LIGHT + MATTER

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Tweezing a New Kind of Atomic Clock

p. 13

JILA

CU Boulder and NIST

JILA staff created a video for the fellows to thank them for all they do to keep JILA running.

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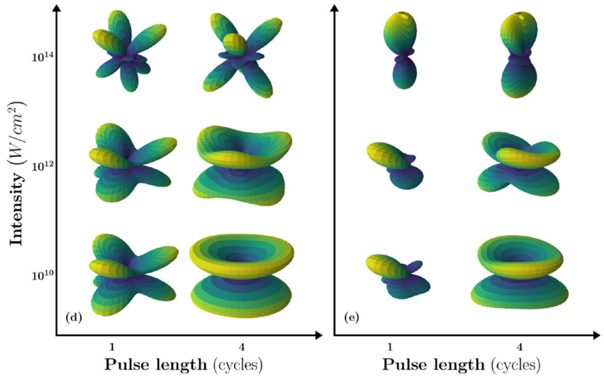
Stories

In the News

Measuring Spinning Donuts



(d) Photoelectron angular distributions for ionization of neon atom, prepared in $2p_{-1}$–$3d_2$ superposition, as function of intensity and pulse length. (e) The same as (d) including additionally ionization from the $2p_0$ and $2p_1$ states.
Image Credit: The Becker Group

Atoms are busy objects. Electrons whiz around the nucleus of the atom in attoseconds—quintillionths of a second. Those electrons can be orbiting farther out from the nucleus in an excited state, close to the nucleus in the lowest energy level called a ground state, or in a superposition—in two or more energy levels at once.

During ionization, some of those electrons will fly away from the atom. The direction and path those electrons take can tell scientists a lot about the state the atom was in before—ground state, excited state, or superposition.

“We want tools that can identify if it’s this particular state or that particular state. That’s important in the ionization process,” said Joel Venzke, a graduate student at JILA. “[We] would like to know exactly what that superposition is, and what is the relative phase between these two states...we want to follow this motion and be able to write down the wave function at a certain point in time.”

Venzke has developed a set of tools to do this using the time-dependent Schrödinger equation and ultrashort laser pulses to capture the path of the electron and the state of the atom during ionization. The team’s results were published in *Nature Scientific Reports.*

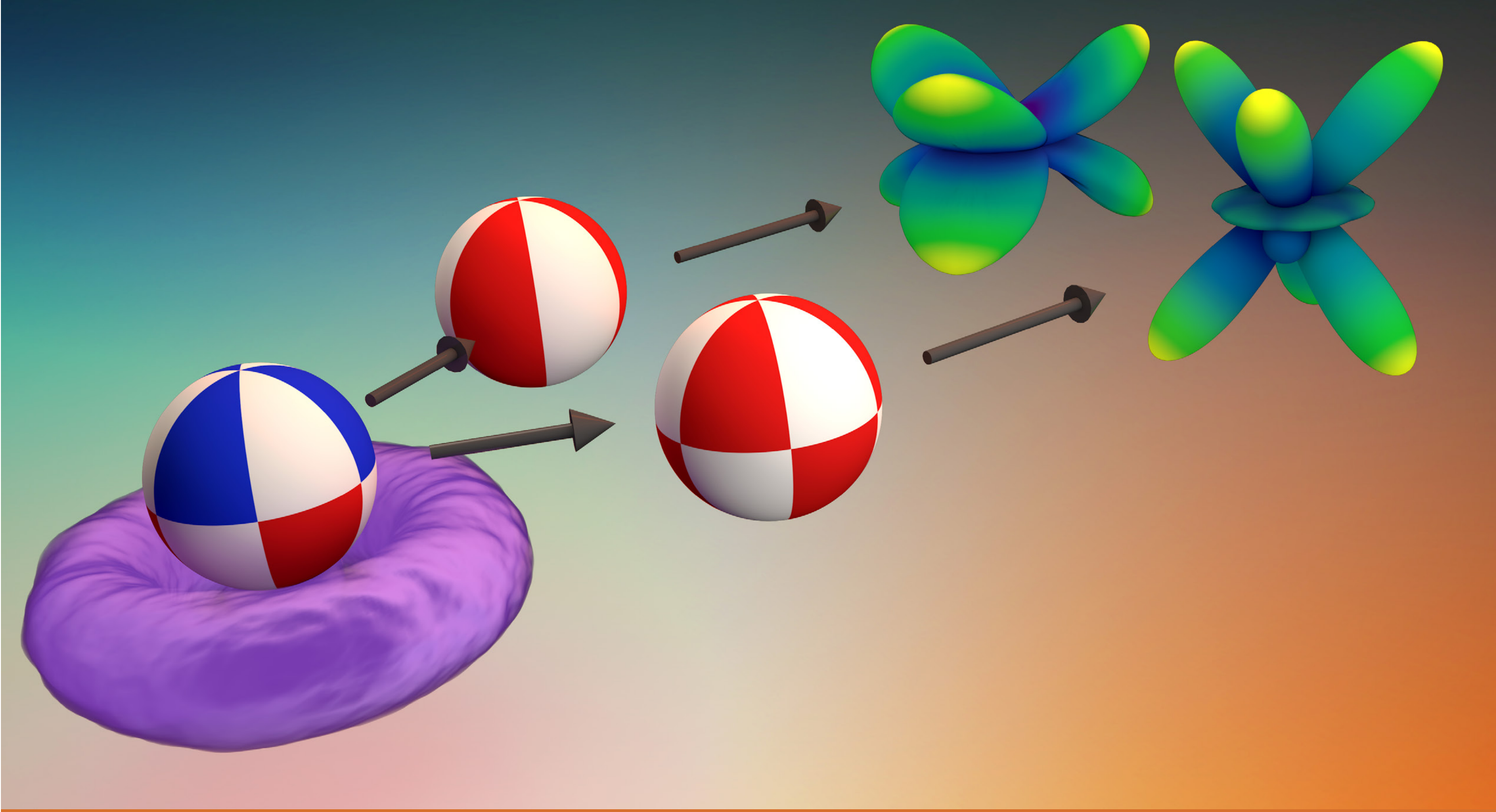
Asymmetry in motion

The way an electron leaves an atom during ionization can tell scientists the state of the atom at the time. JILA’s researchers have used two key tools to track the electron’s escape: attosecond (10^{-18} second) laser pulses and numerical solutions to the Schrödinger equation—a differential equation which describes the evolution of the wave function of a quantum system in time. In this scheme, the electron is stripped from the atom by the attosecond laser pulse, and the rapid laser pulses take snapshot images of the atomic state and the ionization process, by capturing the directions in which the electrons fly.

“If it was in the ground state, the electron wave function is essentially distributed in this ball [around the nucleus]. If it’s in its excited state, it’s in a donut. If it’s in the superposition state, it is moving around,” said JILA Fellow Andreas Becker.

“We’re interested in how does that shape break down from being either this perfect donut or perfect ball into this kind of asymmetric shape [of the ionized electrons],” Venzke added.

Using the Schrödinger equation, scientists can determine the electrons’ “flight paths” from the symmetrical or asymmetrical shapes that illustrate the directions in



During ionization, electrons leave an atom on varying flight paths. By capturing those flight paths, the Becker Group at JILA can determine the state of the atom at that moment.
Image Credit: Steven Burrows/The Becker Group

which the electrons are leaving the atom. Venzke, with some guidance from JILA Fellows Becker and Agnieszka Jaron-Becker, took the lead and developed generalized asymmetry parameters (GAPs) to quantify these uneven, asymmetrical distributions—which tells them valuable new information about how those electrons left the atom.

