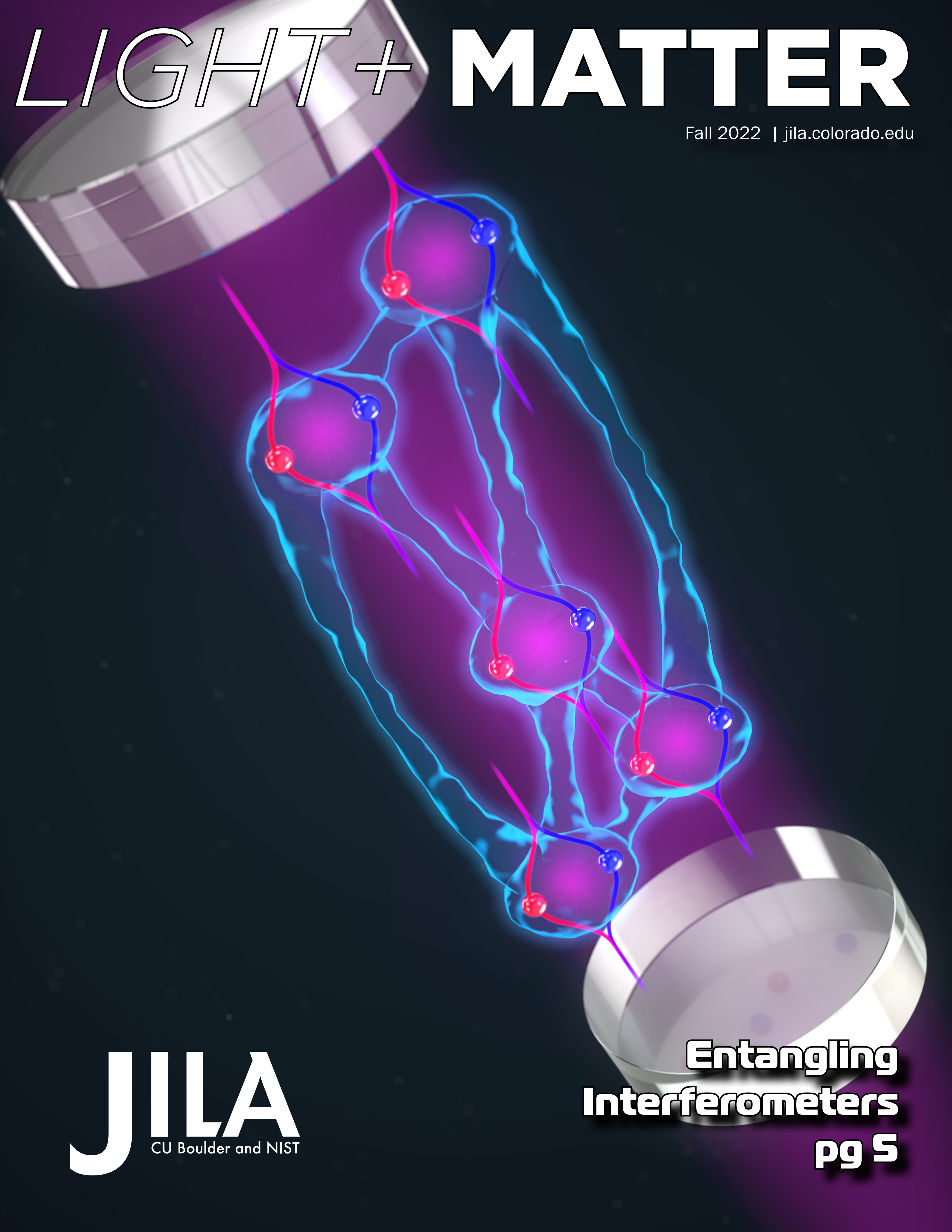

LIGHT+ MATTER

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Entangling Interferometers pg 5

JILA
CU Boulder and NIST

(From left to right then below) JILA custodians Boua Sayavong, Claudia Acosta, Nouan Saengdara and Beatriz Soto are acknowledged for their contributions to JILA by bumping elbows with JILA Chair and NIST Fellow Konrad Lehnert for Custodial Appreciation Day

Credit: Steven Burrows/JILA

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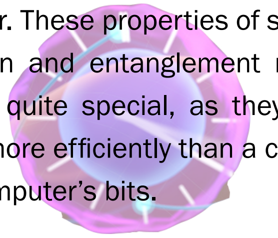
Research Highlights

Feature Articles

Seeing Quantum Weirdness: Superposition, Entanglement, and Tunneling

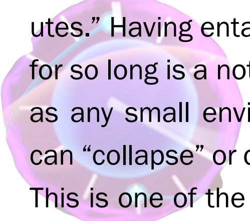
Quantum science promises a range of technological breakthroughs, such as quantum computers that can help discover new pharmaceuticals or quantum sensors for navigation. These capabilities rest on two unusual properties of quantum systems, superposition and entanglement. Just as a computer register stores information in the zeros or ones of classical bits, quantum bits, or qubits, store quantum information—but in the quantum world, superposition allows the qubit to be both a zero and a one at the same time. Furthermore, multiple qubits can be bizarrely correlated through a process called entanglement. When two qubits are entangled with each other, each qubit individually looks to be in a random state, but measuring one qubit reveals perfect information about its entangled partner. These properties of superposition and entanglement make qubits quite special, as they can work more efficiently than a classical computer's bits.



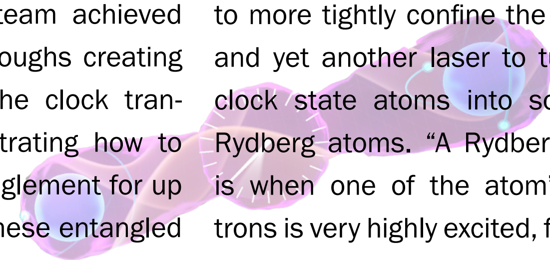
However, a common challenge in actually using these quantum systems arises due to their limited memory time, or "coherence" time, which is often measured in milliseconds. Many researchers at JILA study and use superposition and entanglement of quantum systems, including JILA fellow Adam Kaufman. Previously, Kaufman and his research team focused on improving the coherence time of the strontium atoms' superposition between the ground state and the "clock" state, so named because these two states form the basis for state-of-the-art atomic clocks. As reported in two new papers, researchers from this lab have extended these studies to much larger system sizes, with an atom in a superposition of hundreds of locations, and separately, demonstrating optical clock entanglement with seconds-scale coherence time.

