LIGHT + MATTER

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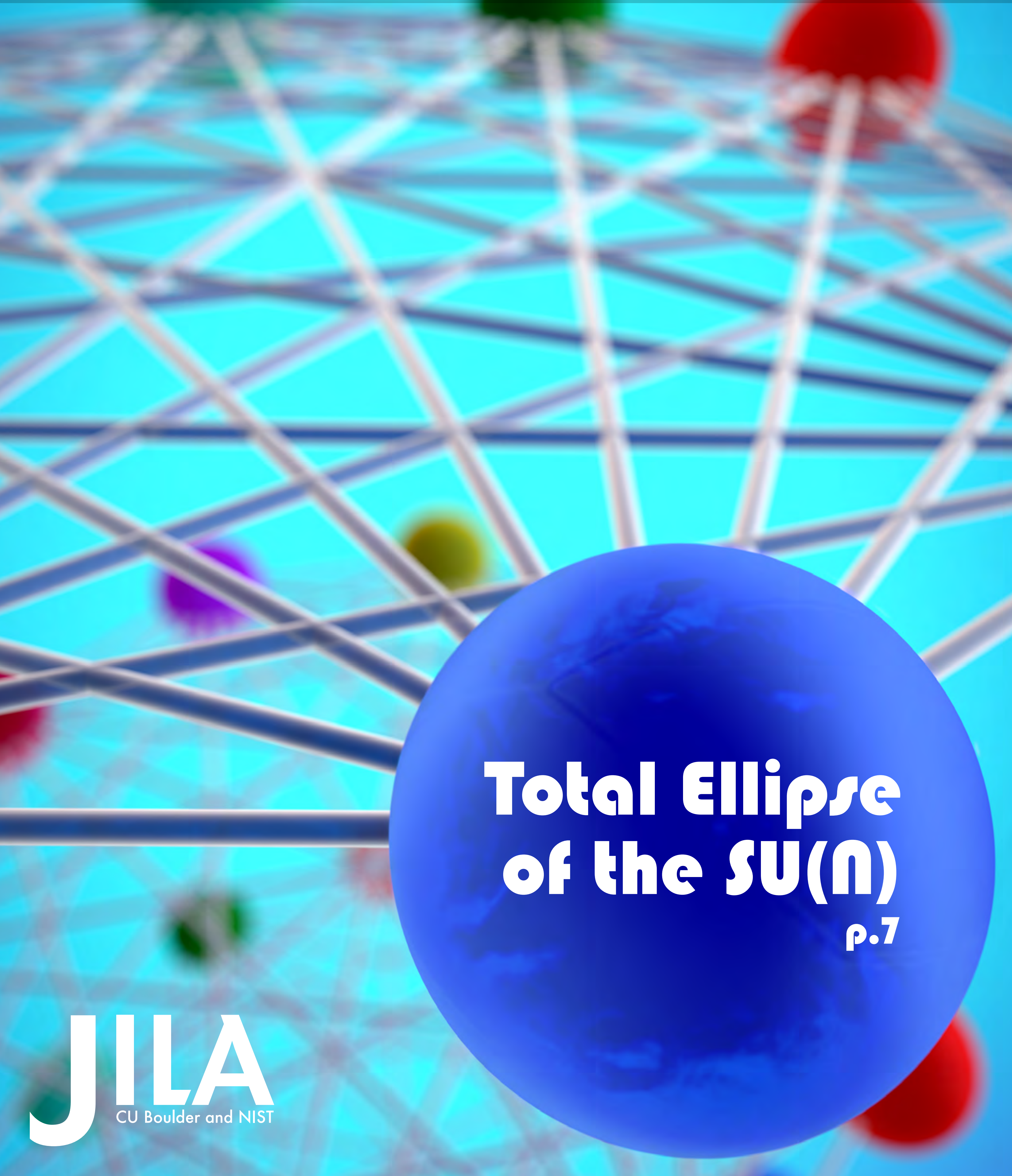

Total Ellipse of the SU(N)

p.7

JILA
CU Boulder and NIST

JILAns got together for a virtual JILAx where they gave 3 minute TED-talk style presentations about any topic except research!

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In the News

The Collective Power of the Solar System's Dark, Icy Bodies

The outermost reaches of our solar system are a strange place—filled with dark and icy bodies with nicknames like Sedna, Biden and The Goblin, each of which span several hundred miles across.

Two new studies by researchers at the University of Colorado Boulder may help to solve one of the biggest mysteries about these far away worlds: why so many of them don't circle the sun the way they should.

The orbits of these planetary oddities, which scientists call "detached objects," tilt and buckle out of the plane of the solar system, among other unusual behaviors.

"This region of space, which is so much closer to us than stars in our galaxy and other things that we can observe just fine, is just so unknown to us," said JILA Fellow Ann-Marie Madigan, an assistant professor in the Department of Astrophysical and Planetary Sciences (APS) at CU Boulder.

Some researchers have suggested that something big could be to blame—like an undiscovered planet, dubbed "Planet 9," that scatters objects in its wake.

But Madigan and graduate student Alexander Zderic prefer to think smaller. Drawing on exhaustive computer simulations, the duo makes the case that these detached objects may have disrupted their own orbits—through tiny gravitational nudges that added up over millions of years.

The findings, Madigan said, provide a tantalizing hint to what may be going on in this mysterious region of space.

Scientists have long struggled to explain the existence of the solar system's "detached objects," which have orbits that tilt like see-saws and often cluster in one part of the night sky.
Image CreditSteven Burrows/Madigan Group

"We're the first team to be able to reproduce everything, all the weird orbital anomalies that scientists have seen over the years," said Madigan. "It's crazy to think that there's still so much we need to do."

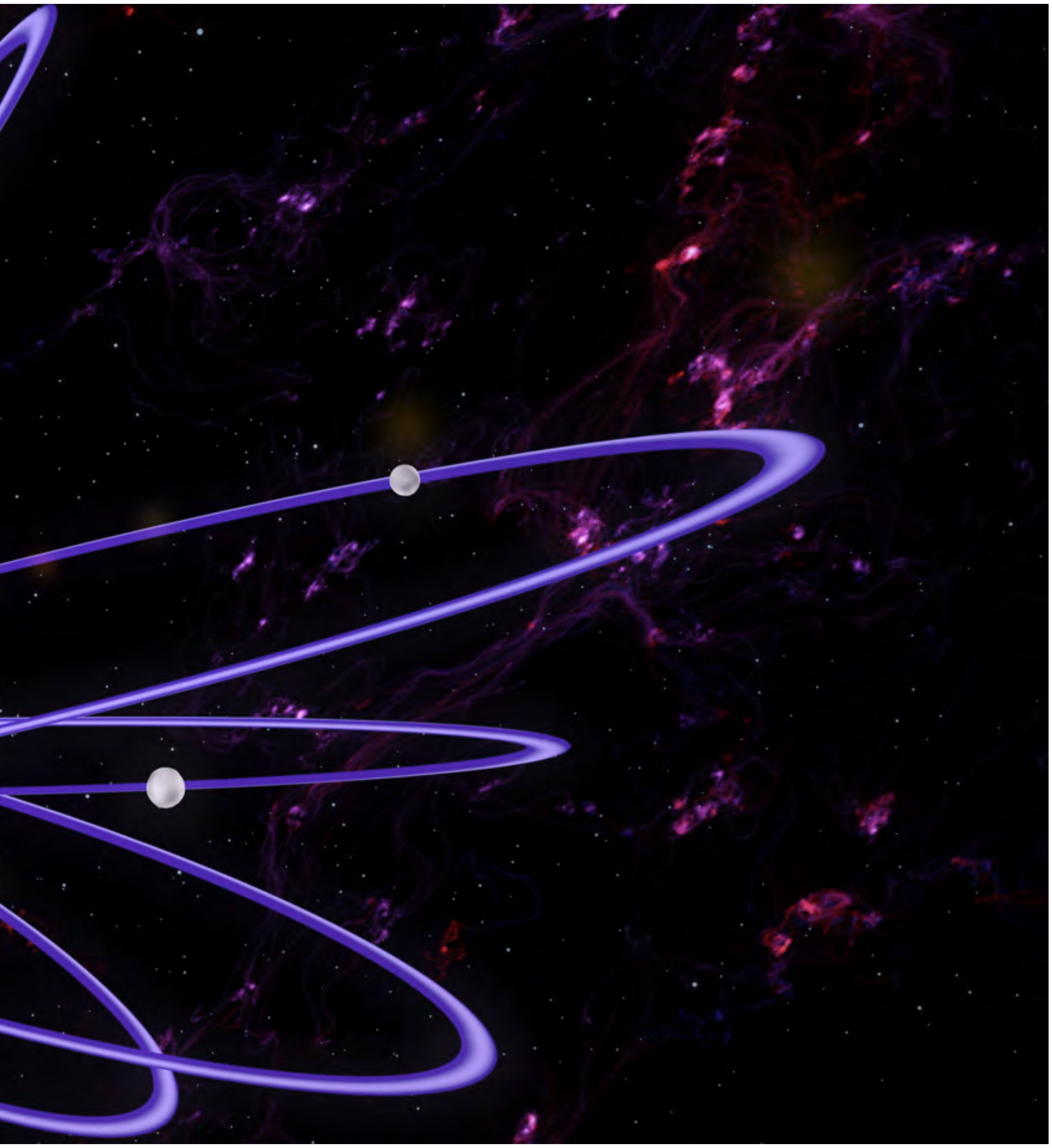
The team published its results July 2 in *The Astronomical Journal* and last month in *The Astronomical Journal Letters*.

Power to the asteroids

The problem with studying the outer solar system, Madigan added, is that it's just so dark.

"Ordinarily, the only way to observe these objects is to have the sun's rays smack off their surface and come back to our telescopes on Earth," she said. "Because it's so difficult to learn anything about it, there was this assumption that it was empty."

She's one of a growing number of scientists who argue that this region of space is far from empty—but that doesn't make it any easier to understand.



Just look at the detached objects. While most bodies in the solar system tend to circle the sun in a flat disk, the orbits of these icy worlds can tilt like a seesaw. Many also tend to cluster in just one slice of the night sky, a bit similar to a compass that only points north.