“The asymmetry tells us something about which of the possible pathways is dominant, or if they are interfering. It tells us how the electron was actually removed from the atom and which pathway did it take, or was there more than one pathway involved in it.”

Studying and quantifying atoms in their excited or superposition states is really important in physics, Venzke said. And attosecond laser pulses are useful to capture and follow the motion of the electrons in these states. With this insight, scientists can better understand what happens during interactions between atoms—perhaps even capturing videos of those interactions—or whether electrons are exchanging energy and what energy levels they are occupying. More importantly, if scientists can see what happens in these interactions, there’s the possibility that they can manipulate those interactions—although that’s still some way off, Becker added.

“It’s a small piece of the puzzle,” Becker said. “First, we have to understand. Then, once we understand, we can try to control it… there are many steps in between. But it’s part of the process.”

Joel Venzke, Andreas Becker, Agnieszka Jaron-Becker, *Nature Scientific Reports* **10,** 16164 (2020)

Advanced Atomic Clock Makes a Better Dark Matter Detector

JILA researchers have used a state-of-the-art atomic clock to narrow the search for elusive dark matter, an example of how continual improvements in clocks have value beyond timekeeping.

Older atomic clocks operating at microwave frequencies have hunted for dark matter before, but this is the first time a newer clock, operating at higher optical frequencies, and an ultra-stable oscillator to ensure steady light waves have been harnessed to set more precise bounds on the search. The research is described in *Physical Review Letters*.

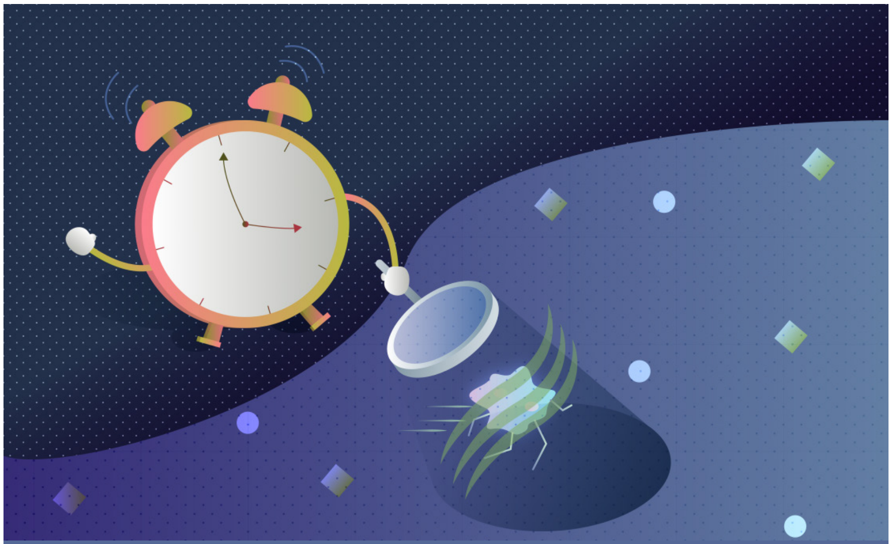
Astrophysical observations show that dark matter makes up most of the “stuff” in the universe, but so far it has eluded capture. Researchers around the world have been looking for it in various forms. The JILA team focused on ultralight dark matter, which in theory has a teeny mass (much less than a single electron) and a humongous wavelength—how far a particle spreads in space—that could be as large as the size of dwarf galaxies. This type of dark matter would be bound by gravity to galaxies and thus to ordinary matter.

Ultralight dark matter is expected to create tiny fluctuations in two fundamental physical “constants”: the electron’s mass, and the fine-structure constant. The JILA team used a strontium lattice clock and a hydrogen maser (a microwave version of a laser) to compare their well-known optical and microwave frequencies, respectively, to the frequency of light resonating in an ultra-stable cavity made from a single crystal of pure silicon. The resulting frequency ratios are sensitive to variations over time in both constants. The relative fluctuations of the ratios and constants can be used as sensors to connect cosmological models of dark matter to accepted physics theories.

The JILA team established new limits on a floor for “normal” fluctuations, beyond which any unusual signals discovered later might be due to dark matter. The researchers constrained the coupling strength of ultralight dark matter to the electron mass and the fine-structure constant to be on the order of 10^{-5} (1 in 100,000) or less, the most precise measurement ever of this value.

“Nobody actually knows at what sensitivity level you will start to see dark matter in laboratory measurements,” NIST/JILA Fellow Jun Ye said. “The problem is that physics as we know it is not quite complete at this point. We know something is missing, but we don't quite know how to fix it yet.”

“We know dark matter exists from astrophysical observations, but we don't know how the dark matter connects to ordinary matter and the values we measure,” Ye added. “Experiments like ours allow us to test various theory models people put together to try to explore the nature of dark matter. By setting better and better bounds, we hope to rule out some incorrect theory models and eventually make a discovery in the future.”



Advanced atomic clock.
Image Credit: N. Hanacek/NIST

Scientists are not sure whether dark matter consists of particles or oscillating fields affecting local environments, Ye noted. The JILA experiments are intended to detect dark matter's "pulling" effect on ordinary matter and electromagnetic fields, he said.

Atomic clocks are prime probes for dark matter because they can detect changes in fundamental constants and are rapidly improving in precision, stability and reliability. The cavity's stability was also a crucial factor in the new measurements. The resonant frequency of light in the cavity depends on the length of the cavity, which can be traced back to the Bohr radius (a physical constant equal to the distance between the nucleus and the electron in a hydrogen atom). The Bohr radius is also related to the values of the fine-structure constant and electron mass. Therefore, changes in the resonant frequency as compared to transition frequencies in atoms can indicate fluctuations in these constants caused by dark matter.

Researchers collected data on the strontium/cavity frequency ratio for 12 days with the clock running 30% of the time, resulting in a data set 978,041 seconds long. The hydrogen maser data spanned 33 days with the maser running 94% of the time, resulting in a 2,826,942-second record. The hydrogen/cavity frequency ratio provided useful sensitivity to the electron mass, although the maser was less stable and produced noisier signals than the strontium clock.

JILA researchers collected the dark matter search data during their recent demonstration of an improved time scale—a system that incorporates data from multiple atomic clocks to produce a single, highly accurate timekeeping signal for distribution. As the performance of atomic clocks, optical cavities and time scales improves in the future, the frequency ratios can be reexamined with ever-higher resolution, further extending the reach of dark matter searches.

"Any time one is running an optical atomic time scale, there is a chance to set a new bound on or make a discovery of dark matter," Ye said. "In the future, when we can put these new systems in orbit, it will be the biggest 'telescope' ever built for the search for dark matter."

Funding was provided by NIST, the Defense Advanced Research Projects Agency and the National Science Foundation.

Written by Laura Ost, NIST

Colin J. Kennedy, Eric Oelker, John M. Robinson, Tobias Bothwell, Dhruv Kedar, William R. Milner, G. Edward Marti, Andrei Derevianko, and Jun Ye, *Physical Review Letters* **125**, 201302 (2020)

New JILA Tools 'Turn On' Quantum Gases of Ultracold Molecules

JILA researchers have developed tools to "turn on" quantum gases of ultracold molecules, gaining control of long-distance molecular interactions for potential applications such as encoding data for quantum computing and simulations.