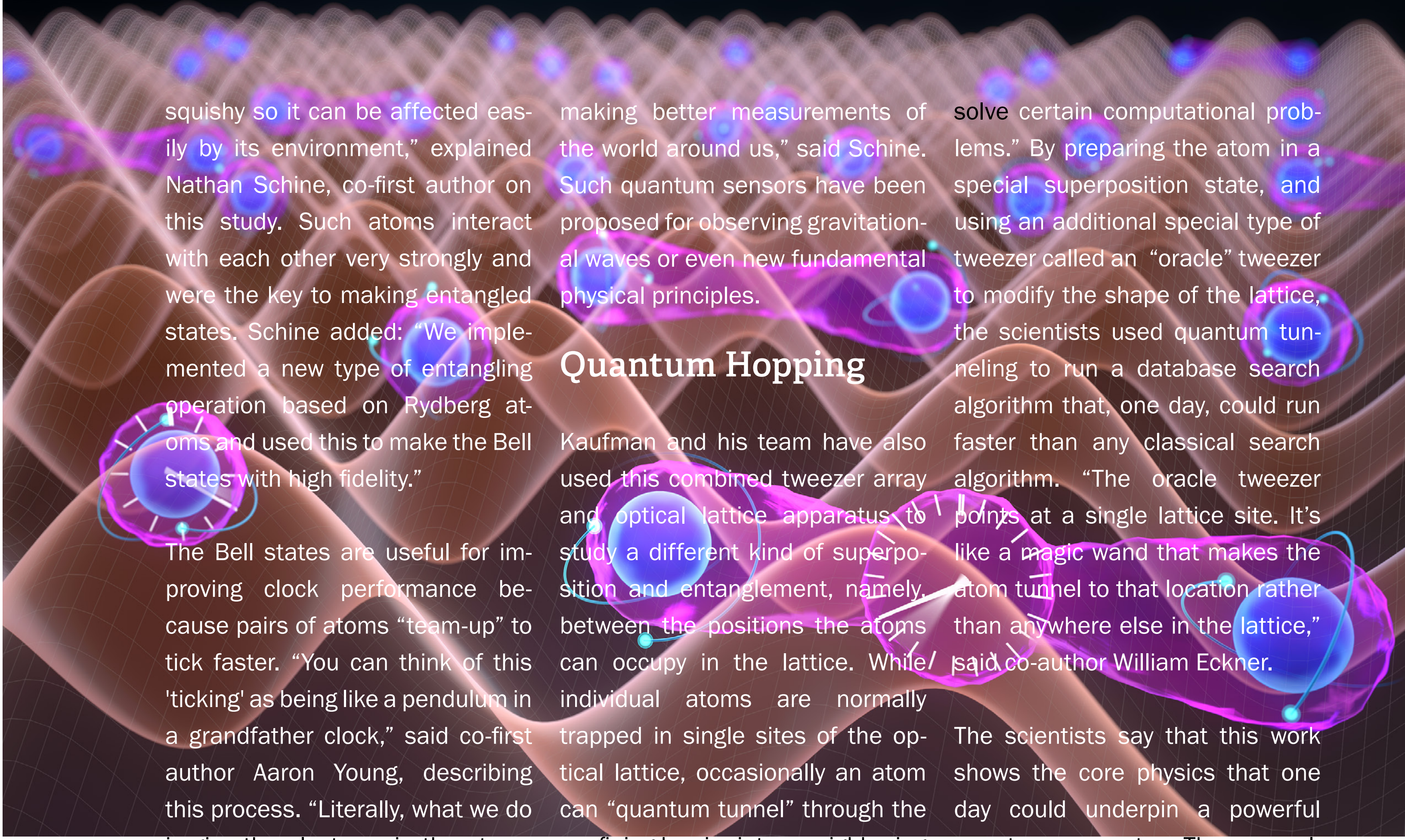
Long-Lived Entanglement

In a new article published in *Nature Physics*, this team achieved two major breakthroughs creating entanglement on the clock transition and demonstrating how to preserve that entanglement for up to four seconds. "These entangled states are called Bell states, and are useful for quantum-enhanced atomic clocks," said Kaufman, referring to a particular quantum state of two atoms in which the atoms are both in the ground state and both in the clock state at the same time. Kaufman continued, "But to be useful for improving clock performance, the Bell states need to persist on long timescales, hopefully, seconds or even minutes." Having entangled states live for so long is a notorious challenge as any small environmental noise can "collapse" or destroy the state. This is one of the reasons why qubits are so fragile.



To create these Bell states, the researchers used a tweezer array, a two-dimensional grid of tightly focused spots of laser light. In each of the spots, a single atom can be trapped and manipulated while inside ofa chamber with an ultra-high vaccuum. The team then used additional lasers in a configuration known as an optical lattice to more tightly confine the atoms, and yet another laser to turn the clock state atoms into so-called Rydberg atoms. "A Rydberg atom is when one of the atom's electrons is very highly excited, far from the core...like popping popcorn, the electron goes from small and tightly bound to relatively big and





squishy so it can be affected easily by its environment," explained Nathan Schine, co-first author on this study. Such atoms interact with each other very strongly and were the key to making entangled states. Schine added: "We implemented a new type of entangling operation based on Rydberg atoms and used this to make the Bell states with high fidelity."

The Bell states are useful for improving clock performance because pairs of atoms "team-up" to tick faster. "You can think of this 'ticking' as being like a pendulum in a grandfather clock," said co-first author Aaron Young, describing this process. "Literally, what we do is give the electrons in the atoms a little kick and they oscillate. How quickly they oscillate and how long it takes them to wind down sets the precision of your clock. What's exciting about this experiment is that we're giving pairs of atoms a much more complicated kick, such that these two little pendula oscillate in a way that's somehow even more coordinated than just having two independent pendulums that are oscillating in lockstep."

This work fits into an ongoing collaboration between JILA fellows Adam Kaufman and Jun Ye, who operate record-setting atomic clocks. "Networking an entangled clock in our lab...with an entangled clock [in the Ye lab] across the hall could be very exciting for making better measurements of the world around us," said Schine. Such quantum sensors have been proposed for observing gravitational waves or even new fundamental physical principles.

Quantum Hopping

Kaufman and his team have also used this combined tweezer array and optical lattice apparatus to study a different kind of superposition and entanglement, namely, between the positions the atoms can occupy in the lattice. While individual atoms are normally trapped in single sites of the optical lattice, occasionally an atom can "quantum tunnel" through the confining barrier into a neighboring site. Over time the atom takes multiple steps in what is called a quantum random walk and ends up in a superposition of an exponentially increasing number of different paths through which the atom has wandered across the lattice.

In a recent article published in *Science*, the Kaufman group observed how a single atom coherently walks over several hundred lattice sites, traversing tens of thousands of different paths. "All those paths coherently interfere, giving us these beautiful interference patterns," lead author Aaron Young explained. "What's more, by carefully controlling all these different paths, we can use the resulting interference to solve certain computational problems." By preparing the atom in a special superposition state, and using an additional special type of tweezer called an "oracle" tweezer to modify the shape of the lattice, the scientists used quantum tunneling to run a database search algorithm that, one day, could run faster than any classical search algorithm. "The oracle tweezer points at a single lattice site. It's like a magic wand that makes the atom tunnel to that location rather than anywhere else in the lattice," said co-author William Eckner.

The scientists say that this work shows the core physics that one day could underpin a powerful quantum computer. They are already hard at work attacking previously intractable problems involving many atoms tunneling around simultaneously in the lattice.

Nathan Schine, Aaron W. Young, William J. Eckner, Michael J. Martin, and Adam M. Kaufman. " Long-lived Bell states in an array of optical clock qubits." Nature Physics. 18(9): 1067–1073 (2022).

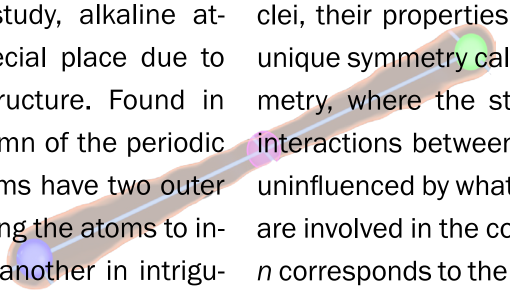
Aaron W. Young, William J. Eckner, Nathan Schine, Andrew M. Childs, Adam M. Kaufman. " Tweezer-programmable 2D quantum walks in a Hubbard-regime lattice" Science. 377(6608): 885-889 (2022).

Written by Kenna Hughes-Castleberry

Above: Long-lived entangelement of Bell state pairs compared to single unentangled atoms in a 3D optical lattice. The Bell state "stopwatch" (right) ticks twice as fast than that of a single atom (left), holding the promise of higher stability and higher bandwidth for optical clocks.