Madigan and Zderic wanted to find out why. To do that, they turned to supercomputers to recreate, or model, the dynamics of the outer solar system in greater detail than ever before.

"We modeled something that may have once existed in the outer solar system and also added in the gravitational influence of the giant planets like Jupiter," said Zderic, also of APS.

In the process, they discovered something unusual: the icy objects in their simulations started off orbiting the sun like normal. But then, over time, they began to pull and push on each other. As a result, their orbits grew wonkier until they started to resemble the real thing. What was most remarkable was that they did it all on their own—the asteroids and minor planets didn't need a big planet to throw them for a loop.

"Individually, all of the gravitational interactions between these small bodies are weak," Madigan said. "But if you have enough of them, that becomes important."

Earth times 20

Madigan and Zderic had seen hints of similar patterns in earlier research, but their latest results provide the most exhaustive evidence yet.

The findings also come with a big caveat. In order to make Madigan and Zderic's theory of "collective gravity" work, the outer solar system once needed to contain a huge amount of stuff.

"You needed objects that added up to something on the order of 20 Earth masses," Madigan said. "That's theoretically possible, but it's definitely going to be bumping up against people's beliefs."

One way or another, scientists should find out soon. A new telescope called the Vera C. Rubin Observatory is scheduled to come online in Chile in 2022 and will begin to shine a new light on this unknown stretch of space.

"A lot of the recent fascination with the outer solar system is related to technological advances," Zderic said. "You really need the newest generation of telescopes to observe these bodies."

Written by Daniel Strain

Alexander Zderic and Ann-Marie Madigan, *The Astronomical Journal* **160,** 50 (2020)

Falling Dominos and an Army of Schrödinger's Cats

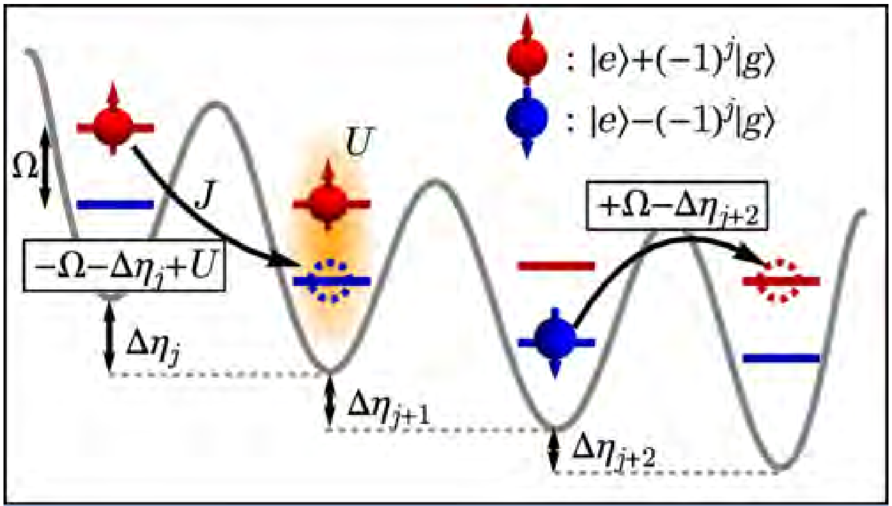
Schrödinger's Cat is one of the most famous thought experiments in quantum mechanics. Physicist Erwin Schrödinger's thought experiment goes like this: suppose you have a cat sealed in a box with a contraption that may or may not go off to release a poison. The only way to confirm the cat's fate is to open the box. Until the box is opened, the cat is both alive and dead.

Being in a superposition of two states at a time is an intrinsic property of quantum objects like atoms which, for example, can exist in two opposing spin states simultaneously: spin up and spin down. This is referred to as a "cat state" in reference to Schrödinger's cat. That makes superposition states really useful for physicists.

Quantum mechanics is bound by uncertainty; you can know with great certainty an object's position but not its momentum, and vice versa. Atoms are also intrinsically fuzzy objects. You cannot know with full certainty which specific direction its spin is pointing. However, when arrays of atoms become entangled—like in a cat state—they can cancel out each other's quantum noise and become less fuzzy.

"Cat states have been one of the states that reaches this quantum mechanical bound. You cannot be more precise, in principle, than a cat state," JILA Fellow Ana Maria Rey explained.

But preparing cat states has been extremely difficult, especially with a large number of atoms. NIST's Dave Wineland gained renown for generating a cat state in six atoms—a record number in 2005.



Schematic of the optical lattice system, confined to 1D. The red- and blue-labeled single-particle eigenstates of the collective drive field are superpositions of bare atomic states {g, e}.
Image Credit: Rey Theory Group

Mikhail Mamaev, a graduate student in the Rey Theory Group, developed a novel scheme to prepare a large number of atoms in cat states using the strontium clock in the Ye Lab at JILA. Not only can this new method prepare a large number of atoms in a cat state, they can be measured easily. These findings were published in *Physical Review Letters* on June 16.

"He starts with something that is very classical, and then step by step, he is converting this classical object into a highly entangled object using the exquisite resolution of the clock," Rey said.

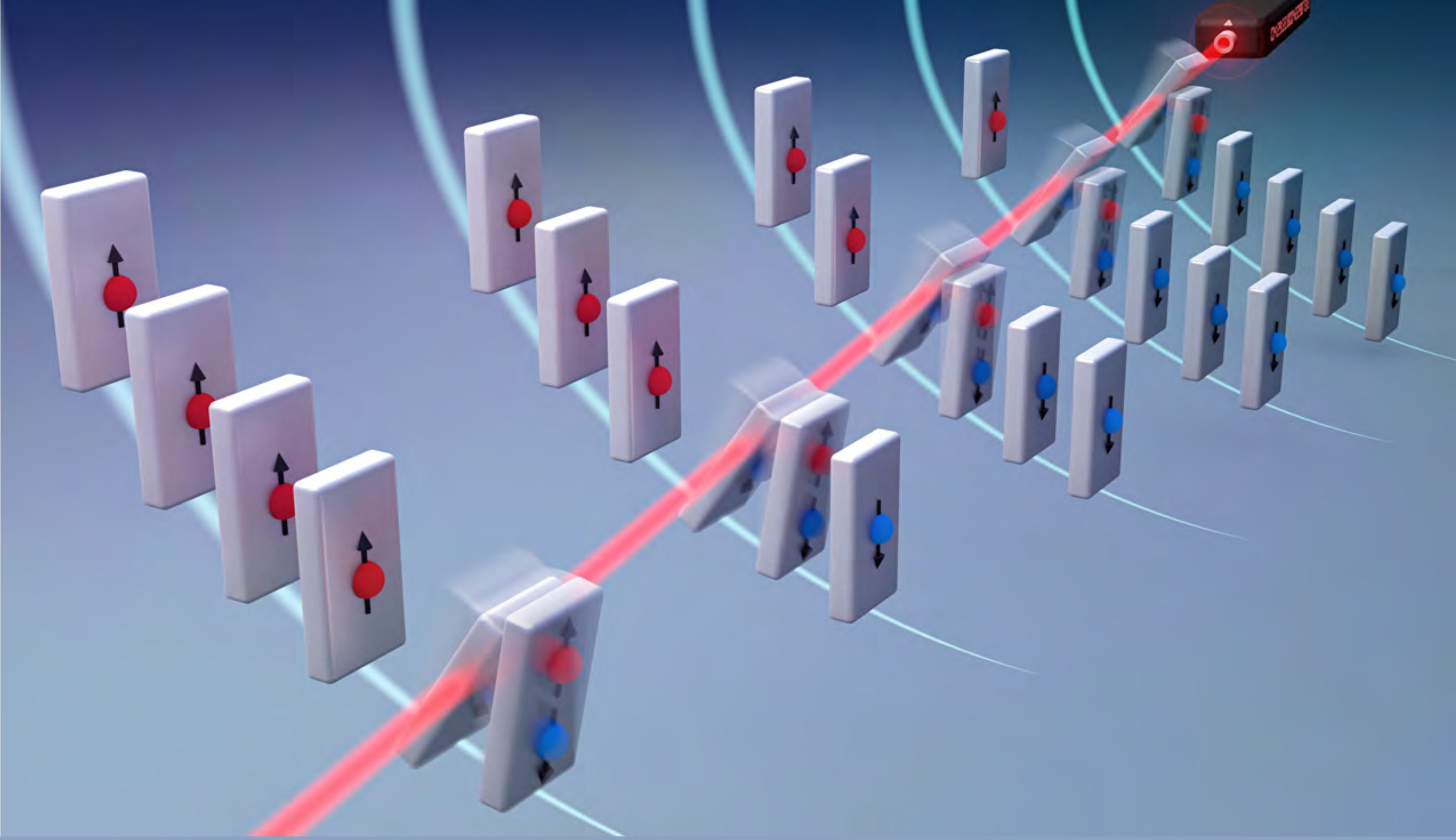
Falling dominoes

Typically, physicists prepared cat states by starting with all the atoms in the ground state—spins pointing down—and slowly start changing the parameters to change the energy of the entire system and create that superposition. But the more atoms you add, the longer it takes and the more difficult that process is, Rey said. And they're delicate.

"It is harder to entangle many atoms because then you can kill the superposition. If you flip one [atom], it kind of disappears," Rey said.

What Mamaev's approach does is covert a local superposition—a local quantum state involving just two atoms—into a many-body cat state in a step-by-step fashion using the laser from the strontium clock as the flipping device, Rey explained. The process starts with a collection of atoms with their spins all pointing down. The atoms sit in an optical lattice, which can be thought of as an egg crate with each atom in an individual well. Starting in the corner of the array, Mamaev can use the clock's laser to force one atom to tunnel into its neighbor's well.

It costs the atoms too much energy



The Rey Theory Group has devised a way to generate multiple cat-state atoms using the laser from the strontium optical atomic clock to force them to tunnel and entangle, much like a falling set of dominos.
Image Credit: Steven Burrows and the Rey Theory Group/JILA

to share their egg carton well with another atom. However, if the atom is illuminated by the laser, it acquires the sufficient energy to tunnel further, flipping itself as it moves.
"When it tunnels over, it flips itself... It's in a quantum superposition," Mamaev said. The cat is now both dead and alive.