The new scheme for nudging a molecular gas down to its lowest energy state, called quantum degeneracy, while suppressing chemical reactions that break up molecules finally makes it possible to explore exotic quantum states in which all the molecules interact with one another.

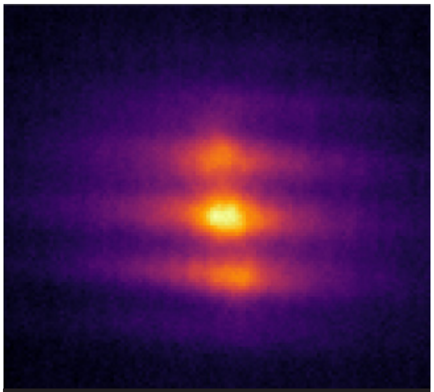
The research is described in a *Nature* paper published online Dec. 9.

"Molecules are always celebrated for their long-range interactions, which can give rise to exotic quantum physics and novel control in quantum information science," NIST/JILA Fellow Jun Ye said. "However, until now, nobody had figured out how to turn on these long-range interactions in a bulk gas."

"Now, all this has changed. Our work showed for the first time that we can turn on an electric field to manipulate molecular interactions, get them to cool down further, and start to explore collective physics where all molecules are coupled to each other."

The new work follows up on Ye's many previous achievements with ultracold quantum gases. Researchers have long sought to control ultracold molecules in the same way they can control atoms. Molecules offer additional means of control, including polarity—that is, opposing electrical charges—and many different vibrations and rotations.

The JILA experiments created a dense gas of about 20,000 trapped potassium-rubidium molecules at a temperature of 250 nanokelvin above absolute zero (about minus 273 degrees Celsius or minus 459 degrees Fahrenheit). Crucially, these molecules are polar, with a positive electric charge at the rubidium atom and a negative charge at the potassium atom. The differences between these positive and negative charges,



Shadows of atoms trapped in layers of a web of laser light, or an optical lattice, before they are paired into ultracold potassium-rubidium molecules.
Image Credit: Ye Group/JILA

called electric dipole moments, cause the molecules to behave like tiny compass magnets sensitive to certain forces, in this case electric fields.

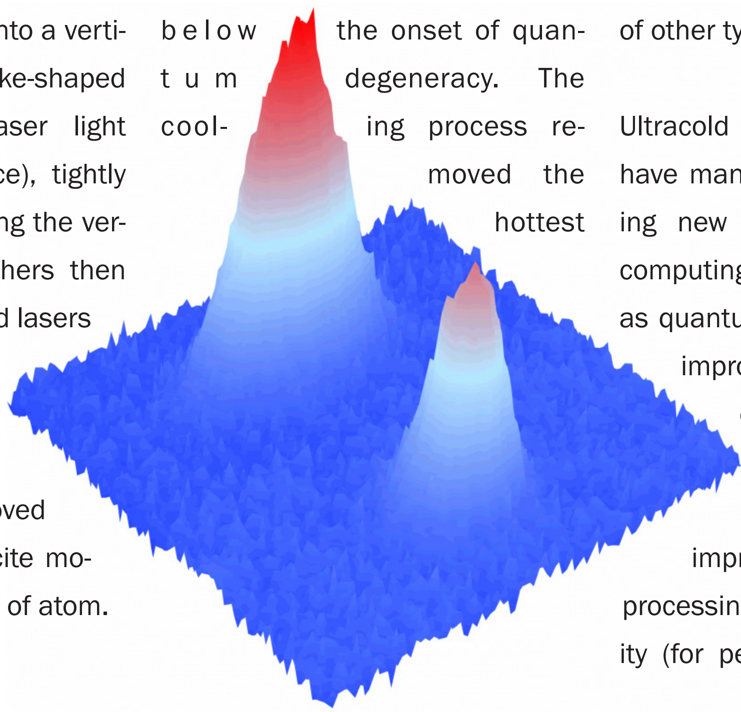
When the gas is cooled to near absolute zero, the molecules stop behaving like particles and instead behave like waves that overlap. The molecules stay apart because they are fermions, a class of particles that cannot be in the same quantum state and location at the same time and therefore repel each other. But they can interact at long range through their overlapping waves, electric dipole moments and other features.

In the past, JILA researchers created quantum gases of molecules by manipulating a gas containing both types of atoms with a magnetic field and lasers. This time the researchers first loaded the mixture of gaseous atoms into a vertical stack of thin, pancake-shaped traps formed from laser light (called an optical lattice), tightly confining the atoms along the vertical direction. Researchers then used magnetic fields and lasers to bond pairs of atoms together into molecules. Leftover atoms were heated and removed by tuning a laser to excite motion unique to each type of atom.

Then, with the molecular cloud positioned at the center of a new six-electrode assembly formed by two glass plates and four tungsten rods, researchers generated a tunable electric field.

The electric field set off repulsive interactions among the molecules that stabilized the gas, reducing inelastic ("bad") collisions in which the molecules undergo a chemical reaction and escape from the trap. This technique boosted rates of elastic ("good") interactions more than a hundredfold while suppressing chemical reactions.

This environment allowed efficient evaporative cooling of the gas down to a temperature below the onset of quantum degeneracy. The cooling process removed the hottest molecules from the lattice trap and allowed the remaining molecules to adjust to a lower temperature through the elastic collisions. Slowly turning on a horizontal electric field over hundreds of milliseconds reduced the trap strength in one direction, long enough for hot molecules to escape and the remaining molecules to cool down. At the end of this process, the molecules returned to their most stable state but now in a denser gas.



False-color image of a gas of potassium-rubidium polar molecules (left) becoming denser and colder in reaching a state called quantum degeneracy (right), in which the individual molecules' matter waves overlap to create an interdependent system.
Image Credit: Ye Group/JILA

The new JILA method can be applied to make ultracold gases out of other types of polar molecules.

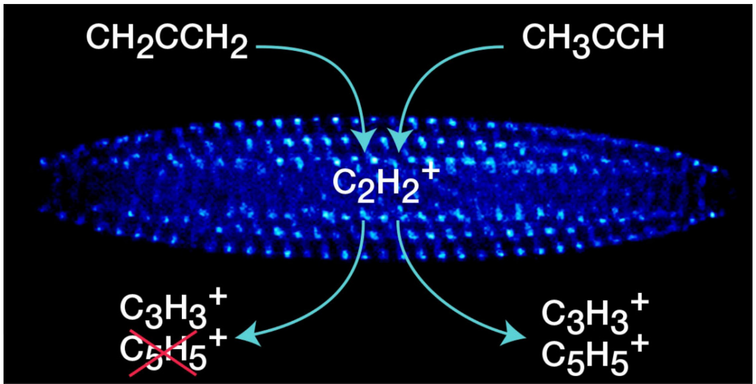
Ultracold molecular gases may have many practical uses, including new methods for quantum computing using polar molecules as quantum bits; simulations and improved understanding of quantum phenomena such as colossal magnetoresistance (for improved data storage and processing) and superconductivity (for perfectly efficient electric power transmission); and new tools for precision measurement such as molecular clocks or molecular systems that enable searches for new theories of physics.

Written by Laura Ost, NIST

Giacomo Valtolina, Kyle Matsuda, William G. Tobias, Jun-Ru Li, Luigi De Marco and Jun Ye, *Nature* **588**, 239–243 (2020)

Electron Fly-Bys on the Chemical Reaction Pathway

In chemistry, the shape of a molecule matters. Different arrangements of the same molecule are called isomers, and scientists have spent decades pondering how that shape affects chemical reactions.