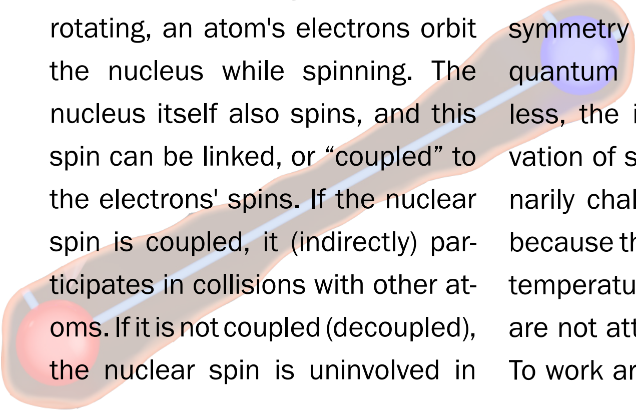
Credit: Steven Burrows/Kaufman

Clearing Quantum Traffic Jams under the SU(*n*) of Symmetric Collisions



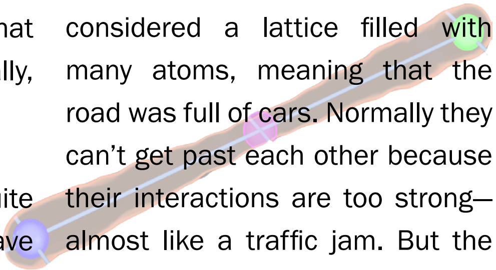
Of all the atoms that quantum physicists study, alkaline atoms hold a special place due to their unique structure. Found in the second column of the periodic table, these atoms have two outer electrons, allowing the atoms to interact with one another in intriguing ways. “They have received a lot of attention in recent years among the physics community because of two reasons,” explained JILA and NIST Fellow Ana Maria Rey. “One is that they have a unique atomic structure, which makes them ideal for atomic clocks. This is because they have a long-lived electronic excited state that can live longer than 100 seconds. The second is that their electronic and nuclear spin degrees of freedom are highly decoupled and therefore the nuclear spins do not participate in the atomic collisions.”

Like planets orbiting the Sun while rotating, an atom's electrons orbit the nucleus while spinning. The nucleus itself also spins, and this spin can be linked, or “coupled” to the electrons' spins. If the nuclear spin is coupled, it (indirectly) participates in collisions with other atoms. If it is not coupled (decoupled), the nuclear spin is uninvolved in these collisions. For decoupled nuclei, their properties give rise to a unique symmetry called SU(*n*) symmetry, where the strength of the interactions between the atoms is uninfluenced by what nuclear spins are involved in the collisions. “Here *n* corresponds to the number of nuclear spin states,” Rey added. “In an alkaline earth atom like strontium, it can be up to 10.” In a new paper published in *PRX Quantum,* Rey and her team of researchers proposed a new method for seeing the quantum effects enabled by SU(*n*) symmetry in current experimental conditions, something that has been challenging, historically, for physicists.



“The SU(*n*) symmetry is really quite a unique property which can have tremendous consequences in the quantum world,” Rey said. “Theorists have predicted unique equilibrium states emerging from SU(*n*) symmetry including what are called quantum spin liquids. Nevertheless, the issue is that the observation of such phases is extraordinarily challenging for experiments because they require extremely low temperatures which at the moment are not attainable [or] accessible.” To work around this challenge, the team proposed to study the quantum dynamics that SU(*n*) symmetry enables in an out-of-equilibrium setting, with a proposed system having a very strong synthetic magnetic field, which would affect how the atoms behaved, allowing for more fine tuning without the need for ultracold temperatures.

A Quantum Traffic Jam



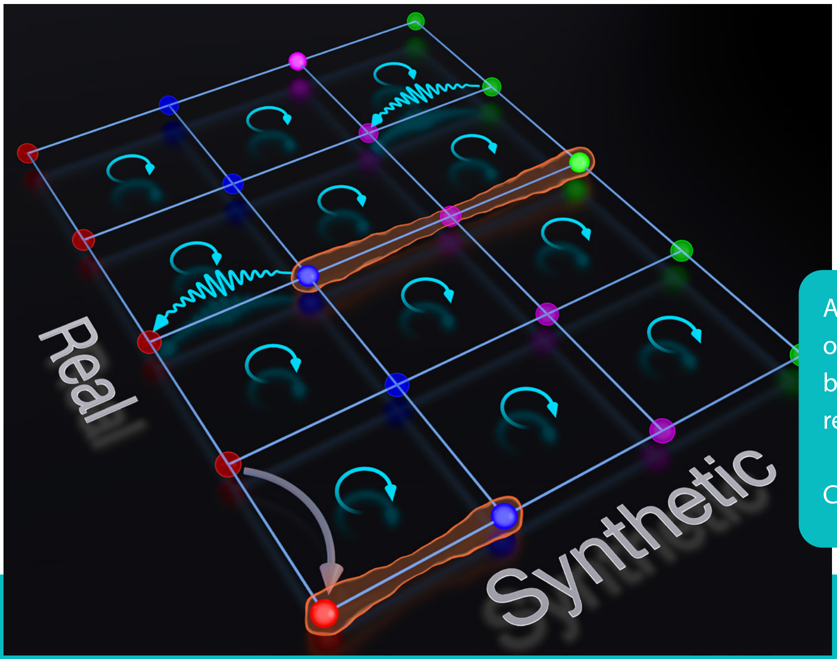
Imagine the quantum world as a road, where each atom is a car taking up space. Rey and her team considered a lattice filled with many atoms, meaning that the road was full of cars. Normally they can’t get past each other because their interactions are too strong—almost like a traffic jam. But the nuclear spin can help. Rey elaborated: “Because we have at hand up to n=10 nuclear spin levels for these atoms, we decided to look at them as an additional dimension, i.e., a synthetic dimension. More specifically, if we imagine the atoms are confined to move along a one-dimensional array of wells, then the combination of the spatial 1-D array and then-internal [nuclear spin states] levels can be visualized as a synthetic *n*-leg ladder.”

So, the nuclear spin states can be thought of as additional lanes on the road, which can help clear the jam. Under the right conditions (resonances of the magnetic field) the interactions, or “collisions”, can even make it easier for the atoms to get past each other.

The team proposed using laser beams to couple the nuclear spins in such a way that they act as if they were charged particles in a magnetic field—the field enables the atoms to change their spin when they move, allowing them to “change lanes”. “Using lasers, we could emulate a magnetic field that pierces through this ladder,” said Mikhail Mamaev, first author and graduate student in Rey's group. “So, when you've got a synthetically 2-D system with magnetic fields, the typical signature is that of chiral flow. If I have this ladder, stuff on top of the ladder will flow one way, and stuff on the bottom of the ladder will flow in the equal and opposite way.” This means that the researchers can predict the particles’ movements. Mamaev continued: “Near the resonances enabled by interactions, which happen when atoms are driven at the right conditions, they can move past each other by trading the driving energy for interaction energy, and feature such asymmetric flow patterns in response to the magnetic field.” Looking at the interactions in the quantum traffic jam, the researchers found that the particles could move around each other by switching energies. With their proposed new method, Rey and her team offered a new way to study the role played by SU(*n*) symmetry interactions that allow atoms to pick any lane they want.

Digging into the Quantum Hall Effect

For decades, physicists have been interested in a process called the quantum Hall effect. “It's a phenomenon where a transverse electric field develops in a solid material when it carries an electric current and is placed in a magnetic field that is perpendicular to the current,” stated Rey. “In the quantum version of the Hall effect, the longitudinal current features a series of spikes, or resonances at certain values of magnetic field. That means at specific values of the magnetic field, electrons become mobile and generate a special current of their own.” The researchers found a similar process within their simulations when considering SU(*n*) symmetric interacting cold atoms in synthetic magnetic fields. “We found that at specific values of the laser intensity used to engineer the effective magnetic field, atoms become free to move. These ‘resonances’ resemble the ones found not only in the quantum Hall effect but also in what is called the fractional quantum Hall effect that emerges when electrons are strongly interacting,” Rey said.



An artistic rendering of the two planes of the atom's movement, with the real being a 1D lattice and the synthetic referring to the nuclear spin of the atom.