They start with two atoms and from there, the rest of the array falls like dominoes. By using the laser as a pointer, the atoms can sequentially be flipped step-by-step. If the first atom was flipped up by the first step, so will the rest of the atoms after the sequence is done. If not, they'll all stay down in their wells the whole time. Soon, the array is in a cat state—all equally up and down at the same time.

"It's step by step. You can control which one to move by the precision of the clock or the frequency of the clock," Rey said.

When all the dominoes have fallen, the atoms are entangled, and all that's left is to measure that entanglement. Fortunately, there's still doublons or pairs of atoms at the end of the array—the last domino. Using those leftover doublons, the team can determine if they successfully created a cat state.

"You measure only the corner and you can get the signal," Rey said. And being able to do this with a single pair of atoms is a boon to the whole process.

Strength in an army of cats

This experiment also has a significant advantage over previous cat state-generating protocols. Unlike most of the prior work on this, this protocol makes not one cat, but an entire legion—an army of cats, coming from the different rows of the lattice. Each cat which can help provide a constructive signal for measurement, which can boost the performance of metrology tools that rely on atomic frequency, like optical atomic clocks.

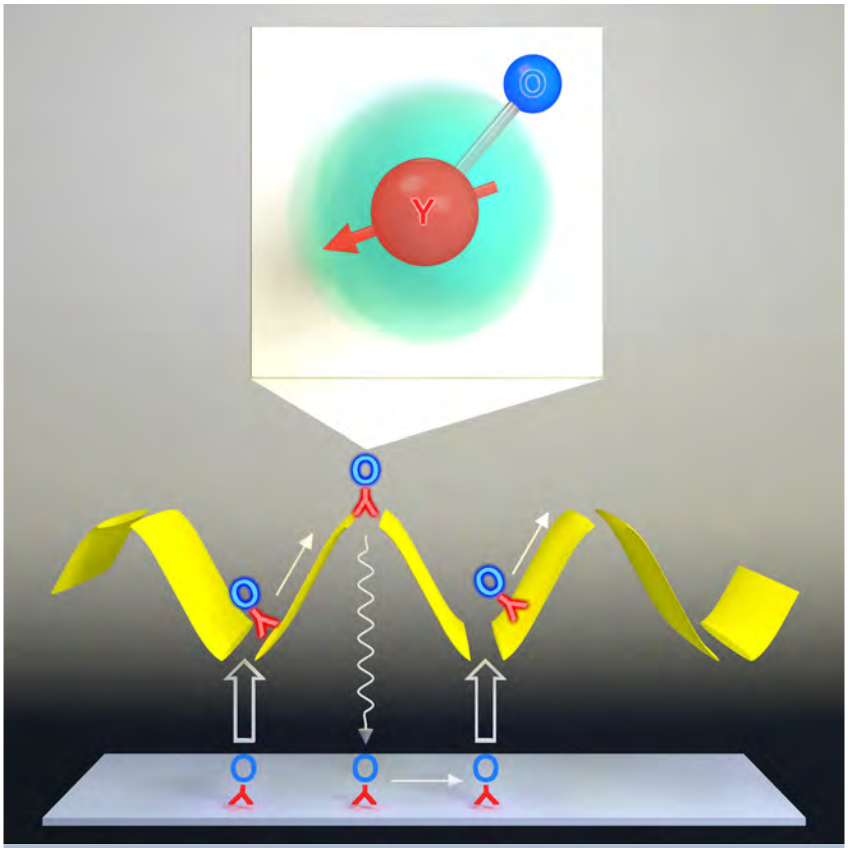
Mikhail Mamaev and Ana Maria Rey, *Physical Review Letters* **24,** 240401 (2020)

The Sisyphean Task of Cooling Molecules

If you want to control the quantum world, it helps to make things really cold—like a few millionths of a degree above absolute zero. When atoms reach those ultracold temperatures, they slow down and scientists can better probe them and study their interactions.

Ultracold atoms have been well-explored for decades, and are the basis for precision metrology tools like atomic clocks. With dense collections of ultracold atoms, physicists have been able to study how atoms interact, leading to new understanding of strange quantum mechanical phenomena.

Yet, atoms are fairly simple—a nucleus with orbiting clouds of electrons. So what could we learn from more complex systems like molecules?



A new cooling scheme from the Ye Group brings yttrium monoxide molecules to 4 microKelvin.
Image Credit Steven Burrows/Ye Group

"Molecules have very different properties," said Shiqian Ding, a postdoctoral researcher in the Ye Lab. Compared to atoms, molecules have more degrees of freedom and richer energy structures, which create opportunities to see new quantum mechanical phenomena, understand how chemistry works on the most fundamental level, and develop new technology platforms for quantum control. However, that complexity also makes it more challenging to extend laser cooling techniques—which work so well with atoms—to molecules.

Techniques exist to bring a pair of cold atoms together to form a molecule, but laser cooling molecules can bring a more diverse set of molecules to ultra-low temperatures. Using a technique called gray molasses cooling, Ding and his team—Yewei Wu, Ian Finneran, Justin Burau, and JILA Fellow Jun Ye—have cooled yttrium monoxide molecules to 4 microKelvin—4 millionths of a degree above absolute zero.

They found that this technique is not only efficient, but also robust, keeping molecules cold even under unusual circumstances, such as in the presence of a very large magnetic field. They also proposed and demonstrated a novel scheme to combine this robustness with a trapping force to increase the molecular density by a factor of 10. Their findings were published in *Physical Review X* on June 3.

The trouble with molecules

A common and efficient way to cool atoms is using lasers. Electrons in the lower orbit absorb a photon from the laser and go to a higher orbit. The electrons then come back to the same ground orbit by emitting another photon. Both of these processes cause the atoms to recoil. Repeating these processes hundreds of thousands of times removes most of the kinetic energy of the atoms, i.e., cools them down.

That's harder to do with a molecule, Ding explained. In a molecule, electrons orbit around more than one nuclei. When an electron drops back to the ground state by emitting a photon, the recoil also affects the motion between the nuclei in the molecule, causing them to vibrate, rotate, or both. A separate laser is required to address each vibration/rotation state in order to continuously scatter photons. Usually, you might need tens or even more lasers, each tuned to exactly the right frequency for each possible state, he pointed out. This is obviously not realistic.

A few molecules are an exception to this picture, like yttrium monoxide. In yttrium monoxide, only one electron is active and it orbits mostly around the yttrium nucleus, and barely interacts with the oxygen nucleus. When this electron falls back to the lower orbit, it hardly excites the relative nuclei motion. In this case, much fewer quantum states get involved and only a few lasers are required to cycle hundreds of thousands of photon-scattering events to perform laser cooling.

Ding and his fellow researchers tried a well-established technique called gray molasses cooling on the molecule—with some surprising results.

"Because molecules like to turn dark with photon scattering, finding a cooling technique that works by using dark states can be a natural way forward. We found this technique to be exceptionally efficient and robust for cooling yttrium monoxide molecules." Ding said.

Up and down the hill

To understand how gray molasses cooling works, it helps to think of the Greek myth of Sisyphus, who was forced to eternally push a boulder up a hill, only for it to fall back down.

Ding and his team create many artificial hills with interference of laser light for yttrium monoxide molecules to climb. Once the molecule reaches the hilltop, the lasers transfer it back to the bottom, where the molecule is in what is known as a dark state, Ding explained. In the dark state, if the molecule is not moving, it will not "talk" to the lasers anymore, i.e., it does not feel the existence of the hills the lasers create.

But if the molecule starts moving, the hills show up! Just like the mythical Sisyphus, the process keeps repeating itself and the molecule loses energy on the way. As it loses energy, it gets colder.

The yttrium monoxide reached 4 microKelvin—that's 4 millionths of a degree above absolute zero. It's the coldest temperatures physicists have reached for laser-cooled molecules, Ding pointed out.

What makes this cooling technique even more appealing is its exceptional robustness for cooling yttrium monoxide. If the laser was a little out of tune, it still worked. Even when the molecules were surrounded by a large magnetic field, they kept cold.

"That's striking. We are talking about 20, 25 Gauss [of magnetic field]," he said. With other systems, even 1 Gauss can seriously hurt the cooling effect, he explained. But for an yttrium monoxide molecule, the active electron is mostly orbiting around the yttrium nucleus, and the magnetic field sensitivity of the electron is largely mitigated by its coupling to the yttrium nucleus.

"Because of the special structure of yttrium monoxide, the cooling is just not sensitive to the magnetic field," Ding added.