By studying the reactions of neutral and ionic gases, the Lewandowski Group and their collaborators learned that the shape of a molecule makes a significant difference in the chemical reaction pathway and the final products of the reaction.
Image Credit: Lewandowski Group/JILA

Molecules react, bond, and separate along a reaction pathway, twisting into different shapes and combinations before delivering their final products. Tracking that pathway, especially with two molecules that are otherwise identical, is extremely complicated for theorists and experimentalists alike—and leaves them with a lot of questions about the importance of the initial isomer's shape.

"How does the structure influence reactions and the reaction pathway? If you have the same atoms put together in one way reacting with an ion versus another way, how does that change the pathway they go on, and ultimately the products that they produce?" asked JILA Fellow Heather Lewandowski.

To follow the paths of the isomers, the Lewandowski Group and their theory collaborators became detectives, looking for clues in the reactions between acetylene ions and propyne, and acetylene ions and allene. After years of careful study and theory calculations, their findings have been published in *Physical Chemistry Chemical Physics*—providing another piece of the puzzle in chemical reactions and the formation of the cosmos.

Heavy hydrogen tags

The group started with acetylene—the same gas you would find in a welding torch—and trapped it in an ion trap. Then they studied its reactions with two different isomers of C_3H_4—allene and propyne. The acetylene and propyne or allene react, bonding and breaking apart. Then they open the trap and accelerate the ions, sucking them into an ion detector. Ions arrive at the detector at different times based on their mass—heavier ones later than the lighter ones.

Without any tools to directly probe the molecules along their reaction pathway, the Lewandowski Group worked closely with theorist John Stanton and his group at the University of Florida. To help track that pathway, the Lewandowski Group added deuterium—a "heavy" hydrogen atom—to their molecules. That heavier atom acts like a tag, adding a little extra mass to some of the final products. As the two molecules combine and break apart, the product with deuterium appears later on the ion detector.

If the deuterium ended up with one set of products, the theorists could calculate that the reaction took one pathway versus another. The Lewandowski Group painstakingly swapped deuterium into different combinations for the acetylene, allene and propyne to track all of the possible outcomes, and working with their theory collaborators to calculate what each outcome meant.

“We sort of do this piece by piece, and we gather all these data together to be able to make a self-consistent picture. It’s taken us several years,” Lewandowski explained. “This is really quite a complex reaction to understand at this level of detail.”

Eventually the team was able to clearly draw the reaction pathways from the acetylene and propyne, and the acetylene and allene combinations. Acetylene and allene only resulted in a single product, whereas there were many possible products from acetylene and propyne.

“Our question was if you have allene or propyne, do these react differently with acetylene just because they have this different structure? The answer is fundamentally yes,” Lewandowski said.

The electron fly-by

More importantly, these products revealed how these reactions start for these molecules: charge exchange. Lewandowski described charge exchange as an electron fly-by between the neutral molecule (the allene or propyne) and the molecule missing an electron (the acetylene).

“The idea is, for one of these reactions, the electron hops when these molecules are very far apart, in a relative sense,” she explained. In the allene-acetylene reaction, the electron can just hop on as the molecules speed past each other.

For propyne, the electron can’t hop on during a molecule fly-by. In order to hop, the molecules have to get close enough to crash.

“It hops, but they are already so close they come in and form a complex,” Lewandowski said, resulting in multiple outcomes. “The real difference between these two is that for one reaction they charge exchange when they are far apart and then the molecules keep on going, and therefore produce only one ion product. The other reaction trades that electron, and then falls together and sticks together and then reacts. That initial stage causes these two wildly different outcomes...The shape drives the reactions.”

That’s important information to understand how neutral and ionic molecules react. But these cold molecules also resemble how atoms in space might interact. These studies can help us understand how complex molecules form in space. However, there’s still a lot yet to learn, and many more puzzle pieces to gather before that picture is complete, Lewandowski added.

“We have one more piece in the puzzle in understanding how ions and neutral molecules react,” she said. “One of the ideas is to build on this with other ions and other neutral molecules to put this puzzle together.”

P. C. Schmid, J. Greenberg, T. L. Nguyen, J. H. Thorpe, K. J. Catani, O. A. Krohn, M. I. Miller, J. F. Stanton and H. J. Lewandowski, *Physical Chemistry Chemical Physics* **22**, 20303-20310 (2020)

To achieve upconversion photoluminescence in rubrene, the Weber group found near-infrared light kickstarted a process called triplet-triplet annihilation, which works like a molecular version of Thunderdome: four photons enter, one photon leaves.
Image Credit: Steven Burrows/The Weber Group

The Rules of Photon Thunderdome

When it comes to photoluminescence, the rules for most materials are simple: shine a photon on the material, and one photon comes out. Other materials take some coaxing—shine two photons in and get a shorter wavelength photon out in a process called upconversion photoluminescence, or UCPL.

Many organic materials require a chemical sensitizer to get that upconversion photoluminescence—except for rubrene. This orange-tinted organic crystal can perform this upconversion photoluminescence process without an added sensitizer.

“The mystery was: why does this work for pure rubrene?” JILA Fellow Mathias Weber asked.

To answer this question, the Weber Group needed to learn the rules and the players for UCPL within the crystal. In their recently published study in the *Journal of Physical Chemistry Letters*, they found that this process plays out like “photon Thunderdome,” which could help scientists and engineers create new light sources and new technology that can harness the non-visible spectrum of light.

Photon Thunderdome

From earlier research, it was clear that UCPL is caused by a process called triplet-triplet annihilation, in which two particles with parallel spins combine, but at first it was not clear how the light was initially absorbed. Regular rubrene molecules don't absorb near-infrared light.

Another weird behavior found in earlier research has to do with the number of incoming photons required to get one photon out. For simple photoluminescence, one needs one photon to go for one photon to go out. For triplet-triplet annihilation, two photons need to go in for one to come out. In rubrene, UCPL takes four photons.

Weber grinned as he summarized this as a molecular version of Thunderdome:

"Two photons enter, one photon leaves. In rubrene, the rule of Thunderdome is four photons enter, one photon leaves."

To get to the bottom of how UCPL in rubrene works, the Weber Group needed to learn exactly which wavelength of light caused this reaction, and what inside the crystal started the process. They scanned the wavelength of invisible near-infrared light they shone on a rubrene crystal, tuning their laser until they saw a flash of yellow light—a sign of UCPL. These near-infrared wavelengths told them what exactly started the UCPL process—positively-charged ions (called cations) and negatively-charged ions (called anions), probably on the crystal's surface.

Two photons kick one cation and one anion into excited states. The cation and anion interact, combining their charges, and creating a rubrene molecule in its singlet ground state, and one in a triplet state. Another two photons achieve the same outcome with another pair of ions. The two triplets then combine, producing an excited singlet. That excited singlet fluoresces, and scientists see a blip of yellow light.

Now that the Weber Group knew that they needed a cation and an anion to get the process going, they could model it. In modeling the process, they were able to explain its other peculiar quality.

"The process needs four photons, so the output varies with the fourth power of the intensity of the incoming light. If you double the intensity of the incoming light, your output is sixteen times higher than before, and our model can account for that," Weber said.

The ability to sustain UCPL is an interesting material property, because the photons released in upconverted photoluminescence have a higher energy than the photons that went in, Weber pointed out. In photovoltaics, upconversion can be used to convert low-energy photons that cannot directly generate electricity into higher-energy photons that can. Although pure rubrene doesn't do this very efficiently, understanding this process could lead to better solar cells.