Credit: Steven Burrows/Rey Group

Thanks to this new method, the researchers have proposed a workaround for the required cold temperatures needed in these types of experiments, making the study of SU(*n*) quantum interactions more accessible. As Mamaev added: “We did a lot of work in trying to translate how our theoretical predictions could be implemented in the state-of-the-art experiments that we have here at JILA and elsewhere.”

Mikhail Mamaev, Thomas Bilitewski, Bhuvanesh Sundar, and Ana Maria Rey. "Resonant Dynamics of Strongly Interacting SU(n) Fermionic Atoms in a Synthetic Flux Ladder." PRX Quantum 3(3): 030328. (2022).

Written by Kenna Hughes-Castleberry

An Entangled Matter-Wave Interferometer: Now for the First Time with Double the Spookiness

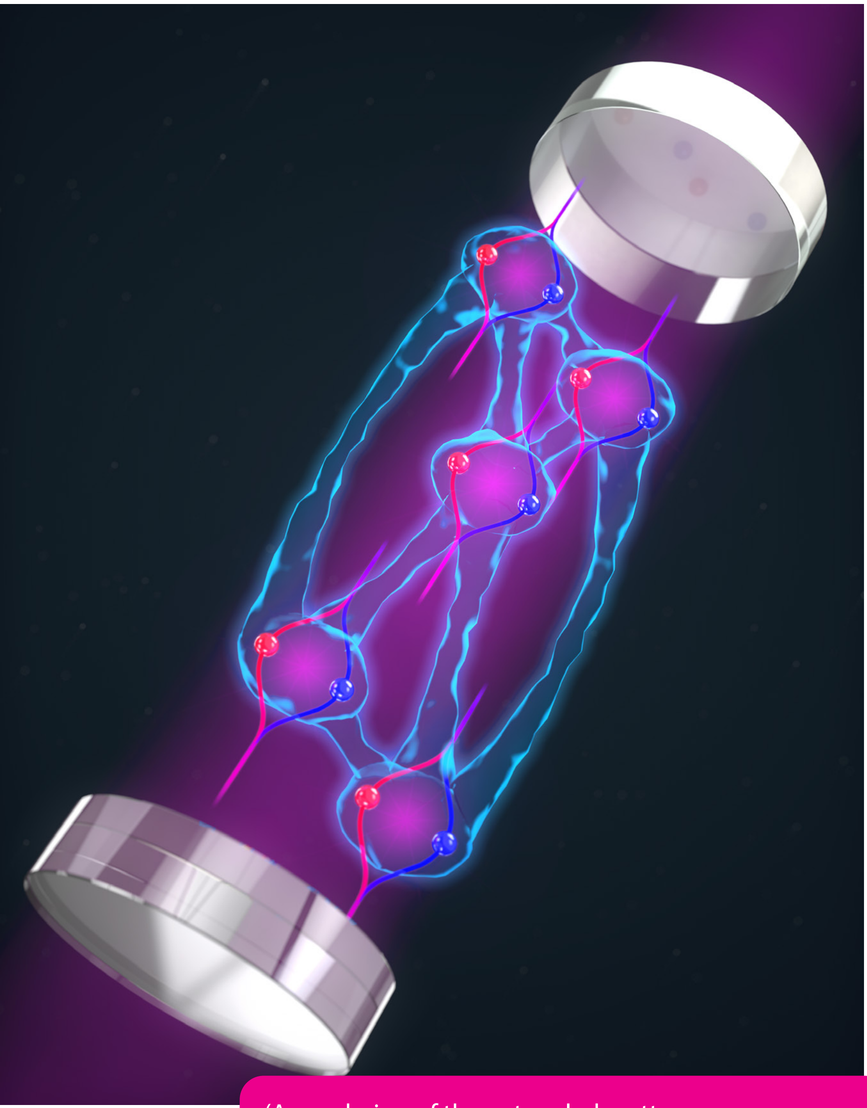
JILA and NIST Fellow James K. Thompson's team of researchers have for the first time successfully combined two of the "spookiest" features of quantum mechanics to make a better quantum sensor: entanglement between atoms and delocalization of atoms. Einstein originally referred to entanglement as creating spooky action at a distance—the strange effect of quantum mechanics in which what happens to one atom somehow influences another atom somewhere else. Entanglement is at the heart of hoped-for quantum computers, quantum simulators and quantum sensors. A second rather spooky aspect of quantum mechanics is delocalization, the fact that a single atom can be in more than one place at the same time. As described in their paper recently published in *Nature*, the Thompson group has combined the spookiness of both entanglement and delocalization to realize a matter-wave interferometer that can sense quantum accelerations with a precision that surpasses the standard quantum limit (a limit on the accuracy of an experimental measurement at a quantum level) for the first time. By doubling down on the spookiness, future quantum sensors will be able to provide more precise navigation, explore for needed natural resources, more precisely determine fundamental constants such as the fine structure and gravitational constants, look more precisely for dark matter, or maybe even one day detect gravitational waves.

Generating Entanglement

To entangle two objects, one must typically bring them very, very close to each other so they can interact. The Thompson group has learned how to entangle thousands to millions of atoms even when they are millimeters or more apart. They do this by using light bouncing between mirrors, called an optical cavity, to allow information to jump between the atoms and knit them into an entangled state. Using this unique light-based approach, they have created and observed some of the most highly entangled states ever generated in any system be it atomic, photonic, or solid state. Using this technique, the group designed two distinct experimental approaches, both of which they utilized in their recent work. In the first approach, called a quantum nondemolition measurement, they make a premeasurement of the quantum noise associated with their atoms and simply subtract the quantum noise from their final measurement. In a second approach, light injected into the cavity causes the atoms to undergo one-axis twisting, a process in which the quantum noise of each atom becomes correlated with the quantum noise of all the other atoms so that they can conspire together to become quieter. "The atoms are kind of like kids shushing each other to be quiet so they can hear about the party the teacher has promised them, but here it [is] the entanglement that does the shushing," says Thompson.

Matter-Wave Interferometer

One of the most precise and accurate quantum sensors today is the matter-wave interferometer. The idea is that one uses pulses of light to cause atoms to simultaneously move and not move by having both absorbed and not absorbed laser light. This causes the atoms over time to simultaneously be in two different places at once. As graduate student Chengyi Luo explained, "We shine laser beams on the atoms so we actually split each atom's quantum wave packet in two, in other words, the particle actually exists in two separate spac-



(Avrendering of the entangled matter-wave interferometer studied by the Thompson Group.

Credit: Steven Burrows/Thompson Group

es at the same time." Later pulses of laser light then reverse the process bringing the quantum wave packets back together so that any changes in the environment such as accelerations or rotations can be sensed by a measurable amount of interference happening to the two parts of the atomic wave packet (much like is done with light fields in normal interferometers, but here with de'Broglie waves, or waves made of matter) The team of JILA graduate students figured out how to make all of this work inside of an optical cavity with highly-reflective mirrors. They could measure how far the atoms fell along the vertically-oriented cavity due to gravity in a quantum version of Galileo's gravity experiment in which he dropped items from the Leaning Tower of Pisa, but with all the benefits of precision and accuracy that comes along with quantum mechanics.