Into the trap

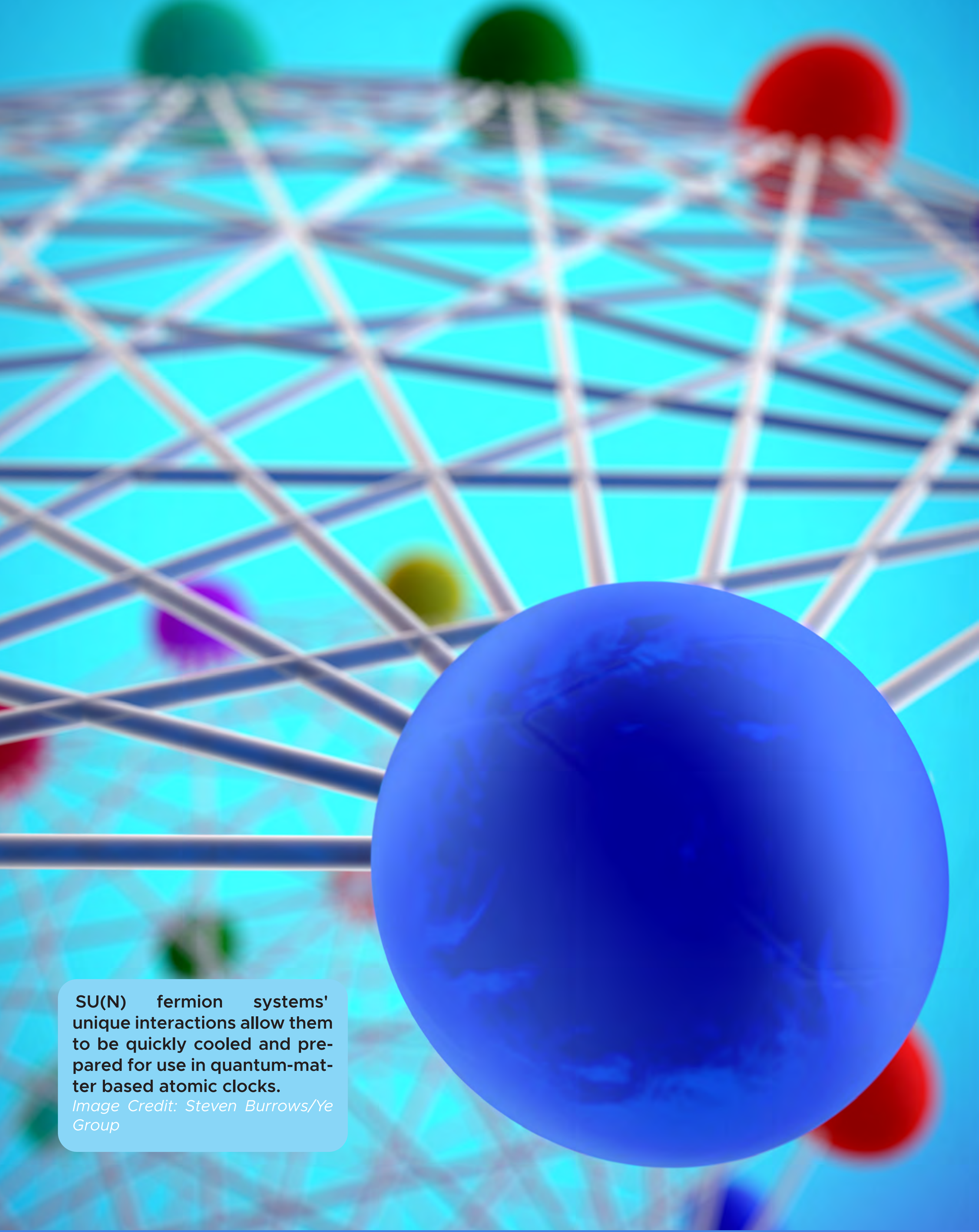
This robustness is ideal to get the ultracold molecules into a trap to study them. Think of a kid on a swing. If the kid has more energy, she can reach higher and further; if she has less energy, she will settle closer to the bottom. Similarly, with robust cooling, colder molecules tend to gather at the bottom of a trap, leading to a higher molecular density.

Ding and his team managed to employ the cooling robustness against the magnetic field to compress the molecular cloud. The trick is to apply a magnetic gradient to attract the molecules towards the trap center and at the same time cool them down with the gray molasses cooling technique. This way, as the molecular cloud is compressed, they remain cold.

"We can increase the density by a factor of 10 using this technique… Now our molecules are very cold, but the density is not high enough yet to see all these quantum properties. That's our next goal." Ding said.

One possible way to increase the density further is to load the molecules into an optical dipole trap. This trap normally perturbs the structure of molecules, resulting in an elevated temperature. But the cooling robustness of yttrium monoxide might be able to hold the molecules cold in the trap, and, as a result, produce a higher density. Once they are tightly packed in the trap, the molecules will be able to interact—and that's when scientists can see the interesting quantum mechanical properties. Using these cold, trapped molecules, physicists may also be able to study chemical processes that have mostly been studied in theory.

Shiqian Ding, Yewei Wu, Ian A. Finneran, Justin J. Burau, and Jun Ye, *Physical Review X* **10**, 021049 (2020)



SU(N) fermion systems' unique interactions allow them to be quickly cooled and prepared for use in quantum-matter based atomic clocks.
Image Credit: Steven Burrows/Ye Group

Total Ellipse of the SU(*N*)

There was something odd going on with the SU(*N*) fermions in the Ye Lab.

Normally, when a noninteracting Fermi gas of atoms is released from a trap, it expands isotropically. The atoms' pent-up kinetic energy sends them shooting away from each other in a ballistic expansion, forming a round, spherical pattern—that shape reflects the isotropic momentum distribution of the trapped gas. But with the SU(*N*) fermions, the Ye Group saw an anisotropic cloud—an ellipse, not a sphere.

"We were like, 'what is going on?'" said Lindsay Sonderhouse, a graduate student in the Ye Group. "This is like a smoking gun signature of interactions in the gas. And we saw this, despite the fact that we have such a negligibly small scattering length."

In other words, the atoms had pronounced interactions, even though they could barely "see" each other.

To understand this strange shape, Sonderhouse and the Ye Group studied the interactions and thermodynamics of SU(*N*) fermion systems. They collaborated with Ana Maria Rey's group, who provided detailed modeling for the SU(*N*)-symmetric interacting system. They discovered an unexpected relationship between the gas's interactions and its thermodynamics, and that these fermion systems are an untapped resource for atomic cooling—reducing cooling time to a mere 600 milliseconds. Their results were recently published in *Nature Physics*.

"That is the fastest evaporation time that has been seen for fermions," Sonderhouse said. "It's a very interesting, unique form of quantum matter to study. Practically, it is also a useful experimental tool that we can add to our toolbox in cold atom systems."

Causing the ellipse

SU(*N*) systems are pretty unusual in the atomic world. For a single component system, fermions all shy away from each other; two identical spin-state fermions can't occupy the same energy level. In those systems, fermions fill in each available energy level from ground up, forming a "Fermi sea." But SU(*N*) fermion systems have multiple spin components. A single non-interacting Fermi sea turns into multiple Fermi seas that are interacting with each other, giving rise to interesting dynamics.

And, unlike other fermionic systems, the spins in SU(*N*) fermions all look the same. Sonderhouse worked with strontium-87 atoms, where the large number of nuclear spin states under SU(*N*) symmetry is unprecedented —these atoms can have up to ten spin states per energy level. This is distinct from the two-component Fermi gases that are more commonly studied.

In single component systems, the fermions don't interact with each other at ultralow temperatures. Multiple components are required to make the atoms interact. And in SU(N) fermions, these atoms' scattering lengths are all equal—meaning if two of these fermions collide, they will scatter the same way regardless of their individual spin properties. This gives SU(*N*) systems an astonishing symmetry.

"Their collisional properties are independent of the spin, and that is unique in SU(*N*) atoms. That is not normally true," she said.

As the team studied the elliptical cloud, they learned that these characteristics explained what they were seeing.

"Those multiple components turned out to be the reason why the gas could experience so many interactions, causing that anisotropic cloud," Sonderhouse said. "Since we have ten components, there are a lot of different particles that the fermions can interact with at low temperatures. We are effectively increasing our interaction parameter very efficiently by increasing the number of spin components."

Seeing that elliptical cloud then led the group to ask: how does the strong interaction in this gas modify its thermodynamics?

A quick chill

To understand its thermodynamics, the Ye Group tried to compress the SU(*N*) cloud. But as the atoms were forced closer to each other, they repelled each other.

"If [the atoms] are repulsively interacting with one another, they don't want to be close to one another...As you compress them, they resist that compression," Sonderhouse said. In that way, they mimicked colder, non-interacting Fermi systems.

"You can basically have a noninteracting Fermi system that is really cold (where it has a Fermi pressure to stop the system from collapsing onto itself), and that will give you the same low compressibility as if you had an interacting system that is kind of hot," she added.

This indistinguishability made it hard for the group to disentangle the two effects by looking at the compressibility alone.

However, together with theory colleagues, they found hidden anisotropies in the shape of the cloud that provided much needed insight.

Now Sonderhouse and her colleagues could figure out how the system's thermodynamics and its multiple, symmetrical, interacting components worked. And they realized that by using evaporative cooling techniques, these atoms could be chilled to ultralow temperatures in only 600 milliseconds—much faster than what has been seen previously.

As a result of the rapid evaporation, the total preparation time of the Fermi gas was under three seconds.

That means less downtime to prepare atoms for metrology tools like optical atomic clocks—something the physics community has been looking for, Sonderhouse added. Shorter preparation times for the atoms means that the clocks can run more often and take more measurements.

"It used to take us 15 seconds in preparation time before we measured [the atoms], and with these new techniques, we can do it in under three seconds. So, that is a very big improvement," she said.

Lindsay Sonderhouse, Christian Sanner, Ross B. Hutson, Akihisa Goban, Thomas Bilitewski, Lingfeng Yan, William R. Milner, Ana M. Rey, and Jun Ye, *Nature Physics,* (2020), https://doi.org/10.1038/s41567-020-0986-6

Grabbing Proteins by the Tail

Cells are surrounded by a membrane containing carefully folded proteins. Those membrane proteins interact with the watery environment inside and outside the cell and the fatty environment of the membrane that keeps the inside and the outside of the cell separated.

That gives them an important role: they are how the inside of the cell talks to the outside of the cell, allowing viruses to attack or letting in medications to treat disease, said David Jacobson, a post-doc in the Perkins Group at JILA. That's why roughly half of proposed and current drugs target membrane proteins.

Studying these membrane proteins is crucial for biomedical research, but they are tricky to measure in a lab. Many biochemical techniques for measuring membrane proteins remove them from their native bilayer by washing them in a detergent—potentially altering how they interact with their surroundings or how they are folded.