UCPL could also be used in relatively simple sensors in future quantum technology. For example, the process could be used to test the quality of novel light sources that produce "entangled light", such as photon pairs rather than one photon at a time.

J. Curtis Beimborn II, Wyatt Zagorec-Marks, and J. Mathias Weber, *The Journal of Physical Chemistry Letters* **11** (17), 7212–7217 (2020)

Now Hiring: The New Quantum Workforce

Scientists believe we are living in the Second Quantum Revolution, a period of rapid advances in technology based on discoveries in quantum science.

Companies from giants like IBM and Google to small startups are eager to create and perfect these new quantum technologies—and that requires training a new kind of workforce.

Universities are currently adapting their curriculum to prepare their students to enter that workforce. But what exactly do these jobs require? What kind of work is out there? That's what JILA Fellow Heather Lewandowski wanted to know.

"Everybody was saying we need to develop all these different degree programs to create the quantum workforce. But there was no data backing it," Lewandowski said. "I think that our group has the ability to probe this from a rigorous, educational research point of view."

In hour-long interviews, Lewandowski's postdoc Michael Fox asked 21 companies about these positions and what skills they required. After some analysis, Lewandowski and her group found that not everyone needs a PhD in physics to find a job in this field. Their findings were recently published in *Physical Review Physics Education Research*.

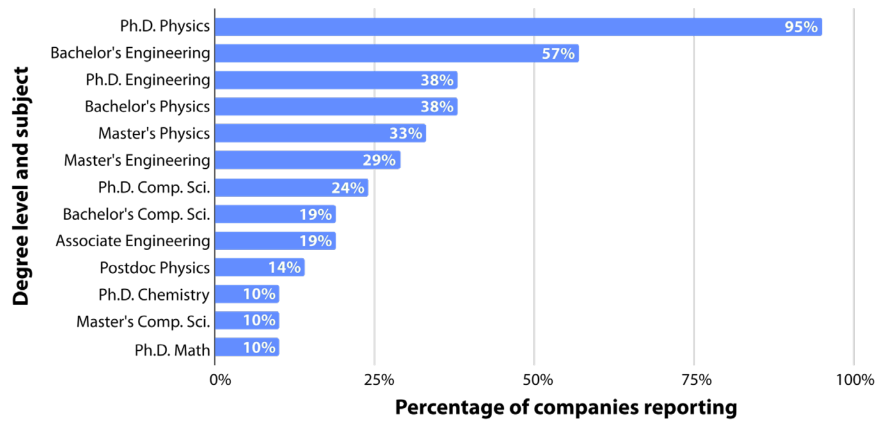
Classical skills with quantum knowledge

The quantum industry is very broadly defined, but the Lewandowski Group found five general categories among these companies: quantum sensors, quantum networking and communication, quantum computing hardware, quantum computing algorithms and applications, and facilitating hardware such as lasers, cryogenics or other specialized tools for the above listed technologies. The scientific jobs in these industries also fell into five categories: engineer, experimental scientist, theorist, technician, and application researcher.

Quantum sensors, computers, and communications are still in their infancy, and many companies are heavily invested in doing their own research and development. That's where physics PhDs are most needed, Lewandowski found. These are the group leaders, the idea people. People with specialized knowledge of quantum physics lead R&D projects and development in the industry.

They also found that PhD physics courses in quantum mechanics, electromagnetism, atomic physics, and statistical mechanics are valuable, and the practical experience of designing and running experiments was highly desirable.

But of all of these positions, engineers (or positions titled engineers) are in the highest demand. However, the Lewandowski Group found



The top 13 degree and subject combinations found in the quantum industry. The percentage corresponds to the number of companies, of the 21 in our sample, reporting at least one employee with the given combination of degree and subject.
Image credit: Michael F. J. Fox, Benjamin M. Zwickl, and H. J. Lewandowski, Preparing for the quantum revolution: What is the role of higher education? *Phys. Rev. Phys. Educ. Res.* 16, 020131 (2020).

that these companies weren't always looking for PhDs, but often talented classical engineers.

"Physicists design something and then engineers optimize it...They want people that can speak quantum and know the basics but that are really good in their own discipline, in particular the engineers," Lewandowski said. "You need to be a really good engineer first. Whether you are an electrical engineer or mechanical engineer, you want to have good classical skills first. Then you might want to do a minor in quantum engineering where you are going to take a few extra courses that cover some quantum mechanics and applications."

That's good news for those who have been working as electrical engineers or mechanical engineers, she pointed out. These highly-skilled engineers can take a few courses in quantum physics to gain the understanding they need to work in these new industries.

And, despite the anticipation around quantum computers, there was a lower demand for computer scientists. However, the team found the most highly requested skill was coding—classical coding, not quantum coding.

Rethinking quantum workforce education

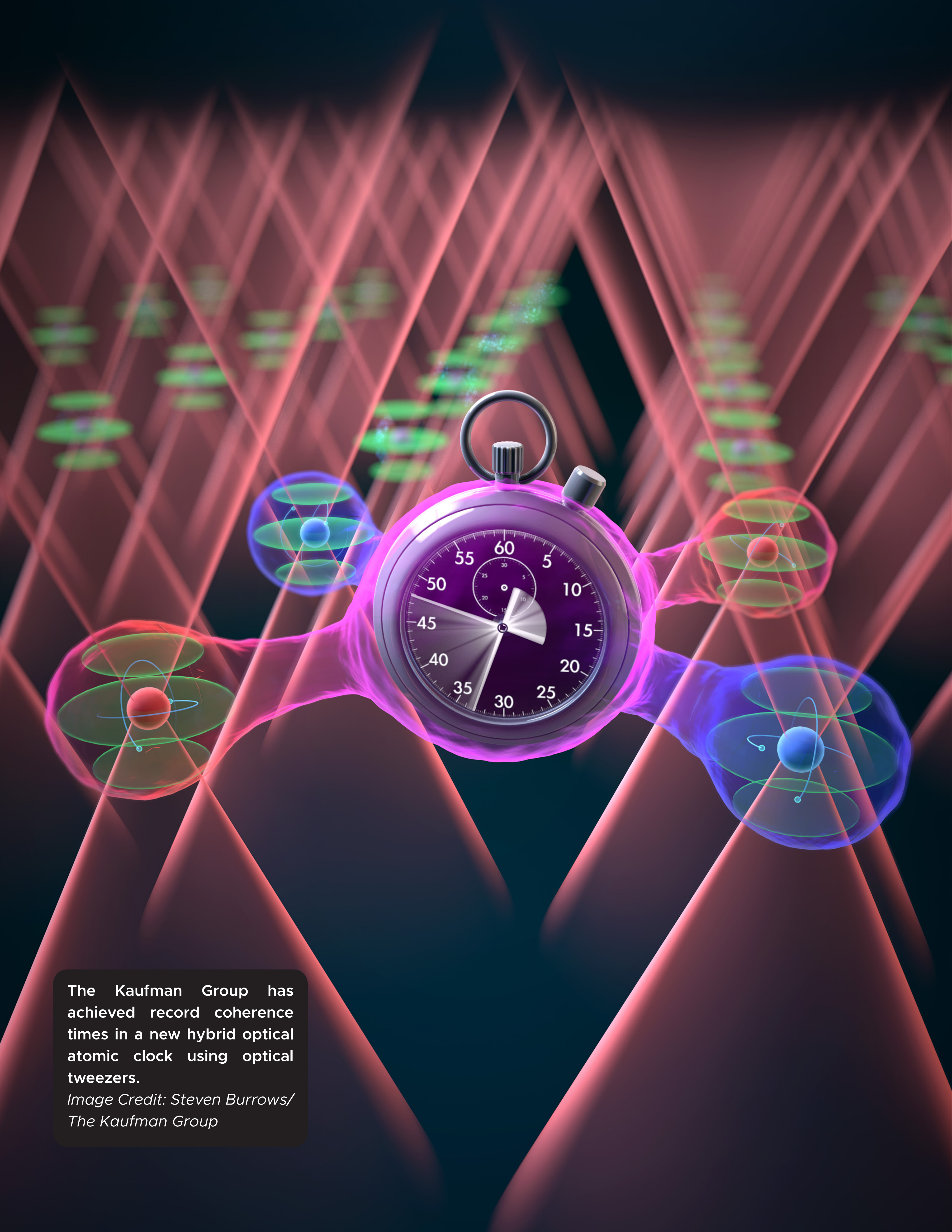
It's important for students and educators to remember that this is a growing industry; there's no reliable data available to say how many of these jobs are currently available or will exist in the near future, Lewandowski pointed out.

