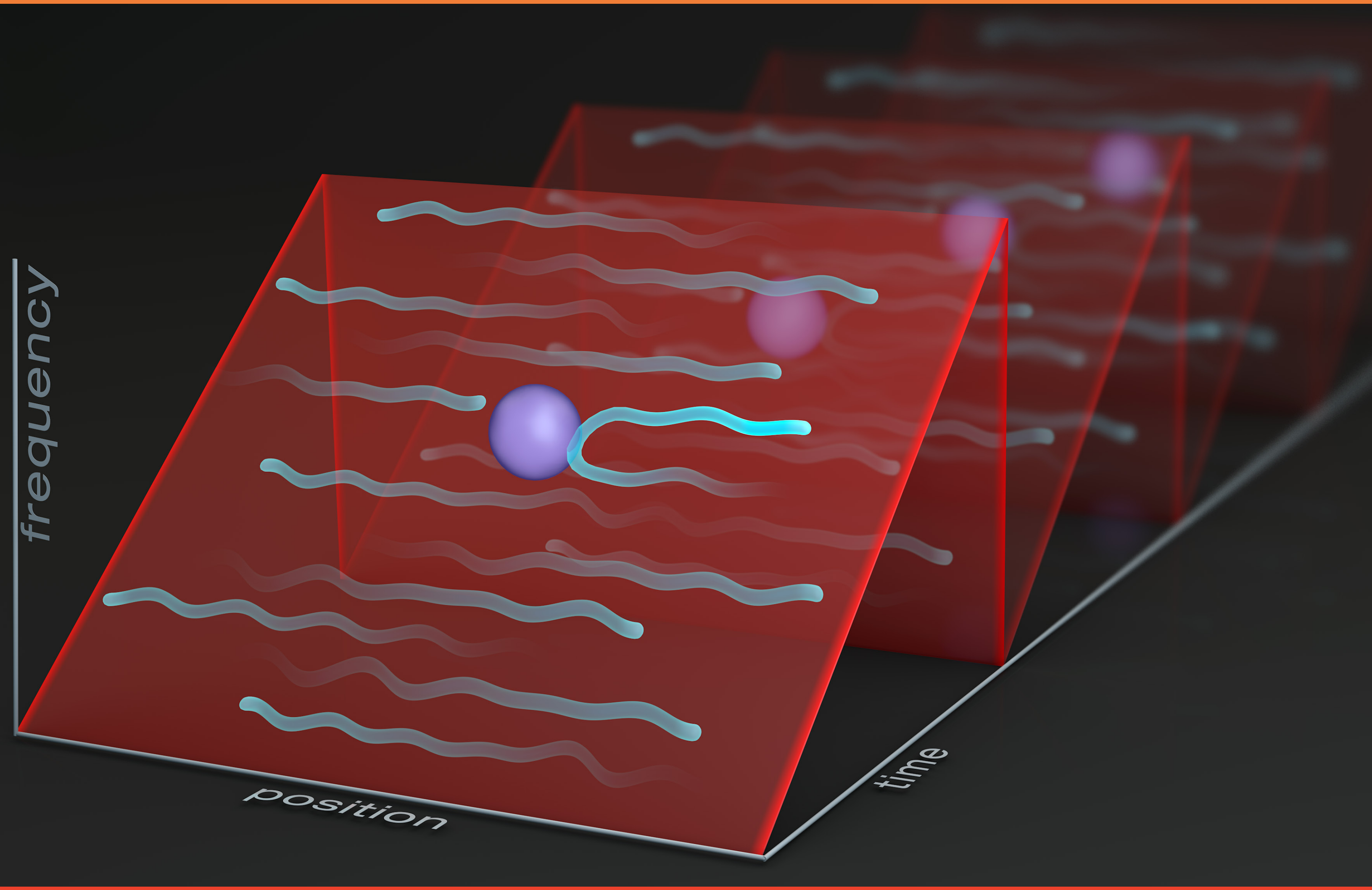
The group confirmed spin exchange interactions were indeed occurring by witnessing one-axis twisting. According to Rey, if a circle represents standard quantum noise, then one-axis twisting is "the circle sheering into an ellipse." By redistributing the quantum noise along one dimension, it is reduced along the other. This one-axis twisting is a first step towards spin squeezing, added Thompson, which is a type of entanglement.

And the group was further pleased when they saw an "energy gap" emerge. An energy gap is like a penalty: atoms that misalign must pay for their rebellion with an energy fee. According to Thompson, the energy gap is generated by an effective magnetic field that can be sourced to the strong atom alignment. In other words, the aligning atoms encourage all others to align. "They create a kind of peer pressure," said Thompson, "it's hard to go against the crowd."