Doubling the Spookiness

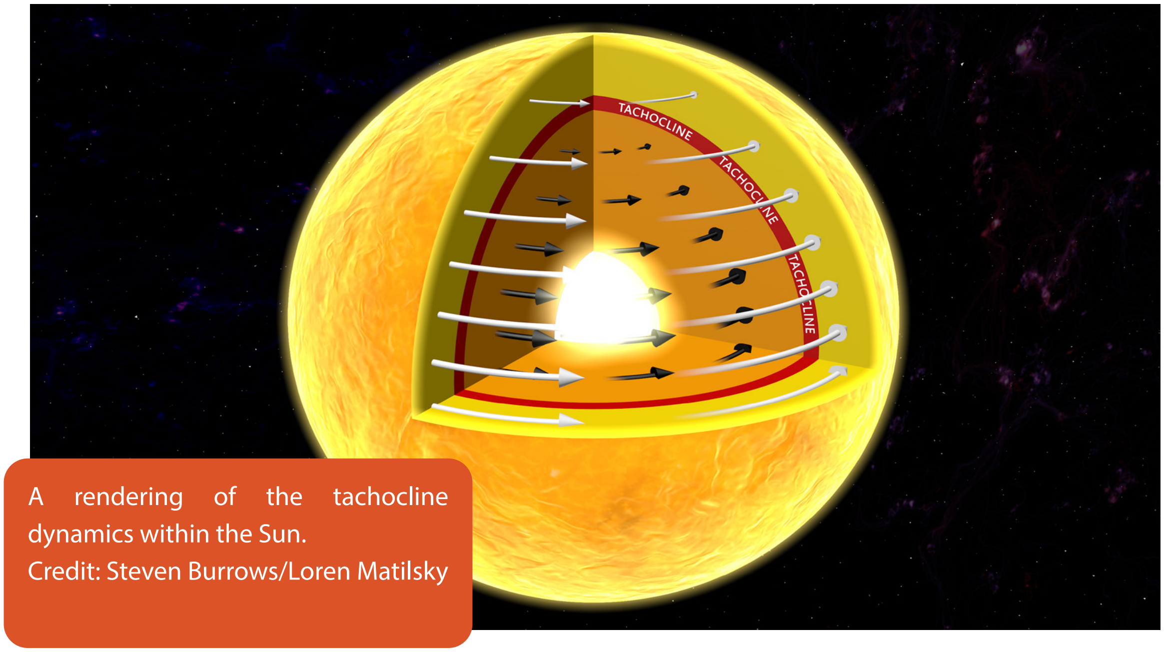
By learning how to operate a matter-wave interferometer inside of an optical cavity, the team of graduate students lead by Chengyi Luo and Graham Greve were then able to take advantage of the light-matter interactions to create entanglement between the different atoms to make a quieter and more precise measurement of the acceleration due to gravity. This is the first time that anyone has been able to observe a matter-wave interferometer with a precision that surpasses the standard quantum limit on precision set by the quantum noise of unentangled atoms.

Thanks to the enhanced precision, researchers like Luo and Thompson see many future benefits for utilizing entanglement as a resource in quantum sensors. Thompson elaborated, "I think that one day we will be able to introduce entanglement into matter-wave interferometers for detecting gravitational waves in space, or for dark matter searches—things that probe fundamental physics, as well as devices that can be used for every day applications such as navigation or geodesy." With this momentous experimental advance, Thompson and his team hope that others will use this new entangled interferometer approach to lead to other advances in the field of physics. With optimism, Thompson reflected, "By learning to harness and control all of the spookiness we already know about, maybe we can discover new spooky things about the universe that we haven't even thought of yet!"

Graham P. Greeve, Chengyi Luo, Baochen Wu, and James K. Thompson. "Entanglement-enhanced matter-wave interferometry in a high-finesse cavity." Nature, 610: 472–477 (2022)

Written by Kenna Hughes-Castleberry

Tackling the Sun's Tachocline



A rendering of the tachocline dynamics within the Sun.
Credit: Steven Burrows/Loren Matilsky

Sitting 150 million kilometers away from the Earth, the Sun produces puzzling phenomena, such as solar flares, that physicists are working to understand. One of these puzzles involves the Sun's tachocline, a belt of heat transition. “A tachocline is when the radiative interior of a star rotates like a solid ball, but the convection zone [an unstable outer heat layer in a star] rotates differently,” explained former JILA graduate student Loren Matilsky. “For geometric reference in the Sun, the outer 30% by radius is the convection zone, and the inner 70% by radius is the radiative interior.” Before leaving JILA to become a postdoctoral researcher at the University of California Santa Cruz, Matilsky collaborated with JILA Fellow Juri Toomre to study the Sun's tachocline using computer simulations. In a new paper published in *The Astrophysical Journal Letters,* Matilsky and Toomre developed a new type of simulation, one where the tachocline is self-consistent and not artificially enforced, meaning that it arises on its own. According to Matilsky: “As far as we know, it's the first time this type of self-consistent tachocline behavior has been published for a fully nonlinear fluid dynamical global simulation.”

Sun Simulations

There are many types of simulations astrophysicists use to learn more about the Sun's tachocline. When the tachocline was discovered in 1992, physicists needed to come up with different reasons for why this transitional belt of heat existed on the Sun's surface, including whether a magnetic field affected the flow. “Immediately after the tachocline's discovery, there were two [main] competing theoretical explanations for why it would exist,” said Matilsky. “The ‘fast’ scenario means there is no magnetic field, so the fluid outer layers are essentially experiencing shear instabilities, which arise when the spatial rate of change of the rotation rate is strong compared to the viscosity.” When the outer convective zone tries to burrow inward toward the solid core, the fluid dynamics of the scenario flattens out the zone. Which, according to the “fast” theory creates the transition layer of the tachocline. “It's called fast,” Matilsky continued, “because these instabilities operate on a timescale of a convective overturning time, or rotation period, so about every few days or maybe a month.”

Compared to the millions of years it takes for a star to mature, a few days to a month is rather rapid.

In contrast, the second "slow" scenario includes a magnetic field as a source of the tachocline. As Matilsky explained: "The scenario is 'slow' because it wipes out differential rotation [the convective zone] on the long timescale (around billions of years) of deep global circulation." The magnetic field helps to create the tachocline in this scenario, as opposed to fluid dynamics in the first scenario. Matilsky compared the magnetic fields to rubber bands that would prefer not to be pulled. Similarly, if the field lines are stretched enough, there is a backlash and the burrowing process for the tachocline stops.

There is, however, a third scenario involving a cyclical dynamo, a process that creates the Sun's magnetic field. "The dynamo field was assumed to follow the Sun's observed 22-year cycle for solar hotspots. The 22-year cycle refers to the fact that sunspots emerge in greater numbers, and with greater intensity, every 11 years. From one of these 'sunspot cycles' to the next, the field polarity reverses, making a 22-year cycle." explained Matilsky. In the third scenario, the dynamo helps drive the tachocline, and this scenario is what Matilsky and Toomre explored in the simulation.

From the simulation, the researchers found that the tachocline became self-contained, arising on its own. "It was a self-consistently enforced tachocline," Matilsky said. "I think there is a definite possibility that if you don't try to confine the tachocline artificially, it might just be there if you add a magnetic field."

This self-contained tachocline may help astrophysicists to learn more about another of the Sun's phenomena, its magnetic field. "The main goal, I would say, of all solar physics is to understand the Sun's dynamo, because we have these flares—coronal mass ejections—which makes [sic] the news because they are firing high-energy particles that hit satellites in space, they're disrupting power grids, and that actually affects life on Earth. That comes from the solar magnetic field." Matilsky and other physicists reason that the Sun's dynamo must originate at the tachocline, as opposed to previous thinking which suggested the dynamo originated via something else. "Because the tachocline is the interface between differential rotation and solid body rotation, there's a lot of shear happening, and many believe that that [shear] is what is creating this powerful magnetic field," Matilsky added.

More on Exoplanets and Stellar Evolution

While the new simulation suggests a strong link between the tachocline and magnetic field, it also hints at more explanations about exoplanets. "Our paper may also provide significant insights into stellar dynamos," said Matilsky. "We discover exoplanets all the time. Their space weather is really violent compared to the stuff we experience on Earth. So, if other stars have tachoclines, that may tell us if they have dynamos, which could affect exoplanets' space weather."

Insight into these tachoclines may also uncover more history about our Sun's origins. "During the early stages of stellar evolution, there's a whole bunch of theories relying on whether the magnetic field homogenizes the rotation rate or not," Matilsky added. "Throughout all this, the presence or not of a tachocline (the boundary between homogenous [solid body] rotation rate and differential rotation) would definitely affect stellar evolution." While there is still more research to be done, this paper is one more step forward to learning more about puzzling solar phenomena, such as flares, happen.