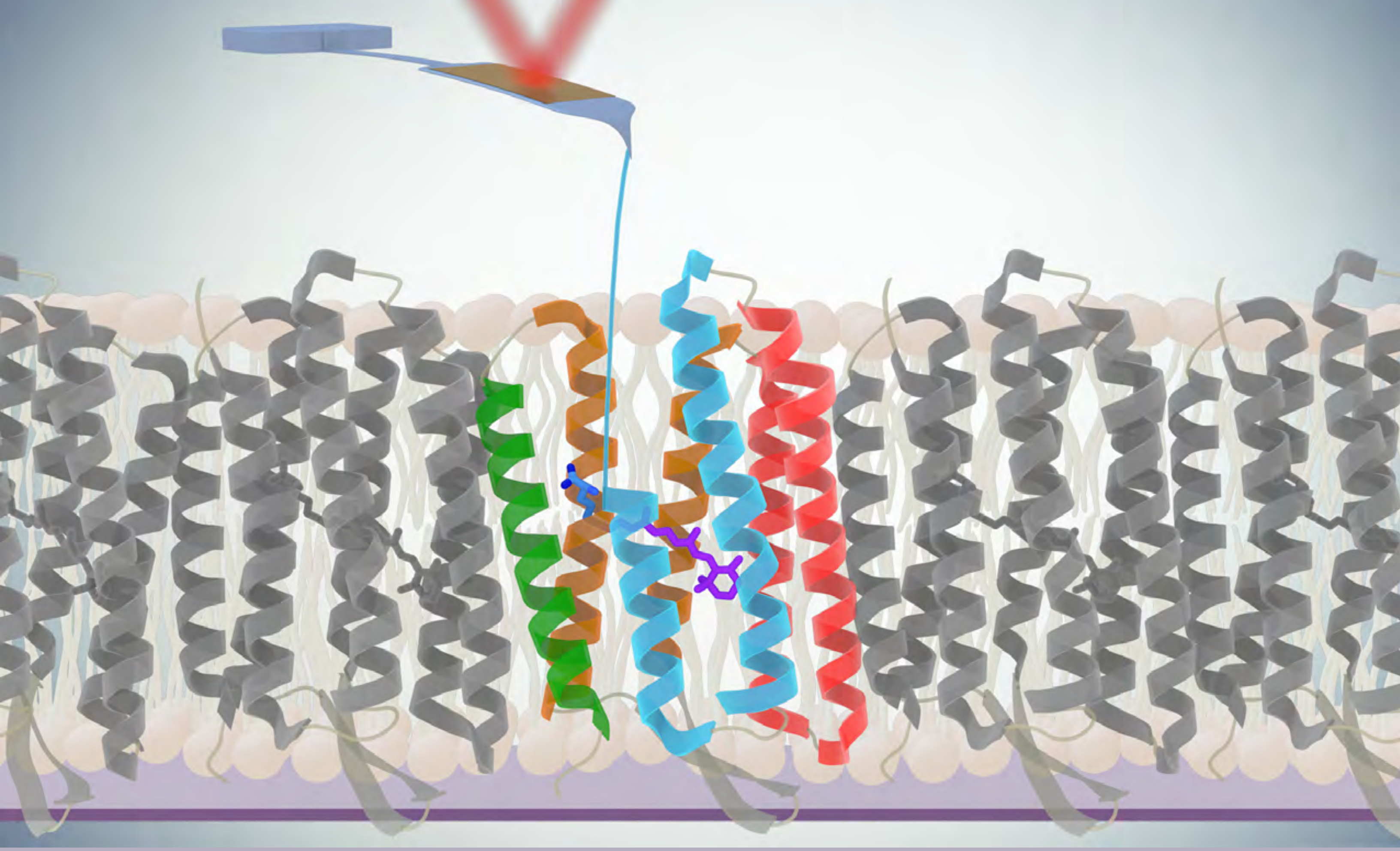
The Perkins Group has worked out a method of measuring membrane proteins using atomic force microscopy (AFM) tools. In a new study published on August 5 in *Physical Review Letters*, the team uses AFM to unfold and refold bacteriorhodopsin—a membrane protein found in microorganisms called archaea—precisely measuring the free energy it takes to do so and demonstrating a new means of studying and manipulating the proteins.

Unfolding and refolding

While a membrane protein is linear chain of amino acids, it folds into a unique three-dimensional structure. This three-dimensional structure depends on interactions between amino acids that make up the protein, which is what the Perkins Group wants to measure. One way to measure the strength and nature of those interactions is to grab the end of the protein chain with the AFM tip and pull, unfolding the protein structure.

"If we exert enough force, it starts to unfold," Jacobson explained. "The unfolding force is related to the strength of the interaction that holds the proteins together. The stronger the stabilizing interactions, the more force it takes to pull it apart."

Biophysicists, including the Perkins Group, have been doing this for years, Jacobson said—usually with brute force, thrusting the AFM tip into the membrane protein. That works, but it doesn't stick very well, which makes it difficult to perform multiple measurements, Jacobson added. Previous studies measured the force to unfold the entire structure and divided it among the 248



The Perkins Group uses atomic force microscopy tools to "unravel" amino acids in cell membrane proteins.
Image Credit Steven Burrows/Perkins Group

amino acids in the protein.

To make a more precise measurement, the Perkins Group chemically treated the 10-nanometer AFM tip so it bonds with the amino acids at the end of the protein. Then, they gently touch the tip to the very end of the protein chain and pull—only enough to unravel five or eight amino acids.

As the amino acids unfold, the cantilever holding the AFM tip flexes. Then the scientists relax the tension, allowing the small segment of amino acids to fold back into their shape.

Measuring the cantilever's flex with each unfold and refold tells scientists how much free energy is required to manipulate this protein structure. And this method can be done in the membrane's native bilayer, replicating its native environment.

Rebuilding new structures

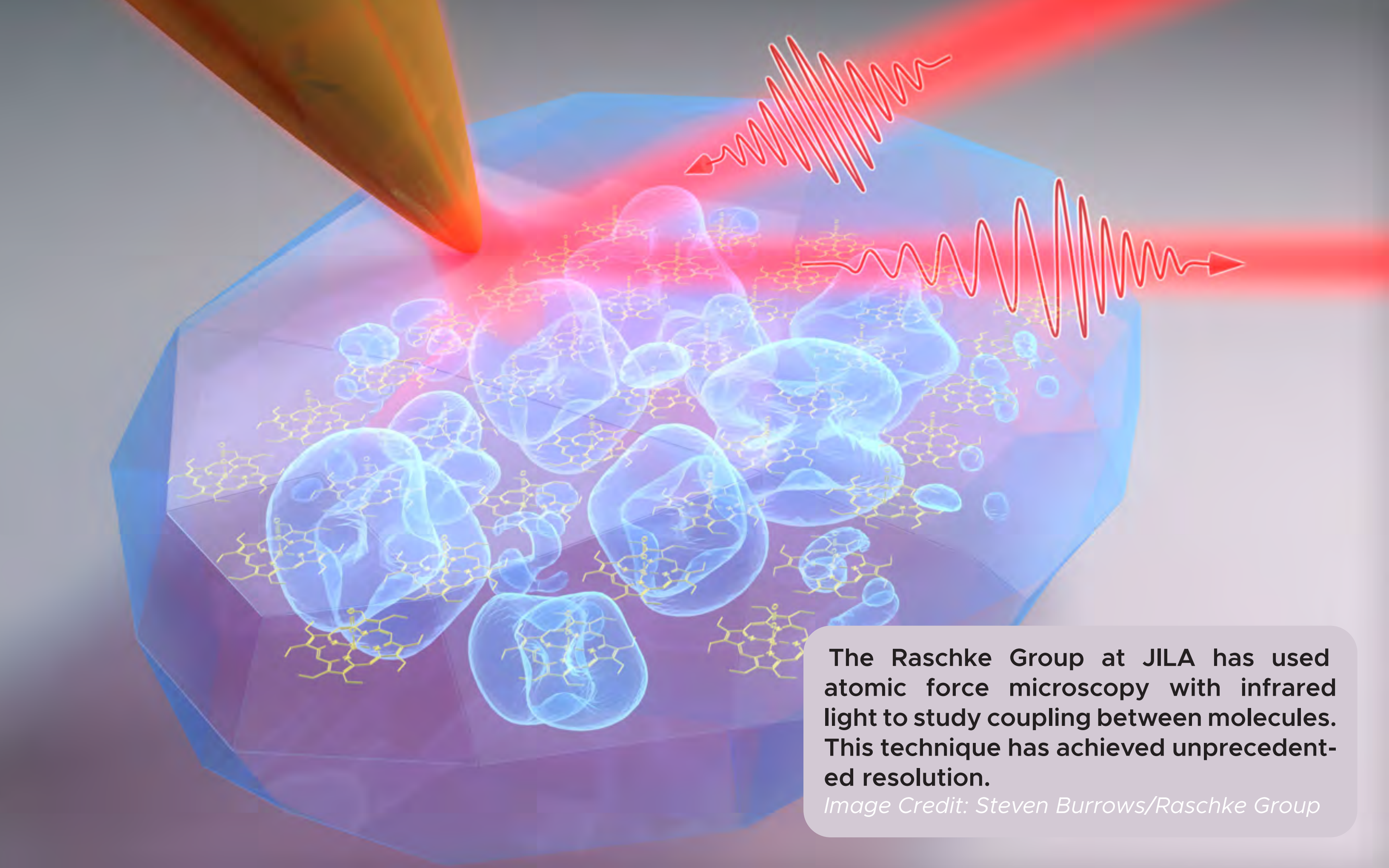
Precisely manipulating a few amino acids opens the door to understanding an individual amino acid's role in the cell's function, Jacobson pointed out.

"All the chemistry of the cell is driven by proteins and a lot of the structure of the cell is made of proteins. The proteins don't work if they are not folded up into their correct three-dimensional structure. The three-dimensional structure depends on the interactions between the amino acids," he said.

This method also allows scientists to make changes and mutations to those amino acids, and study the effect of those changes.

"In principle, this technique can be applied to any membrane proteins... It opens the door to measuring, making mutation studies to measure the contribution of these individual amino acids to the overall stability of the protein," Jacobson added.

Hao Yu, David R. Jacobson, Hao Luo, and Thomas T. Perkins, Physical Review Letters **125,** 068102 (2020)



The Raschke Group at JILA has used atomic force microscopy with infrared light to study coupling between molecules. This technique has achieved unprecedented resolution.
Image Credit: Steven Burrows/Raschke Group

Reading the Secrets of the Nanoworld with Infrared Light

Life requires energy, and nature has perfected systems for creating and transporting energy inside a living thing. These incredible feats are possible because of interactions between molecules—particularly interactions between types of molecules called porphyrins.

"Porphyrins are important for energy conversion and transport," explained Thomas Gray, a graduate student in the Raschke Group at JILA. "Your body uses it to transport energy and oxygen, and plants use it in photosynthesis."

Molecular interactions—including coupling—are like nature's secret language, said JILA Fellow Markus Raschke. And, it's a language that scientists are continually working to decipher.