In their paper, the group made recommendations for universities on courses that will best prepare students for working in this field in various roles. Those include lab skills, particularly in optics and photonics, as well as engineering and collaborative coding skills.

"Our goal is really to reach university faculty and administrators in particular, because they are the ones developing programs and thinking about resources," Lewandowski added.

And for students, she offered this advice: "You don't need multiple degrees. You can get an engineering degree with a couple of these courses. Or, if you really want leadership of a lab or leadership of R&D, it looks like a PhD in physics is still the way to go for now."

Michael F.J. Fox, Benjamin M. Zwickl, and H.J. Lewandowski, *Physical Review Physics Education Research* **16**, 020131 (2020)



The Kaufman Group has achieved record coherence times in a new hybrid optical atomic clock using optical tweezers.

Image Credit: Steven Burrows/ The Kaufman Group

Tweezing a New Kind of Atomic Clock

Atoms are tricky to control. They can zip around, or even tunnel out of their containment. In order for new precision measurement tools and quantum devices to work—and work well—scientists need to be able to control and manipulate atoms as precisely as possible.

That's especially true for optical atomic clocks. In these clocks, a cold, excited atom's electrons swing back and forth in what's called a dipole, vibrating like a plucked string. Scientists rapidly count those swings with a laser, dividing a second into quadrillionths of a second.

However, even the best optical atomic clocks face decoherence—the atom falls back to its ground state, the laser loses the signal, and the clock winds down. This means optical atomic clocks can only take measurements for a few seconds before the atoms need to be "reset."

Scientists are continually exploring ways to increase those coherence times. Using optical tweezers, Aaron Young, along with other members of the Kaufman and Ye groups at JILA, have reached record-setting coherence times of more than half a minute. Their findings were recently published in *Nature*.

"The trick is to use separate sets of tweezers to prepare and measure the atoms, and to hang on to the atoms while they ring down. This makes it possible to optimize the second set of tweezers to preserve coherence for as long as possible, without having to worry about competing requirements associated with other phases of the experiment," Young said.

Optical atomic clock technology

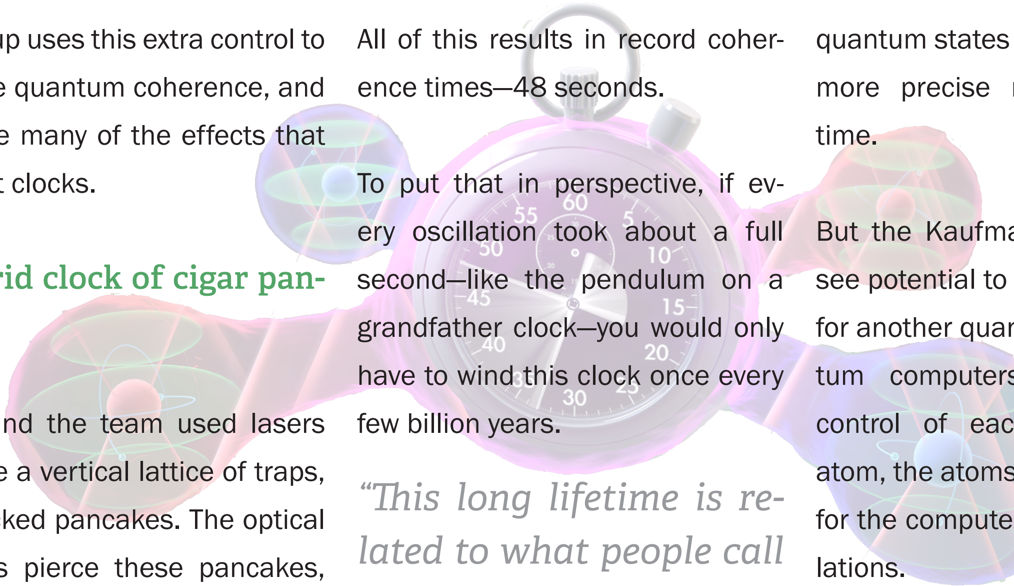
Optical atomic clocks are incredibly varied, but there are two popular means for controlling the atoms: ion traps, and optical lattices for trapping neutral atoms. Each approach has its strengths and weaknesses.

Trapped ion clocks measure the oscillations of a single charged atom, or ion. That atom is pristine, well-characterized, and well-controlled, however, due to the fundamental noise associated with quantum measurements, scientists need to run the trapped ion clock many times to obtain a precise measurement.

Lattice clocks, on the other hand, use standing waves of reflected lasers to form an egg carton-shaped lattice that can hold many atoms. This way, they can interrogate many thousands of atoms in parallel to obtain precise measurements in a short amount of time. But it's difficult to control any of those thousands of atoms individually, and interactions between these atoms must be well-characterized—a rich and complicated endeavor in its own right.

Controlling and preventing these interactions is where optical tweezers come in. Optical tweezers are highly-focused laser beams capable of grabbing and moving individual atoms—something the Kaufman Group has a lot of experience doing.

"With the tweezers, our traps are more or less independent," Young said. It gives you a lot of control over what kind of traps you can make."



The group uses this extra control to preserve quantum coherence, and minimize many of the effects that can limit clocks.

A hybrid clock of cigar pancakes

Young and the team used lasers to create a vertical lattice of traps, like stacked pancakes. The optical tweezers pierce these pancakes, looking like little cigar-shaped tubes. This creates a two-dimensional array composed of hundreds of spherical traps that each contain a single atom.

This pancake-cigar architecture allows for very quick cooling and trapping of the atoms, at which point they are easily transferred to a second set of tweezers designed specifically for clock physics.

Because the atoms are well-chilled, the second set of tweezers can make very shallow traps for the clock. Shallow traps minimize the number of photons that could interfere with the atoms, and they reduce the power required for the laser, making it possible to make more traps, and trap more atoms. They can also space these traps far enough apart so the atoms cannot move around or crash into their neighbors.

All of this results in record coherence times—48 seconds.

To put that in perspective, if every oscillation took about a full second—like the pendulum on a grandfather clock—you would only have to wind this clock once every few billion years.

"This long lifetime is related to what people call a 'quality factor'—it's the number of times an oscillator swings before it rings down. The quality factor of our experiment is the highest we know of in pretty much any physical system, including, depending on how you compare them, various astronomical systems like spinning neutron stars or planetary orbits," Young said.