Loren I. Matilsky, Bradley W. Hindman, Nicholas A. Featherstone, Catherine C. Blume, and Juri Toomre. "Confinement of the Solar Tachocline by Dynamo Action in the Radiative Interior." The Astrophysical Journal Letters, (50:L50, (2022).

Written by Kenna Hughes-Castleberry

JILA FELLOW CARL LINEBERGER RETIRES

Retirement is never easy for a scientist. There are many loose ends to tie up, and the old habits of staying up late or constantly tinkering with new ideas may not go away. This is the case for JILA Fellow Carl Lineberger, who announced his retirement at JILA's 60th anniversary celebration. When asked what he would miss most about his work, Lineberger responded, "I like projects that provide challenges that keep me awake at night. You get a lot of good ideas that wake you up, but you also get a lot of crappy ones." While Lineberger has retired, he continues to retain an office at JILA and is now a JILA Fellow Adjoint. With over 50 years of research at JILA, Lineberger has both witnessed and participated in the evolution of JILA.

Born in North Carolina, Lineberger received his BS, MS, and PhD degrees in Electrical Engineering from the Georgia Institute of Technology. He learned from his research advisor of Dr. Lewis Branscomb's plans to set up a new type of collaborative research Institute in Boulder, called the Joint Institute for Laboratory Astrophysics, now simply known as JILA. After receiving his PhD in 1965, Lineberger planned to do postdoctoral research at JILA under founding member Lewis Branscomb. "I was scheduled to arrive at JILA at about the same as time another newly minted PhD, Dick Zare. I had already met Dick on several occasions, and was looking forward to interacting with him at JILA. However, fate intervened in the form of my obligation to serve two years in the US Army. Consequently, my arrival at JILA was delayed by 3.5 years."

While in the military, Lineberger gained experience in laboratory studies of upper atmospheric chemistry and its relevance to missile detection. This research was carried out at the US Army Ballistic Research Laboratories in Aberdeen, Maryland. "I built a complex apparatus to carry out these studies, but I could not complete the experiments in my two years in a green suit." Lineberger explained, "So, I decided to stay on at Aberdeen for a year or so, as a civilian, to complete my research and get some publications for my efforts. When I was done, I was finally able to get to JILA in August, 1968."

At JILA, Lineberger took over Branscomb's small group of students after only a few months, as Branscomb returned to the National Bureau of Standards (NBS, now the National Institue of Standards and Technology, NIST) as the Director in Washington D.C. in 1970, Lineberger was able to obtain a tenure track position in the Department of Chemistry, at the University of Colorado Boulder, even though he had never taken a formal college chemistry course. Lineberger explained how this could happen. "My education in chemistry was outside of the classroom. After the first exam in a large chemistry class, the freshman instructor, Peter Sherry, asked three of us students to stop attending his class and allow him to teach us quantum mechanics and its application to chemistry three evenings each week over

the full academic year. This experience was the extent of my formal education in chemistry, but it was vastly superior to introductory chemistry and it really changed my life!"

Lineberger's research at JILA focused on using a wide variety of newly developed laser techniques to study the structure and dynamics of gaseous ions relevant to chemical science. Lineberger often asked the talented people in the electronics and machine shops at JILA to build him custom equipment. "My first major project required the construction of a newly developed tunable dye laser. I worked with three shops people over a weekend. On Monday morning they had completed constructing the needed components for a flashlamp-pumped tunable dye laser that were not directly available. That same week Lineberger submitted a manuscript describing the first tunable laser anion photodetachment experiment, improving the accuracy of electron affinity determination by several orders of magnitude.

Lineberger remembers, "I would be in JILA regularly on weekends and see various people from the machine and electronics shops, walking around the labs and pointing out to their families and friends: 'Oh, I built this, I built that.' It was inspiring that they were so appropriately proud of their work! That's the essence of what JILA is all about."

As a JILA Fellow, Lineberger benefitted from the institutional tradition of collaboration. He noted that Jan Hall's curiosity, wisdom and generosity were critical for JILA to thrive in the early days. "At one point early on, Jan came to me and said, 'You know what to do with this photoelectron spectroscopy apparatus in my lab so much better than I do. I want it to be yours.'" Lineberger learned early on that this form of collaboration was truly the "secret sauce" of JILA.

Lineberger's personal collaboration was also essential. In 1979, he and Katherine "Kitty" Edwards were married. "Without her in my life and her unwavering support, so many critical things would never have happened." Lineberger said.

In his long career, Lineberger has published over 250 papers in major scientific journals. He was elected to the National Academy of Sciences in 1983 and the American Academy of Arts and Sciences in 1995. He was awarded the H. P. Broida Prize in Atomic and Molecular Spectroscopy, the Earle K. Plyler Prize by the American Physical Society, the Meggers Prize by the Optical Society of America, the Michelson Prize by the Coblentz Society, the Irving Langmuir Prize in Chemical Physics, and the Peter Debye Prize in Physical Chemistry from the American Chemical Society. In 2015, he received the National Academy of Sciences Award in the Chemical Sciences.

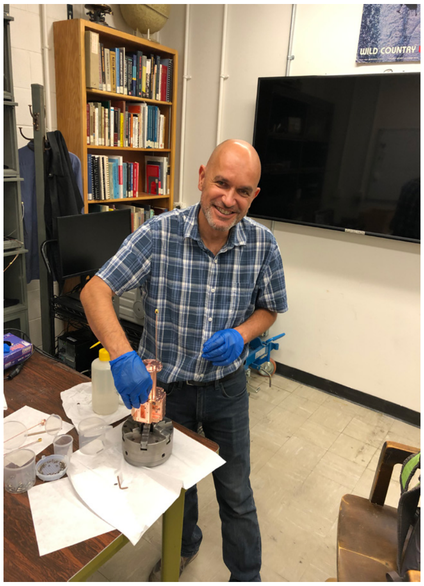
Lineberger served on the US National Science Board, the Governing Board of Directors of the National Science Foundation, from 2010 to 2022.

While Lineberger will no longer be actively participating in research, he plans to contribute to JILA'S work, principally through mentoring. Lineberger has been considered a valued mentor by many JILA researchers over the years and he continues to believe that mentoring is an important tenet for research. According to Lineberger, "It is vital for people to think for themselves. To be successful you must think outside of the box. You must also be willing to think crazy things and see where they might lead!"

Written by Kenna Hughes-Castleberry

Opposite page(top): Carl Lineberger's official photo as a JILA Fellow.
(Opposite page (bottom): Carl Lineberger in his office circa 1980s
Above: Carl Lineberger announces his retirement at the JILA 60th anniversary event.
Credit: JILA Archives

How to Rebuild an Atomic Clock



Atomic clocks are crucial for everyday living as they help our telecommunications, electrical power grids, GPS systems, transportation, and other processes around the world keep precise time. Some of these clocks use lasers and special resonator cavities to measure time intervals. They are some of the most accurate clocks in the world and the most fragile. The cesium atomic clocks play a consequential role, as a specific atomic transition induced in the atomic cesium is used to define the unit of time: the SI second. The National Institute of Standards and Technology (NIST) laboratories in Boulder, Colorado have housed atomic clocks—including the cesium atomic clock NIST-F1 which currently serves as the United States' primary time and frequency standard—for decades, as researchers continue to improve the clocks' accuracies through cutting-edge research. For the NIST-F1 cesium clock specifically, this process has included rebuilding parts of the clock.