"We are made out of molecules, so the way we function is this coupling, the interaction between molecules. There is beauty in these molecular interactions that define life," Raschke said. Molecular coupling is also the basis for a lot of molecular electronics, and technologies that replicates living systems, such as photovoltaic solar panels, he added.

The most common tools to study molecular coupling don't get a high enough resolution to study this phenomenon, and "you really have to look down into the molecular scale to see it," Raschke said.

Now the Raschke Group has developed the tools to see this coupling with a high spectral and spatial resolution. In a recently published study in the *Proceedings of the National Academy of Sciences of the United States of America*, the Raschke Group at JILA focused infrared lasers to an incredibly small spot using a scanning probe microscope to study vibrational excitons, and watch how porphyrin molecules form functional, well-ordered crystals with unprecedented high resolution.

"The power of this is to see really small things," Gray said. "We have high spectral and spatial resolution.

This is some of the highest resolution we have ever gotten."

Reading nature's secrets

Studying molecular interactions has been really tricky, Raschke said. Porphyrin molecules are tiny—only a few billionths of a meter long, thousands of times smaller than a human red blood cell. Using X-rays, electron microscopes and high-powered lasers, scientists have been able to see and study the smallest building blocks of the universe, such as atoms.

But those tools weren't sufficient for this task. Molecular structures are delicate, and high-energy X-rays or electron microscopes can warp and distort the molecular interactions. Infrared light, however, is much gentler, Raschke explained; after all, we interact with infrared radiation all the time. We feel its warmth, but we don't get sunburn.

"The feature of the infrared light is that it is very minimally perturbing," he said. It interacts with delicate molecular structures without damaging them.

When exciting the molecule, the infrared light can specifically sense, i.e., detect, the intermolecular interaction. But the wavelength of infrared light is very long—10,000 times larger than molecule dimensions.

To overcome this problem, the Raschke group used a trick to focus to the light to the right size. They use ultra-sharp tips made out of gold, with a tiny apex only a few nanometers in size. These tips act just like an antenna for infrared light and can focus it down to 1/1000th of its wavelength.

"This is similar to a lightning rod, just for infrared light," Gray explained.

Then the scanning probe microscope acts like just like the needle in an old-school record player, Raschke said. Moving the tip across the sample with the porphyrin nano-crystals, the tip probes the molecules, and sends data and images back to the physicists.

"You are reading the secrets of nature," he said. "You can read what you cannot access with the unaided eye."

Taking shape

Molecules are made of atoms which are held together by electrons, Gray explained. These chemical bonds are stretchy, and when the molecules are excited by the infrared light, the atoms vibrate and oscillate back and forth or up and down as if they were on springs. These bonds, when well ordered, can either stretch in unison (symmetrically) or anti-symmetrically, which determines how two molecules will couple. The coupled molecules link up, and the atomic motion can synchronize over longer and longer chains of molecules.

Studying this synchronized atomic motion, Gray and his co-authors could see that what sometimes looks like a perfect, well-ordered porphyrin crystal is actually still full of broken, incomplete chains.

"They are not well-ordered and there might be a little bit of coupling here and there but it is not strong," Gray explained—although in time, they anneal, ordering themselves.

"What we are able to do is actually measure how many molecules are coupled at that time. There is a hidden disorder that you would not have expected. It's this disorder which limits performance, for example, in molecular electronic devices," he added.

As they become well-ordered, this is the progression of the vibrational state, Gray concluded. That ordering creates delocalization of the molecular wave function, Raschke added. This is a quantum mechanical effect, and it is what gives porphyrin its ability to function. When the individual molecules link up with their neighbors, they can share their wave function and work together.

"You form a new hybrid quantum state between the coupled molecules. That is what is desired," Raschke said. "It allows the charge transfer and energy transport between molecules." That energy and charge transfer is also how porphyrins function in photosynthesis in plants.

High resolution basic research

Achieving this high-resolution imaging of molecular function is not only incredible, it opens doors to study all kinds of phenomenon in the quantum world, Raschke said.

"I think this is actually the best of nano-spectroscopic imaging we ever accomplished. I had not expected this to be resolvable...Here we are dealing with a signal from the interaction of just a few molecules, and yet we are able to really extract all the relevant physical parameters. This is really something qualitatively new," Raschke said.

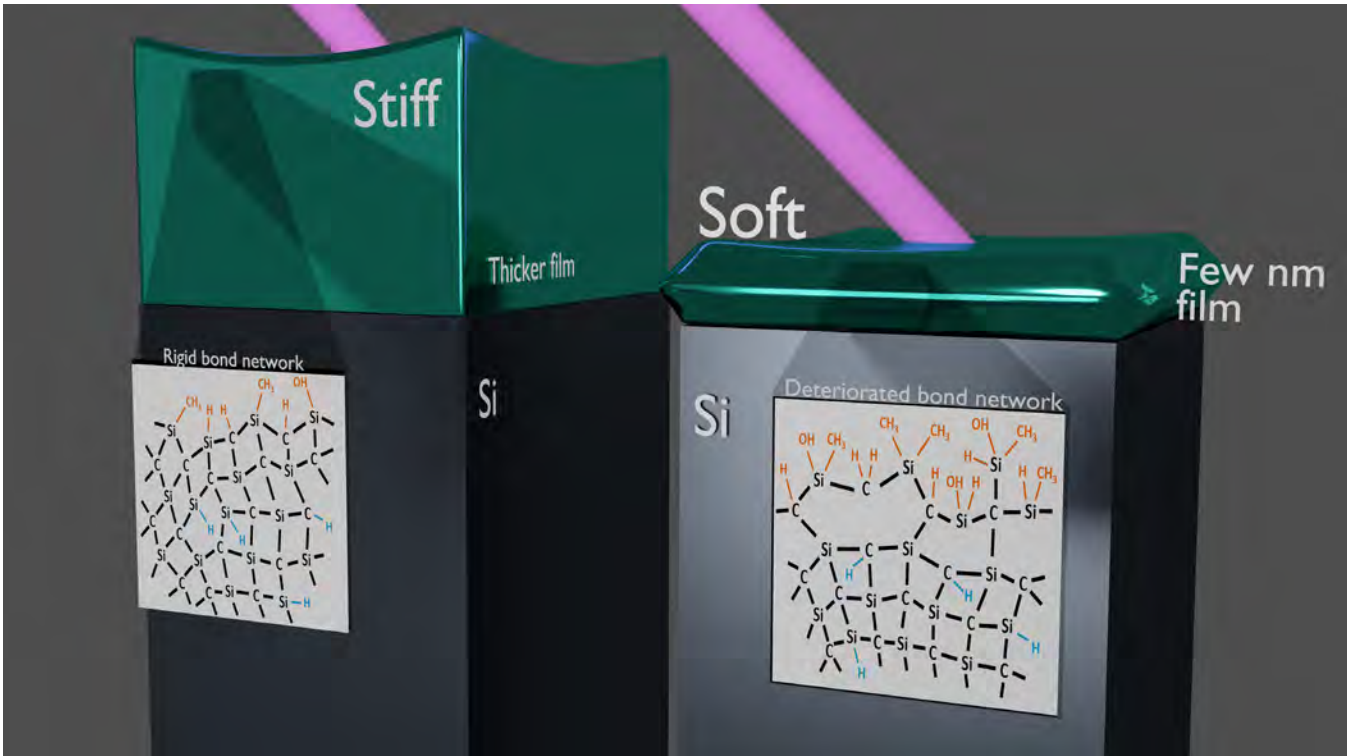
Developing the tools to precisely measure and study the elementary processes of the world around us is a key part of JILA's mission, he added, and the purpose of basic science research.

"In basic science we want to understand these elementary processes. We learn these elementary processes which dictate the macroscopic material properties," Raschke said. "We are expanding these tools and refining them with higher resolution, higher precision to enable those studies."

Eric A. Muller, Thomas P. Gray, Zhou Zhou, Xinbin Cheng, Omar Khatib, Hans A. Bechtel, and Markus B. Raschke, *PNAS* **117** (13), 7030 (2020)

Scientists Open New Window into the Nano World

CU Boulder researchers have used ultra-fast extreme ultraviolet lasers to measure the properties of materials more than 1,000 times thinner than the width of a human hair.



A graphic demonstrating how a material can go from stiff to soft when it is made as a thicker versus a thinner film. The effect occurs when the atomic bonds within a material are disrupted.
Image Credit: Joshua Knobloch/JILA

The team, led by scientists at JILA, reported its new feat of wafer-thinness in the journal *Physical Review Materials* on July 13. The group's target, a film just 5 nanometers thick, is the thinnest material that researchers have ever been able to fully probe, said study coauthor Joshua Knobloch.

"This is a record-setting study to see how small we could go and how accurate we could be," said Knobloch, a graduate student in the KM Group at JILA.

He added that when things get small, the normal rules of engineering don't always apply. The group discovered, for example, that some materials seem to get a lot softer the thinner they become.

The researchers hope that their findings may one day help scientists to better navigate the often-unpredictable nano world, designing tinier and more efficient computer circuits, semiconductors and other technologies.

"If you're doing nanoengineering, you can't just treat your material like it's a normal big material," said Travis Frazer, lead author of the new paper and a former graduate student at JILA. "Because of the simple fact that it's small, it behaves like a different material."

"This surprising discovery—that very thin materials can be 10 times more flimsy than expected—is yet another example of how new tools can helps us to understand the nano world better," said JILA Fellow Margaret Murnane.

Nano wiggles

The research comes at a time when many technology firms are trying to do just that: go small.

Some companies are experimenting with ways to build efficient computer chips that layer thin films of material one on top of the other—like a filo pastry, but inside your laptop.

The problem with that approach, Frazer said, is that scientists have trouble predicting how those flakey layers will behave. They're just too delicate to measure in any meaningful way with the usual tools.

To help in that goal, he and his colleagues deployed extreme ultraviolet lasers—beams of radiation that deliver shorter wavelengths than traditional lasers—with wavelengths well matched to the nanoworld. The researchers developed a set-up that allows them to bounce those beams off of layers of material just a few strands of DNA thick, tracking the different ways those films can vibrate.