More than a clock

"What we've effectively done is put 150 very coherent qubits in the same place, which serves as a really good starting point for engineering interactions," Young said.

A clock with controllable interactions could be used to engineer quantum states that allow for even more precise measurements of time.

But the Kaufman and Ye Groups see potential to use this technique for another quantum device: quantum computers. With exquisite control of each high-coherence atom, the atoms can act as a qubit for the computer to perform calculations.

Young and Kaufman also see this as a "zeroth order step" in physics research. Physicists are continually seeking better control over atoms to manipulate interactions between them, and study the results—and this hybrid tweezer clock is a promising means of achieving that control for long periods of time. By studying and controlling those interactions, physicists can better understand how the quantum world works, and those discoveries could lead to new advances in quantum-based technologies.

Aaron W. Young, William J. Eckner, William R. Milner, Dhruv Kedar, Matthew A. Norcia, Eric Oelker, Nathan Schine, Jun Ye and Adam M. Kaufman, *Nature* **588**, 408-413 (2020)

In the News

JILA Fellow Cindy Regal Named Baur/SPIE Chair in Optics and Photonics

JILA Fellow Cindy Regal

JILA Fellow Cindy Regal has been named the first recipient of the Baur-SPIE Endowed Chair in Optics and Photonics, JILA's first-ever endowed chair position for optics and photonics research.

Regal is a well-renowned and recognized physicist. Her pioneering research has been highly-cited, and earned a CO-Labs Governor's Award for high-impact research in 2016. Among her other achievements, she won a Packard Fellowship in 2011, was named an APS Fellow in 2017, and received a 2020 FRED Award from the Research Corporation for Science Advancement.

Her group at JILA pursues a wide range of research in optics and photonics, particularly using lasers to control and measure quantum objects. Their work uses lasers to cool mechanical vibrations and measure forces at the quantum limit. They also are exploring optical tweezers to control and study rubidium-87 atoms, and have demonstrated the first spin entanglement of ground-state neutral atoms. The Regal Lab also collaborates with the Lehnert Lab to study transducing microwave and optical signals—work that is important for quantum-based devices like computers, communications, and sensors.

The Baur-SPIE Endowed Chair in Optics and Photonics was founded in 2020. It is funded by a gift of $1.5 million from private donors Tom and Jeanne Baur of Meadowlark Optics and a $500,000 matching gift from SPIE, the international society for optics and photonics. In addition, CU Boulder is contributing $500,000 from the university. The chair is designed for early-to-mid-career researchers affiliated with groups historically under-represented at CU Boulder, as well as academics who have an established interest in teaching and mentoring.

OSTP Quantum Division Highlights Q-SEnSE Leadership in Quantum Sensing

Charles Tahan, Assistant Director for Quantum Information Science at the White House Office of Science and Technology Policy (OSTP)—as well as the director of the National Quantum Coordination Office (NQCO)—featured Q-SEnSE in the December 3 edition of Letters from the NQCO Director, highlighting CU Boulder's leadership in quantum sensing and the many "quantum questions" the NSF Quantum Leap Challenge Institute aims to address.

"The Q-SENSE team will tackle a deeply scientific question at the heart of quantum information," Tahan writes. "Does quantum entanglement, not just superposition, provide an advantage for quantum timekeeping, sensing or measurement? Let me give you a sense of how far they will reach to answer these questions.

Some of the best clocks, like those made by NIST at their joint lab (JILA) with the University of Colorado Boulder, reach accuracies of a small fraction of 1018. That means that over the age of the Universe, they may be wrong by one second. Q-SEnSE may make 1020 clocks possible." Such clocks, Tahan explains, can potentially predict future earthquakes and enable fundamental discoveries about nature.

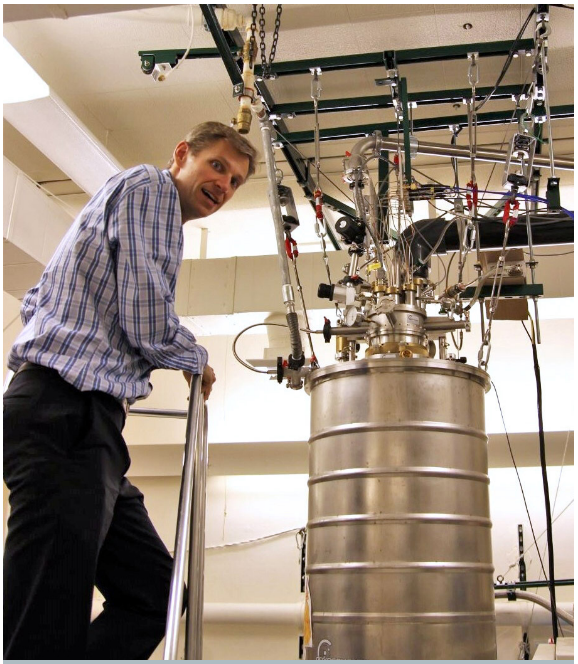
Written by Allison Miller

Konrad Lehnert named as a 2020 AAAS fellow

JILA fellow Konrad Lehnert has been elected as an American Association for the Advancement of Science (AAAS) Fellow by the Council of the AAAS. In 2020, 489 members have earned this lifetime distinction; of which 33 are physicists. Lehnert is the 6th JILA fellow to become an AAAS fellow; he joins Eric Cornell, Henry Kapteyn, Carl Lineberger, Margaret Murnane, and Markus Raschke with this distinction.

AAAS has been electing fellows since 1874, and as a result thousands of prominent scientists have been recognized. AAAS Fellows are determined first by their nomination by three existing Fellows, the steering group of an AAAS section, or the organization's CEO, after which nominees are reviewed and voted on by the AAAS Council.

"I think of the fellowship as recognizing of the accomplishments of the more than 40 students, postdocs and visiting scientists who have come from around the world to advance science by studying and working with me at the University of Colorado," said Lehnert after hearing of his becoming an AAAS fellow.



Konrad Lehnert in lab at JILA

Lehnert was elected by the AAAS council "for his pioneering contributions to quantum science, particularly quantum control and measurement of mechanical oscillators, and sub-quantum limited measurement with applications to dark matter searches."

Lehnert has been a joint fellow of JILA and NIST since 2003. Previous awards include the Kavli Fellow in 2010 and 2011, Fellow of the American Physical Society in 2013, the Governor's award for high impact research (with Cindy Regal) in 2016, the Silver Medal from the Department of Commerce (with Jon Teufel, Ray Simmonds, and Joe Aumentado) in 2019, and the Vannevar Bush Faculty Fellowship in 2020.

Mitch Begelman named CU Distinguished Professor

JILA fellow Mitch Begelman has been named CU Distinguished Professor by the CU Board of Regents. Begelman is the 5th JILA fellow of only 118 CU professors who have been awarded this honor since 1977. He joins JILA fellows Richard McCray, Carl Lineberger, Carl Wieman, and Margaret Murnane with this distinction.