Because the energy gap encourages atoms to maintain their spins, both Rey and Thompson believe the gap could protect entangled states from becoming disentangled. But the group has yet to observe this protection, as they need to first generate entangled states.

This will happen soon, promised Rey. "We have measured this gap. We have shown that this gap exists. And therefore, for the future, when we can generate actual entanglement, it is going to be useful because it is going to be able to protect our entangled states for longer times."✺

M.A. Norcia, Lewis-Swan, R.J., Cline, J.R.K., Zhu, B., Rey, A.M., and Thompson, J.K., *Science* **361** 259–262, (2018).



A JILA collaboration between the Thompson and Holland groups has produced a new laser cooling technique, dubbed SWAP cooling, that cools atoms faster than traditional methods. The technique ramps the laser frequency (red) in a sawtooth pattern. This ramping method permits atoms (purple) to slow not only when they absorb photons (cyan), but also when they emit photons. In Norcia's system, this technique quadrupled the cooling forces experienced by the atoms. Credit: Holland Group, Thompson Group, and Steven Burrows / JILA

A Little Less Spontaneous

Some of the greatest discoveries are accidental. This story is no exception.

A large fraction of JILA research relies on laser cooling of atoms, ions and molecules for applications as diverse as world-leading atomic clocks, human-controlled chemistry, quantum information, new forms of ultracold matter and the search for new details of the origins of the universe. JILAns use laser cooling every day in their research, and have mastered the arcane details of the process.

So it was a surprise when an accidental discovery in a JILA lab, coupled with new theory to explain that discovery, created an entirely new, more robust method of laser cooling, potentially advancing nearly all current JILA research using laser cooling, and opening new areas of research.

The new JILA laser cooling technique, dubbed sawtooth-wave adiabatic passage cooling (SWAP), uses stimulated emission, rather than spontaneous emission, to increase cooling forces. This new technique, detailed in a recent *New Journal of Physics* publication, is ideal for cooling atoms with narrow linewidth transitions, such as those with expansive frequency metrology applications (e.g., atomic clocks). The technique could also have applications for cooling molecules, which are difficult to cool via traditional laser cooling because they have many more internal states than atoms.

"If you undergo spontaneous emission [in a molecule] you can branch into states that are not cooled, or not trapped, and then you'll lose those molecules," explained Matt Norcia, former graduate student on the project, now postdoctoral researcher at JILA. But the control of stimulated emission, present in the new cooling technique, could keep the molecules from decaying into an invisible state.

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Traditional laser cooling relies on a process called spontaneous emission. Atoms absorb photons from an oncoming laser, and this absorption slows the atom down, similar to how catching an oncoming baseball slows down a skateboarder. Slower atoms mean colder atoms, and the more photons caught, the colder the atom.

But an atom can only catch one photon at a time, and an atom must release a caught photon before it can catch a new one. This is where spontaneity becomes important. In traditional laser cooling, atoms drop photons spontaneously, meaning without any external encouragement.

This is where the new laser cooling technique differs, said Norcia. SWAP cooling provides atoms with external encouragement. This process, called stimulated emission, encourages atoms to throw photons in the same direction that the atom is traveling. Similar to how a forward-moving skateboarder slows after throwing a ball forwards, stimulated emission in SWAP cooling also slows the atoms.

In Norcia's system, SWAP cooling exerted slowing forces four times stronger than traditional cooling. This factor of four is derived from, [1] doubling the number of cooling mechanisms–i.e., from only photon absorption, to both photon absorption and stimulated photon emission and [2] doubling the rate of photon absorption, because stimulated atoms can drop photons twice as fast, said Norcia.

But this technique is not all stimulated emission. "Spontaneous emission is still very important for this mechanism, even though it's role is reduced," said Norcia.

Understanding the nuances behind spontaneity's role in this new technique was John Bartolotta's job, a JILA graduate student in the Holland group. According to Bartolotta, spontaneous emission acts as a fail-safe, without which SWAP cooling could easily lead to heating.

"When the velocity [of the atom] is too low, at that point, the time between the resonances just becomes arbitrarily small," said Bartolotta.

This means that, as the atom slows down, the window of time between when the atom can catch a photon, and throw a photon, shrinks (due to a frequency phenomenon called Doppler shifting). Because an atom can only throw a photon so fast, as an atom slows, the probability it will be left holding onto a photon increases. This is bad, because if the atom starts a new ramp cycle while still holding a photon, the atom will be encouraged to throw the photon backwards instead of forwards (due to Doppler shifts causing resonance with counter propagating lasers). And a backwards throw would cause the atom to speed up.