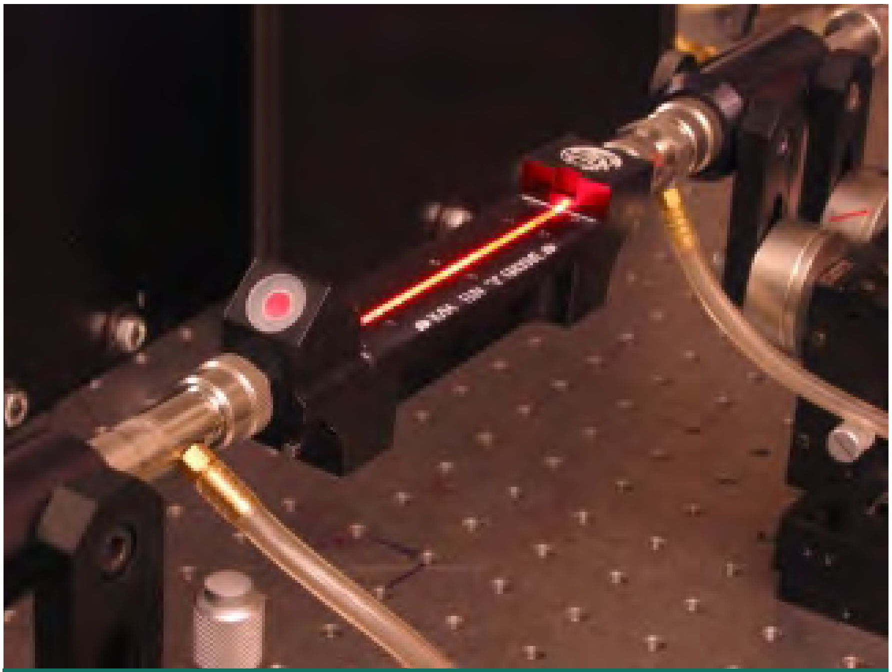
"If you can measure how fast your material is wiggling, then you can figure out how stiff it is," Frazer said.

Atomic disruption

The method has also revealed just how much the properties of materials can change when you make them very, very small.

In the most recent study, for example, the researchers probed the relative strength of two films made out of silicon carbide: one about 46 nanometers thick, and the other just 5 nanometers thick. The team's ultraviolet laser delivered surprising results: the thinner film was about 10 times softer, or less rigid, than its thicker counterpart, something the researchers weren't expecting.

Frazer explained that, if you make a film too thin, you can cut into the atomic bonds that hold a material together—a bit like unraveling a frayed rope.



A "waveguide" that converts traditional laser light into laser-like beams at extreme ultraviolet wavelengths.
Image Credit: Kapteyn-Murnane Group/JILA

"The atoms at the top of the film have other atoms underneath them that they can hold onto," Frazer said. "But above them, the atoms don't have anything they can grab onto."

But not all materials will behave the same way, he added. The team also reran the same experiment on a second material that was nearly identical to the first with one big difference—this one had a lot more hydrogen atoms added in. Such a "doping" process can naturally disrupt the atomic bonds within a material, causing it to lose strength.

When the group tested that second, flimsier material using their lasers, they found something new: this material was just as strong when it was 44 nanometers thick as it was at a meager 11 nanometers thick.

Put differently, the additional hydrogen atoms had already weakened the material—a bit of extra shrinking couldn't do anymore damage.

In the end, the team says that its new ultraviolet laser tool gives scientists a window into a world that was previously beyond the grasp of science.

"Now that people are building very, very small devices, they're asking how properties like thickness or shape can change how their materials behave," Knobloch said. "This gives us a new way of accessing information about nanoscale technology."

Written by Daniel Strain

Travis D. Frazer, Joshua L. Knobloch, Jorge N. Hernández-Charpak, Kathleen M. Hoogeboom-Pot, Damiano Nardi, Sadegh Yazdi, Weilun Chao, Erik H. Anderson, Marie K. Tripp, Sean W. King, Henry C. Kapteyn, Margaret M. Murnane, and Begoña Abad *Physical Review Materials* **4,** 073603 (2020)

What to Know if You're Teaching Physics Labs Remotely

Image credit: Giulia Forsyth/Flicker

As the COVID-19 pandemic swept the world, professors had to pivot their lab courses quickly—sometimes in a matter of hours—to work remotely.

Physicist and physics education researcher JILA Fellow Heather Lewandowski began getting questions from instructors around the country: how do you teach a laboratory class when you can't be in the lab?

Lewandowski received an NSF RAPID Grant to answer this question, and did what scientists do best: she gathered data. She received 106 survey responses from professors nationally and internationally, covering 129 physics education courses. These classes ranged from introductory to more advanced level coursework. Her study was published on arXiv on July 2.

It's important to note that these courses were not intended to be taught remotely, Lewandowski pointed out. There are instructors who regularly work on virtual platforms, but this study looked at lab courses that had to switch to remote learning because of the coronavirus pandemic.

While there were numerous challenges to going remote, "I think we had a unique opportunity to learn some things that will help us when we get back to in-person classes," Lewandowski noted.

Here are some key lessons for those planning courses in a virtual platform:

Re-evaluate your learning goals and encourage self-guided inquiry

If your physics lab needs to taught remotely, this is a good opportunity to re-evaluate what you want students to get from the class, and try something new. With little time to prepare, some instructors this spring changed the learning goals for their classes.

"Some of them were asking themselves for the first time, 'What are my learning goals?'" Lewandowski said. "There are a lot of parts of experimental physics that have to do with design, modeling, communication, writing. And these in particular are a little bit easier to achieve outside of the lab than working with equipment."

One instructor was able to get away from prescriptive lab modules and let students pursue their own self-guided inquiries, Lewandowski added.

"Some students found that they had more opportunity for agency. They were able to explore their own research questions, or control the timing of their own learning. So, I think that is another thing that we really don't want to lose when they come back in person," she said.

Replace the lab with online simulations, take-home lab kits, remote-controlled lab equipment, or what your students have on hand

Lab work is inherently hands-on, but computer simulations can help replicate some parts of the lab. Online simulations like PhET allowed students to work through lab activities from their computers. A few instructors found ways for students to use what they had at hand to understand physics concepts, such as using the camera on their phone to learn about optics.

But not all students have equal access to these things, Lewandowski cautioned; don't assume every student will have a smart phone, easy access to a computer, or a fast, reliable internet connection.

Physics lab course instructors use tools students have at home to teach physics concepts.
Image Credit
Michael F. J. Fox

For introductory courses, many instructors had better success with home lab kits that contained simple equipment and supplies—a few even delivered them to students at home.

For more advanced courses that need specialized, expensive equipment, instructors took advantage of laboratory equipment that could be controlled remotely, or were able to have a teaching assistant or professor run the experiment for students via web conferencing.

Small groups, Zoom breakout rooms help students collaborate

Learning is a social enterprise, and students missed working with their lab work groups. However, some instructors found that using breakout rooms on Zoom and creating smaller working groups helped students collaborate remotely.

"Science is not an individualistic type of endeavor. It requires a community and a team," Lewandowski said. "And I think that's going to be a struggle over this next year, to build that community when everybody is remote."

Have patience, empathy, and know you're not alone

University procedures and recommendations are still changing to respond to the ongoing pandemic. Instructors around the world may find themselves back in the classroom in some places, working entirely remotely, or a hybrid of the two.

Whatever mode you're working in, there are resources available to help you, Lewandowski said. She is also President of the Advanced Lab Physics Association (ALPhA), a professional society of physics instructors in labs, which is curating resources and advice for instructors working remotely (https://advlab.org).

Just remember, this is an unprecedented situation, so be patient with yourself and your students, Lewandowski said. Things will go wrong, and that's okay.

"I think a little flexibility and empathy goes a long way," she added. "You're not alone in this."

Michael F. J. Fox, Alexandra Werth, Jessica R. Hoehn, Heather J. Lewandowski, arXiv:2007.01271 (2020)

In the News

Jun Ye to Lead New $25 Million Quantum Science and Engineering Institute

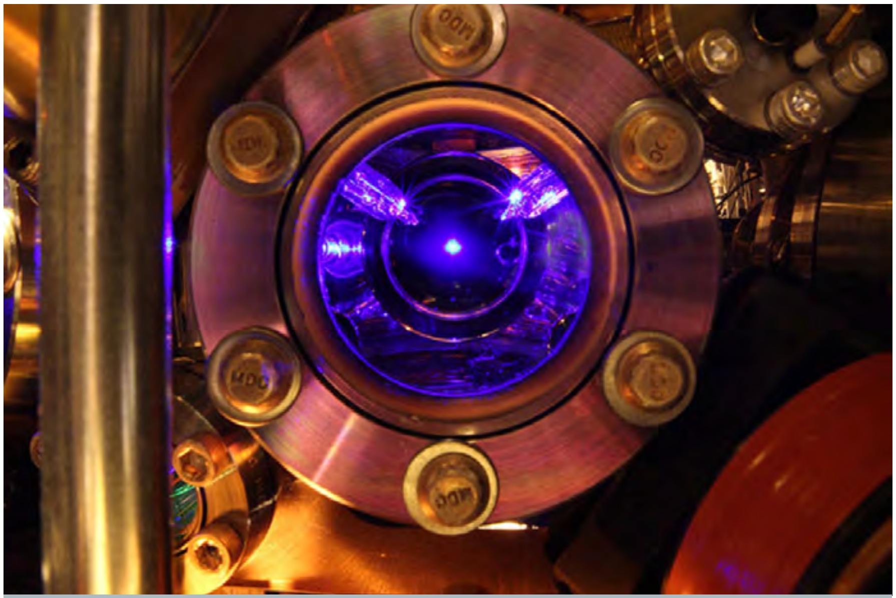
In July, the National Science Foundation announced that the University of Colorado Boulder will receive a $25 million award to launch a new quantum science and engineering research center.

The new center will be led by physicist Jun Ye and is a partnership with 11 other research organizations in the United States and abroad. Together, these pioneers will explore several "grand challenges." They include how exotic quantum phenomena, such as quantum entanglement, will advance new frontiers in measurement science; how quantum sensing can help researchers to discover new fundamental physics; and how researchers can turn those advancements into real-world technologies.