The NIST-F1 clock is also called a "fountain clock" due to the fountain-like movement of the cesium atoms inside the clock that is used to measure time intervals. These cesium atoms begin in a special vacuum chamber, where six infrared laser beams herd the free-flying atoms into a ball. During the creation of this ball, the system is cooled to near absolute zero (zero Kelvin) to slow down the movement of the atoms. After cooling, two vertical lasers toss the ball of cesium atoms into an upward arc (the "fountain") and then all laser beams are shut off. The cesium ball moves upwards for about a meter in a special microwave-filled cavity, which may alter some of the atoms within the ball. The ball then drops, and again, the microwave field may interact with the atoms, causing more of them to change their state. The final atomic state is determined by measuring the fluorescence of the altered atoms induced by another laser beam. The entire process takes around one second, and is repeated multiple times to find the right frequency that excites the specific clock transition of the cesium atoms. Once the microwave frequency is found, at which the microwave signal interacting with the cesium atoms would cause a maximum amount of them to change their state (at maximum fluorescence), that frequency is then used to define a second of time by counting exactly 9192631770 signal periods (as the scientists measured) with a counter.

This definition is then applied to other clocks for calibration and accurate timekeeping.

The microwave cavity is a crucial piece of the timekeeping process, and researchers at NIST hoped to improve the accuracy of the clock by rebuilding the entire cavity. "We had issues with the previous clock cavity that limited the clock's accuracy," explained NIST scientist Vladislav "Vladi" Gerginov. "One of the issues was with the cavity's material (aluminum)." As atomic clocks are extremely sensitive to imperfections in the cavity shape, electrical conductivity, and polish, the cavity's materials have to be made of the right material, and have the exact shape, size and finish for minimizing clock inaccuracies. "One of the crucial steps in building a cesium clock is tuning the frequency of the cavity to match the transition frequency of cesium,"

Opposite page (top) Vladislav "Vladi" Gerginov holds the newly designed copper microwave cavity.
Credit: Hans Green/JILA

Opposite page (bottom): JILA instrument maker Hans Green works on a component of the F1 cesium clock.
Credit: Hans Green/JILA

Left: Curtis Beimborn, Head of JILA's W.M. Keck Metrology Lab and Clean Room, looks at the newly made microwave cavity in the profilometer.
Credit: Kenna Hughes-Castleberry/JILA

explained instrument maker Calvin Schwadron of JILA (a joint institute between NIST and the University of Colorado Boulder). "The frequency that a microwave cavity resonates at depends on the volume inside of it." To do this, the researchers leaned on the expertise found a JILA. According to Curtis Beimborn, Head of the W.M. Keck Metrology Lab and Clean Room at JILA: "The quality of the cavity (*Q*) is very important to improve the clock's performance.

To increase the cavity's *Q*, Gerginov collaborated with the machine and instrument shops at JILA, using the instrument shop and clean room to build the new microwave cavity out of copper. "It's incredibly rare to have a full shop collaboration like this," stated JILA instrument maker Adam Ellzey "All six of us sat in with Vladi during design consultations. In the fabrication stage, we're all regularly checking in with each other to make sure our parts fit and our designs agree. Making components of a clock that will be the nation's time standard is a big deal that has taken some real thought. It's been amazing to watch my fellow instrument makers flex their expertise. I've learned a ton."

The JILA instrument shops are a key factor in making JILA a unique research institution. According to Kyle Thatcher, Head of the instrument shops: "The real value of the JILA Instrument Shop is that scientists get the opportunity to work directly with instrument makers to realize their experimental apparatus. This means that from conception, scientists are able to collaborate on the design, engineering, fabrication, and testing of their device utilizing the shop's vast accumulated institutional knowledge. Additionally, with the Instrument Shop's open-door policy, and being in such close proximity [in the building for the case of JILA], allows for very quick iterative development, troubleshooting, and device modification[and] repair." This process of close collaboration between scientists and instrument makers is rather rare to find in most research institutions, as traditionally, instrument makers work off designs provided by the scientists with very little back and forth, as Thatcher explained. At JILA, the collaboration afforded between the in-house shops and the scientists allows for custom-built instruments that are found nowhere else. This includes the parts for the NIST-F1 cesium clock. "The Instrument Shop was able to work with Vladi and his colleague to help optimize critical features of the system including material selection, component reduction, serviceability and design for manufacturing," explained Thatcher. "More importantly, however, was the ability of Vladi to set up his test equipment from NIST within the shop where he was able, practically in real time, to quantify the performance of parts being made thus enabling the manufacturing processes to be tweaked on the fly improving results."

The process of creating a new cavity involved many different steps, including an ongoing back and forth between Gerginov and the machinists on the design of the cavity. After initial testing of the new copper cavity, the *Q* was roughly a factor of three lower than what was expected and Gerginov suspected that the metal surface finish inside the cavity may be the culprit since the microwave frequency currents are "confined to the surface of the metal, instead of traveling through the bulk [walls]," Gerginov said. "Calvin and Vladi brought it down to the Optical Metrology Lab, and I measured the surface roughness for them using our optical profilometer," Beimborn stated. "Sure enough, the roughness was great enough that all the tiny surface imperfections were adding quite a lot to the distance the microwave frequency currents were traveling in the cavity, which diminished the *Q* factor. After this measurement, Calvin polished the interior of the cavity and I believe Vladi saw a factor of two improvements in the *Q* right away."

Thanks to NIST's close collaboration with JILA, the new cavity will help get the NIST-F1 cesium fountain clock back to work. As Elizabeth Donley, NIST's Time and Frequency Division Chief, said: "The cavity machining in the JILA shop has been a very important part of the work to bring the fountain [clock] back online and we're very grateful for that. It's been great to have the JILA shop as such a valuable local resource." With the clock up and running, NIST researchers can continue to work on pushing the boundaries of atomic clock physics. "The clock will be used at NIST to calibrate the official NIST timescale, as well as other atomic clocks and frequency references," Gerginov added.

Written by Kenna Castleberry

HUMANS OF JILA: DHRUV KEDAR

Walk down to the basement labs of JILA and you're sure to find something interesting. From atomic clocks to biophysics, researchers are hard at work advancing scientific and technological frontiers. One of these researchers is graduate student Dhruv Kedar. Kedar works in JILA and NIST Fellow Jun Ye's lab, focusing on laser development for a range of applications including optical atomic clocks and optical timescales. "We're really just trying to make the world's best lasers as part of the atomic clock," explained Kedar. "We do a good job of isolating out any sort of environmental effects so the atomic frequency of the clock doesn't change but gets more precise." As optical atomic clocks use a series of lasers to control and measure the quantum state evolution inside an atom, which will redefine the SI unit of Second in the foreseeable future, improving the lasers to be themselves free of environmental noise is an important task.

The atomic clock works by measuring how many times a specific atom oscillates between the ground state and the excited state (which is induced by a laser) at a specific frequency. "To be able to use that frequency, you want to have a laser that is really stable [free from environmental noise]," added Kedar. "If you have a stable laser, it acts like an optical oscillator that can keep time on its own, except that the laser frequency drifts over time." This drift creates a problem in keeping time, but there is a solution. "What you want to do is take the laser and measure it against the atom, which then tells you the size of frequency excursion, so you can correct it. That kind of feedback cycle gives you the stability of the atom and imprints that on the laser. So, it's nice to have better lasers, because, when you're making these clocks, you essentially don't have to measure the atom as often as would be required for a poorer laser. If the laser is stable enough, we can use its frequency to establish an optical timescale that surpasses its microwave counterparts in the short term and we currently disseminate this signal to several of our colleagues across JILA."

Atomic clocks are not only a fascinating piece of timekeeping, but as Kedar explained, they also combine both classical and quantum physics. “Generally, people try to make use of quantum resources, meaning they try to use atoms for making clocks rather than physical things like pendulums or quartz oscillators,” he stated. “And here we can do a better job using the quantum properties of these atoms than we can with classical properties. But this laser is actually unusual in that, the best we could do is use a classical material.” This makes Kedar's experimental setup a unique mix of classical and quantum materials. “We're using a resonator cut from a single crystal of silicon, which, there's nothing quantum about that,” he said. “It's inherently designed to be stable and robust against environmental fluctuations that can be of mechanical or thermal origin. And we take the crystal stability and transfer it to the laser. So, it's one of the few experiments in atomic physics where something completely classical currently surpasses what we can do in the quantum realm, at least at relatively short times scales.” The combination of the laser and the atom then allows us to combine the best of both worlds and realize something at the leading edge of measurement science.