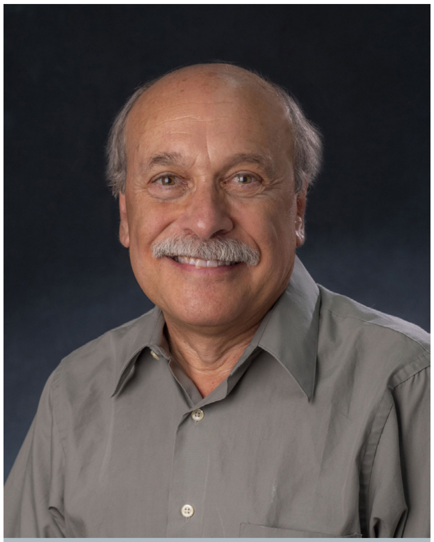
"This is a special honor, since CU is such an amazing community of scholars. Being part of JILA, in particular, has enabled me to work with some of the best faculty colleagues, students and postdocs in the world," Begelman says of the award.

Begelman's research has been recognized through numerous awards. He was awarded a Guggenheim Fellowship, the Helen B. Warner Prize of the American Astronomical Society, an Alfred P. Sloan Foundation Research Fellowship, and a Presidential Young Investigator Award. In 2018, Begelman was named a Professor of Distinction by the College of Arts and Sciences.

His group at JILA investigates high-energy and theoretical astrophysics. His seminal research on the growth of black holes and how they interact with their environments has shed new light on their key role in the Universe. He has also made highly notable contributions to understanding energetic astrophysical plasmas, including those in cosmic jets and accretion disks.

Begelman has fostered the beginning careers of dozens of Ph.D. students and postdoctoral scholars. His leadership has enabled them to go on to form their own research groups throughout the world. Begelman developed the highly popular Black Holes course, of which he says, "Where else would I have had the opportunity to develop and teach one of the first courses anywhere on the astrophysics of black holes, aimed at non-science majors?" In 1996 he was awarded the American Institute of Physics Science Writing Award for "Gravity's Fatal Attraction: Black Holes in the Universe"; a book he co-authored with Sir Martin Rees, which is used for this course.

The title of Distinguished Professor is well deserved of such a prestigious and prolific JILA fellow.



JILA Fellow Mitch Begelman

Jun Ye wins 2020 Micius Quantum Prize

Fellow Jun Ye has been awarded the 2020 Micius Quantim Prize. The Micius Quantum Prize 2020 focuses on the broadly defined field of quantum metrology, recognizing scientific advances ranging from early conceptual contributions to experimental breakthroughs.

The past recipients are people who pioneered quantum information science, such as Peter Shor for work on the Shor algorithm, Ignacio Cirac, Peter Zoller and David Wineland for work on the first quantum logic gate, and Anton Zeilinger for quantum communication, etc. Jun is sharing this year's prize on quantum sensing with Prof. Hidetoshi Katori (Univ. Tokyo) for work on optical atomic clocks and Carl Caves (UNM) who first proposed quantum light for LIGO (in 1980).

Quantum mechanics, discovered at the beginning of the last century, has been an enormously successful theory of nature and has led to the development of many of today's most widely used technologies that have completely changed the landscape of our society.

In past decades, profound progress, made both in our understanding of exploiting quantum superposition and entanglement for new ways of information processing and in the experimental methods of coherent control and interaction of individual quantum particles, has given birth to an emerging field of quantum technologies, also known as the second quantum revolution. This has moved beyond the first quantum revolution that simply exploited naturally occurring quantum effects.

The second quantum revolution has been driving and enabling a new generation of classically impossible tasks ranging from unconditionally secure quantum communications, breathtakingly powerful quantum simulation and quantum computation, to extremely sensitive measurements.

To promote the second quantum revolution, a new science foundation, the "Micius Quantum Foundation" has been established in 2018 thanks to generous donations from private entrepreneurs. This Foundation is named after Micius, an ancient Chinese philosopher who lived in a similar period to the Western philosopher Democritus.

One of the important missions of the Micius Quantum Foundation is to establish the “Micius Quantum Prize” to recognize the scientists who have made outstanding contributions in the field of quantum communications, quantum simulation, quantum computation, and quantum metrology. The revenue of the Micius Quantum Foundation is distributed in the form of prizes. Each honoree will receive a prize of 1.25 million Chinese yuan (after-tax about 150,000 US dollars) and a gold medal.

JILA Fellow Jun Ye

Margaret Murnane and Henry Kapteyn honored by National Academy of Inventors

Two scientists who pioneered technologies for generating coherent X-rays, which helped propel research in dynamic processes in atoms, molecules and materials, have been named fellows of the National Academy of Inventors, the academy announced December 8, 2020.

Margaret Murnane and Henry Kapteyn, physics professors at the University of Colorado Boulder, direct a laboratory in JILA, a joint institute of CU Boulder and the National Institute of Standards and Technology.

They are among 175 inventors to be named 2020 National Academy of Inventors. Murnane and Kapteyn are co-inventors on 17 U.S. patents and have published more than 250 peer-reviewed journal articles. They are co-founders of KM Labs, a startup company that produces high-power, high-performance table-top laser systems.

The National Academy of Inventors Fellows Program highlights academic inventors who have “demonstrated a spirit of innovation in creating or facilitating outstanding inventions that have made a tangible impact on quality of life, economic development and the welfare of society.”

Murnane said she and Kapteyn were were surprised and honored to be named fellows of the National Academy of Inventors.

“This honor means a great deal to us, since our passion is to create new and useful laser light sources in the X-ray region," she said, adding: “We so much enjoy working with CU Boulder students and collaborators from industry and national laboratories."

Kapteyn added, “My goal as a kid was to become an ‘inventor.’ I suppose I made it.”

The Murnane-Kapteyn lab’s next challenge: to create a new generation of X-ray microscopes that can work at the quantum limits of resolution and sensitivity, in real time, she said.

Murnane and Kapteyn joined the CU Boulder faculty in 1999. Murnane is also a professor in the CU Boulder Department of Electrical and Chemical Engineering. Kapteyn also serves as chief technology officer at KM Labs.

They are both members of the National Academy of Sciences and fellows of the American Association for the Advancement of Science and the American Academy of Arts and Sciences. They won the 2020 Franklin Medal in Physics, the 2018 Colorado Governor’s Award for High-Impact Research, and dozens of other honors.

Election to the National Academy of Inventors Fellows Program is the highest professional distinction accorded solely to academic inventors. To date, fellows hold more than 42,700 issued U.S. patents, which have generated more than 13,000 licensed technologies and companies, and created more than 36 million jobs.

In addition, more than $2.2 trillion in revenue has been generated based on National Academy of Inventors fellows’ discoveries.

The 2020 fellow class represents 115 research universities and governmental and nonprofit research institutes worldwide. They collectively hold over 4,700 issued U.S. patents.

Among the 2020 fellows are 24 recipients of the National Academies of Sciences, Engineering, and Medicine, six recipients of the American Academy of Arts and Sciences, and two Nobel Laureates, as well as other honors and distinctions. Their collective body of research covers a range of scientific disciplines including biomedical engineering, computer engineering, materials science, and physics.

The class of fellows will be inducted at the 2021 Fellows Induction Ceremony at the Tenth Annual Meeting of the National Academy of Inventors next June in Tampa, Florida.

Henry Kapteyn and Margaret Murnane at JILA.

The National Academy of Inventors includes U.S. and international universities, and governmental and nonprofit research institutes, with over 4,000 individual inventor members. It was founded in 2010 to recognize and encourage inventors with patents issued from the United States Patent and Trademark Office, enhance the visibility of academic technology and innovation, encourage the disclosure of intellectual property, educate and mentor innovative students, and translate the inventions of its members to benefit society.

Written by Colorado Arts and Sciences Magazine

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

University of Colorado **Boulder**

NIST 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 School 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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