But spontaneous emission corrects this failure mode before it can derail the cooling process. If an atom fails to throw a photon forward via stimulation, that atom could drop the photon spontaneously. This would prevent the atom from starting a new ramp cycle with a photon, and overall prevents the system from heating, said Bartolotta.

In a soon-to-be-publishd article, Bartolotta calculated the efficiency of SWAP cooling for various initial parameters, including an atom's linewidth, which is the inverse of how fast an atom will wait before spontaneously dropping a photon.

"If gamma [the linewidth] is very, very, very small, Doppler [traditional] cooling doesn't seem like a good option, because you have to wait after every single absorption for it to decay," explained Bartolotta. "Whereas here [with SWAP cooling], it actually gets better, and faster, and more robust if gamma is small." This is why atoms with narrow linewidths, such as alkaline-earth metals, are ideal candidates for this cooling process, said Bartolotta.

This cooling technique is simple to implement in the lab. "Basically, I pressed a button on the function generator," said Norcia, the experimentalist.

This function generator swept the frequency of the cooling laser, and the button Norcia pressed changed the shape of the sweep from triangular (ramp up, ramp down), to saw tooth (ramp up, slam down). "We stumbled upon this," said Norcia of his discovery.

"If you think about it, it's not too difficult of a system. It's just a two-level system interacting with a laser," mulled Bartolotta. "It is a nice, elegant problem, and it was surprising that it was so hard to make tractable."

This novel laser cooling technique was experimentally developed by Matt Norcia, JILA graduate Julia Cline, and JILA Fellow James Thompson. The theoretical framework that examined the breadth of applications of this technique was developed by theorists John Bartolotta and JILA Fellow Murray Holland. The technique was first published in February 2018 in *New Journal of Physics*.

JILA experimentalists are already hard at work applying this technique to more technical cooling schemes. They have already seen promising results (to be published soon) along a Raman transition. And soon they hope to publish results of using this technique to create a 3D Magneto-Optical Trap of Strontium, said JILA Fellow James Thompson.✺

M.A. Norcia, Cline, J.R.K., Bartolotta, J.P., Holland, M.J., and Thompson, J.K., *New Journal of Physics* **20**, 023021 (2018).

Classic Sci-Fi Scramble

Unscramble the titles of 20 classic science fiction novels. The first correctly-answered puzzle dropped off to Kristin Conrad (X415) will win a $25 gift card.

EHT HSOEMLIDED NMA	
EDR RSAM	
ROLWSEF OFR ANLGENOR	
EHT FVORERE AWR	
ETH UNONIDFTOA LORTGIY	
DRILNORGW	
TEH SRATS MY OTTSNANIIED	
EHT MRNIATA NRHCSLCIOE	
TEH LTEF HADN OF ENSKSDAR	
A NAICLCET FRO EOBWLIIZT	
RE'DSNE EMAG	
HTE MIET HMEICAN	
RNEEAUNRMOC	
ENTIENEN R-ETOYHGIUF	
HET SSSDSPEIDEOS	
UEEDNVSRZO IHTW RAAM	
SENRGATR NI A GSATNER DLAN	
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HNIEORYP	

JILA is a joint institute of the University of Colorado Boulder and the National Institute of Standards and Technology

University of Colorado **Boulder**

National Institute of Standards and Technology
U.S. Department of Commerce

About JILA

JILA was founded in 1962 as a joint institute of CU Boulder and NIST. JILA is located at the base of the Rocky Mountains on the CU Boulder campus, next to the Duane Physics complex.

JILA's faculty includes two Nobel laureates, Eric Cornell and John Hall, as well as two John D. and Catherine T. MacArthur Fellows, Margaret Murnane and Ana Maria Rey. JILA's CU members hold faculty appointments in the Departments of Physics; Astrophysical & Planetary Science; Chemistry; Biochemistry; and Molecular, Cellular & Developmental Biology as well as in the School of Engineering. NIST's Quantum Physics Division members hold adjoint faculty appointments at CU in the same departments.

The wide-ranging interests of our scientists have made JILA one of the nation's leading research institutes in the physical sciences. They explore some of today's most challenging and fundamental scientific questions about quantum physics, the design of precision optical and x-ray lasers, the fundamental principles underlying the interaction of light and matter, and processes that have governed the evolution of the Universe for nearly 14 billion years. Research topics range from the small, frigid world governed by the laws of quantum mechanics through the physics of biological and chemical systems to the processes that shape the stars and galaxies. JILA science encompasses eight broad categories: Astrophysics, Atomic & Molecular Physics, Biophysics, Chemical Physics, Laser Physics, Nanoscience, Precision Measurement, and Quantum Information Science & Technology.

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