As a graduate student at JILA, Kedar feeds his lifelong passion for physics through his research. He also enjoys the close-knit feeling of the physics community. “Particularly in atomic physics, the community isn't so big,” Kedar stated. “So, you get to know everybody.” This small community also makes the experiments more personal for the researchers. As Kedar elaborated: “The experiments are generally very small. You don't have these very large collaborations where you may only see one part of the experiment. There are only a couple of graduate students in each of those experiments. So, you really get to know everything about it, like, it's your experiment. You build it up, you understand everything and having that sense of ownership is really, really nice. As a graduate student, you can feel like you've built something and contributed to something and it's great.” This sense of ownership is reflected across JILA as a whole, from other research groups to JILA's instrument and machine shop, allowing all to take pride in their work. “Much of the work conducted in our lab would not be possible without JILA's resources. Many components we place in the cavity's cryogenic environment were designed and constructed in the JILA machine shop, and we detect our cavity signal with some of the worlds best low-noise photodetectors made by members of the electronics staff. The intangible contributions of people like Beth [Kroger, JILA Chief of Staff} who work to make JILA an inclusive, equitable, and comfortable work environment are incredibly valuable. Everyone here has a hand in enabling the world-class research that occurs in the labs.”

While being a part of Ye's lab, Kedar feels honored to work under such a well-known scientist. “Jun is an incredible genius,” Kedar said. “Jun is one of those people you can always go and talk to him if you have an idea. And he will always give you the time of day. He just loves talking about science and has a really infectious enthusiasm.” Kedar highlighted the effort Ye makes to answer all his teams' questions. “If I send him an email,” Kedar said, “I'll get an email back from him at like two AM, every day like clockwork. He's just so reliable, and it's his love of physics. It can't help but really inspire you to do the same thing and become excited about what you're doing. It just makes everything you're doing really fun.”

Written by Kenna Castleberry

Graduate student Dhruv Kedar explains his laser set up in the laboratory. Credit Kenna Hughes-Castleberry/JILA

JEDI Projects: The JILA Values Summit

For an institution as big as JILA, setting its values can be difficult. Having a set of values gives an instituion an infrastructure to develop policies or programs around. The values project at JILA has been led by JEDI (JILA Excellence in Diversity and Inclusivity) a group within the institution focused on bettering JILA's community. Working with JILA's independent consultant Regan Byrd, JEDI has been working to get input from the JILA community to establish JILA's values.

While the values will be amended as the institution changes over time, setting the initial values has been an almost Herculean task. Byrd, who has worked with JILA for several years, taught community leaders within JILA to lead small groups so JILAns could input their values in a more personal and informal way. While the initial sign up for these community input groups was around 55 individuals, by the time the community leaders were educated and the groups finally met a month later, the actual turn out was lower.

Those who did participate were given a list of value words to choose from. Individuals within the groups were asked to group their choices by similarity, and then operationalize them in a sentence. For example, using "inclusivity" as "including others in events." From there, participants ranked their values based on importance. While the four community groups met throughout the last week of September, open sessions were also held during this time for JILAns to drop by. Even a virtual survey was passed around so JILAns who were not in-person could input their suggestions for the values.

After Byrd collected all the input, JILA then held a Values Summit in early October to discuss the process and narrow down JILA's top 10 values. While attendance from the Summit was rather low, those who did attend were very passionate about the project, and were excited to see where it was headed.

At the Summit, Byrd presented a word-cloud of the values people had chosen. A word-cloud uses the frequency of word choice to make words different sizes depending on their popularity. For the values project, the word "community," was the top choice, followed by words like "personal development," "collaboration," "teamwork," and "growth." JILAns already see all of these values as important in the JILA community."

But to have an established set of values will hopefully help to make the institution's community even stronger and more productive. Many hope to see the values implemented in future JEDI projects, such as in mentoring programs or evaluation methods. While JILA still has yet to properly vote on the final list of values, many are excited to see this new change within the institution. To have an established set of values will, as is hoped, help to make the institution's community even stronger and more productive

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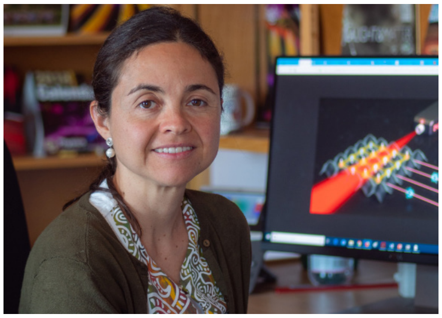
Written by Kenna Hughes-Castleberry

Below: The wordcloud shown at the JILA Values Summit in October. Credit: Regan Byrd

NEWS AND AWARDS



News

JILA and NIST Fellow Ana Maria Rey is featured in an "Optica Community" Story. The piece, called *The Atomic Clockmaker: How a woman from Colombia overcame obstacles to become a leading theoretical physicist and develop the world's most accurate atomic clock,* features Rey's life story and work.

JILA and NIST Fellow Ana Maria Rey is featured in a Quantum Systems Accelerator Article. Quantum Systems Accelerator, a National QIS Research Center funded by the United States Department of Energy Office of Science, featured Rey in a new article series in honor of Hispanic Heritage Month. In this article, Rey shares her story and her current research.

Top: JILA and NIST Fellow Ana Maria Rey's work was featured in a Quantum Systems Accelerator article.
Credit Quantum Systems Accelerator

Botton: JILA Fellow and NIST Physicist Adam Kaufman has won the 2023 New Horizons in Physics Breakthrough Prize
Credit: Kenna Hughes-Castleberry/JILA.

Awards

Physicist Adam Kaufman of both JILA and the US Department of Commerce's National Institute of Standards and Technology (NIST) has been awarded the 2023 New Horizons in Physics Prize from the Breakthrough Prize Foundation for his work in advancing the control of atoms and molecules to improve atomic clocks and quantum information processing. Kaufman shares the prize with selected winners of other institutions. The prize committee selected the winners "to the development of optical tweezer arrays to realize control of individual atoms for applications in quantum information science, metrology, and molecular physics."

JILA Fellow and NIST Physicist Adam Kaufman is awarded the 2023 I.I. Rabi Prize in Atomic, Molecular, and Optical Physics. "I was surprised when I was notified and feel extremely honored" Kaufman stated. This prize, awarded in odd-numbered years, recognizes influential early-career research in the fields of AMO physics. Along with $10,000 dollars in prize money, recipients receive a certificate citing their contributions. The recipient will receive the prize at a ceremony at the next DAMOP conference in Spring, 2023. "My group has focused on developing tools to control arrays of alkaline-earth atoms at a single-particle level," Kaufman said about his work. "We have translated these new tools to quantum science applications in metrology, quantum information, and intersections between the two." Several JILA Fellows have been awarded this prize in the past, including Eric Cornell, Deborah Jin, and Jun Ye.

JILA Fellow Margaret Murnane has been selected as a recipient of the 2022 Institute of Physics Isaac Newton Medal and Prize. This prestigious award honors the legacy of the famous physicist Sir Isaac Newton, by commending those who have made world-leading contributions in the field of physics. Murnane was selected as one of this year's award recipients for her influential work in advancing laser technology, optics research, and quantum information science.

JILA graduate student Aaron Young, a researcher in JILA Fellow and NIST Physicist Adam Kaufman's laboratory, has been awarded a 2022 University of Chicago Quantum Creators Prize. This prize is given by the Chicago Quantum Exchange to promote further research in quantum physics.

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 in 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, and Developmental Biology, as well as in the College of Engineering.

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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jila.colorado.edu