"Imagine if we can build robust quantum systems that can go outside of our labs, that can completely change how we sense the physical world, how we navigate and how we communicate with each other," said JILA Fellow Jun Ye. "We're asking how we can take advantage of recent advances in quantum physics to actually solve useful problems for society."

The new center is named Quantum Systems through Entangled Science and Engineering (Q-SEnSE), a nod to its focus on building close ties between scientists and engineers.

"We are proud to partner in this new center, which will address key priorities for NIST and the nation—quantum science, measurement science, and advancing U.S. innovation," said



Strontium optical atomic clock in Ye Lab at JILA.
Image Credit Brad Baxley, JILA

Under Secretary of Commerce for Standards and Technology and NIST Director Walter G. Copan. "NIST and JILA are recognized world leaders in quantum science, and we're delighted with the strength of the team that has been assembled with Jun Ye as the first director of Q-SEnSE."

Ye added that the new center, CU Boulder's third major NSF center, will also focus on educating and training the young people who will become the quantum workforce of the future. CU Boulder has a strong tradition and strength in this area, and is already forming partnerships with schools and community colleges across the Rocky Mountain region to do just that.

Establishing the Q-SEnSE center is the latest step in the university's campaign to grow Colorado into what Ye calls "the quantum capital of the world."

"This center is an exciting next step to expand on our CUbit Quantum Initiative, which brings together JILA, Engineering, Sciences, NIST and academic and industry partners in the region," said Vice Chancellor for Research and Innovation Terri Fiez. "Q-SEnSE will allow us to leverage the full power of our combined quantum capabilities to lead the global quantum revolution."

Future clocks

The new center emerges, in part, from decades of research by Ye and his students and colleagues on atomic clocks—devices that use networks of strontium atoms to track the passage of time with previously unimaginable accuracy. Such clocks, he added, could also become precise navigational or scientific sensors, capable of detecting even minute shifts in Earth's gravitational pull.

But the practical application of such technologies has, to date, lagged behind their promise and performance in the lab.

"A major challenge is: How do we engineer these sensitive systems to be robust?" said Ye, also a professor adjoint in the Department of Physics at CU Boulder. "It's not just about putting them in a box."

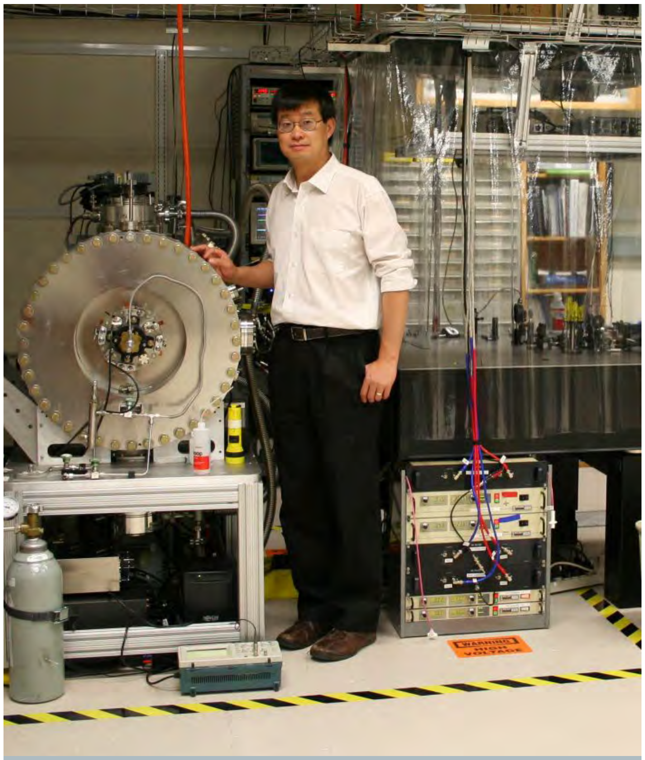
The new NSF center will work toward that goal. Over five years, Ye and his colleagues at CU Boulder and its 11 partner organizations will not only explore the fundamental physics underlying devices like atomic clocks. They'll also partner with engineers to turn those dynamics into tools that anyone can use.

Forming those new connections among disciplines has also been a key component of CU Boulder's CUbit Quantum Initiative, launched in 2019.

"A challenge as big as quantum requires collaboration between many types of scientists and engineers. This type of collaboration requires a catalyzing event," said Greg Rieker, an associate professor in the Paul M. Rady Department of Mechanical Engineering and a co-principal investigator of Q-SEnSE. "This grant is the event that we needed."

Ye added that the center isn't just a Colorado initiative—solving these global challenges will take leaders from across the globe.

"This center will have a national impact because it takes national leaders to solve these grand challenges together," Ye said. "We feel really fortunate to have great people from both coasts and up and down the Rocky Mountains on our team."



Jun Ye in lab at JILA.
Image Credit: Brad Baxley, JILA

International partnership

The new center will include researchers from Harvard University, MIT, Stanford University, University of Delaware, University of Oregon, University of New Mexico, and the University of Innsbruck in Austria. Several government labs, including NIST, Los Alamos National Laboratory, MIT Lincoln Laboratory and Sandia National Laboratory, will play major roles in the initiative.

Other CU Boulder investigators in the center include Svenja Knappe, Dana Anderson, Penina Axelrad, Juliet Gopinath, Murray Holland, Shu-Wei Huang, Adam Kaufman, Konrad Lehnert, Heather Lewandowski, Claire Monteleoni, Cindy Regal, Ana Maria Rey and James Thompson.

"We are excited to participate in this QLCI, which will advance scientific, technological educational and industrial foundations for quantum sensors, measurements and networks," said Mark Kasevich, professor of physics and applied physics at Stanford.

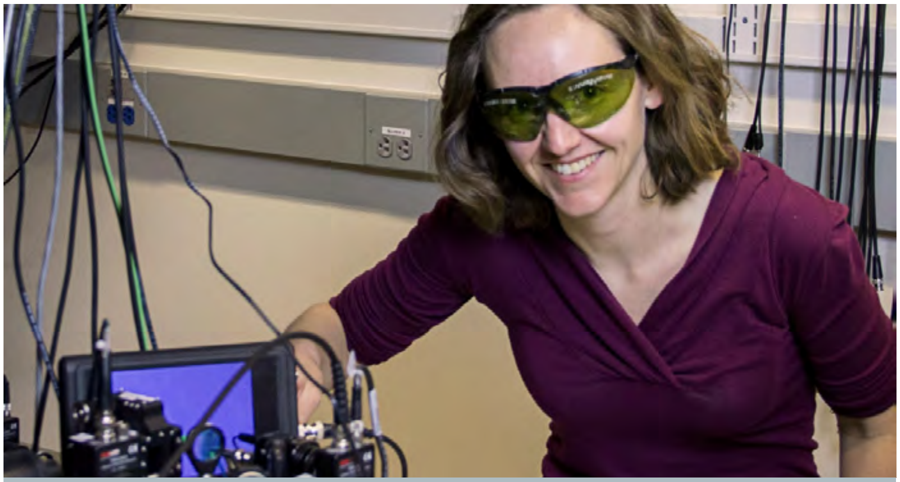
"Q-SEnSE will tackle the goals of the National Quantum Initiative head on: addressing basic research in Quantum Information Science (QIS), expanding the number of researchers, educators and students with training in QIS and promoting the development and inclusion of multidisciplinary curriculum and research opportunities for QIS at the undergraduate, graduate and postdoctoral level," said Ivan Deutsch, director of the Center for Quantum Information and Control at the University of New Mexico.

"Quantum technologies are likely to provide significant breakthroughs in areas such as new sensors, precision timekeeping, fundamental new discoveries through precision measurements and possibly quantum computing," said Vladan Vuletic, professor of physics at MIT. "There is now a worldwide race between Europe, Asia and the U.S. to develop and apply quantum technologies, and the new Institute will train a significant number of students in this emerging area."

Written by Daniel Strain

JILA Fellow Cindy Regal Wins 2020 FRED Award

JILA Fellow Cindy Regal has been selected as the 2020 recipient of Research Corporation for Science Advancement's Cottrell Frontiers in Research Excellence and Discovery (FRED) Award. The $250,000 FRED Award recognizes and rewards innovative research that could transform an area of science.



Cindy Regal in lab at JILA.
Image credit: JILA

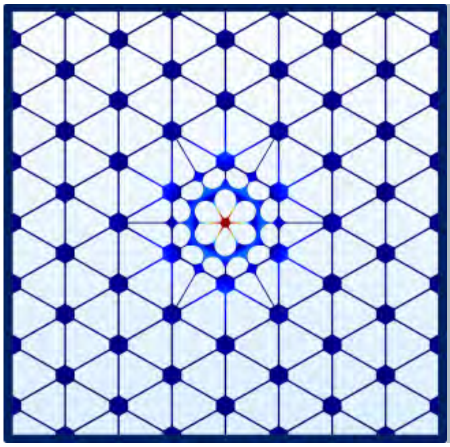
Regal is a distinguished scientist whose pioneering work has been highly cited and recognized by the physics community. She won the RCSA's Cottrell Scholar Award in 2014, a Presidential Early Career Award for Scientists and Engineers (PECASE) in 2012, and a Packard Fellowship in Science and Engineering in 2011. She was also named an American Physical Society Fellow in 2017.

Her work has focused on using mechanical vibrations in solids to explore quantum information and quantum optics. Regal's research has also contributed to the development of atomic quantum bits, and devised ways to cool and detect motion of tangible objects at their quantum ground state.

"This is high-impact work that could accelerate basic science," said RCSA Senior Program Director Silvia Ronco. "As a dedicated teacher and outstanding scientist, Cindy represents the best of our Cottrell Scholar community."

Regal's FRED Award project will investigate mechanical films suspended with an engineered lattice of tethers.

"We are going to study and harness some mechanical objects that look rather like a spider web or a snowflake, depending on your angle. And if we are successful in this approach, these suspensions will be sensitive enough to, for example, detect and image nuclear spins by picking up on miniscule forces," Regal said. "We are very excited to pursue the science the Research Corporation will enable through this project."



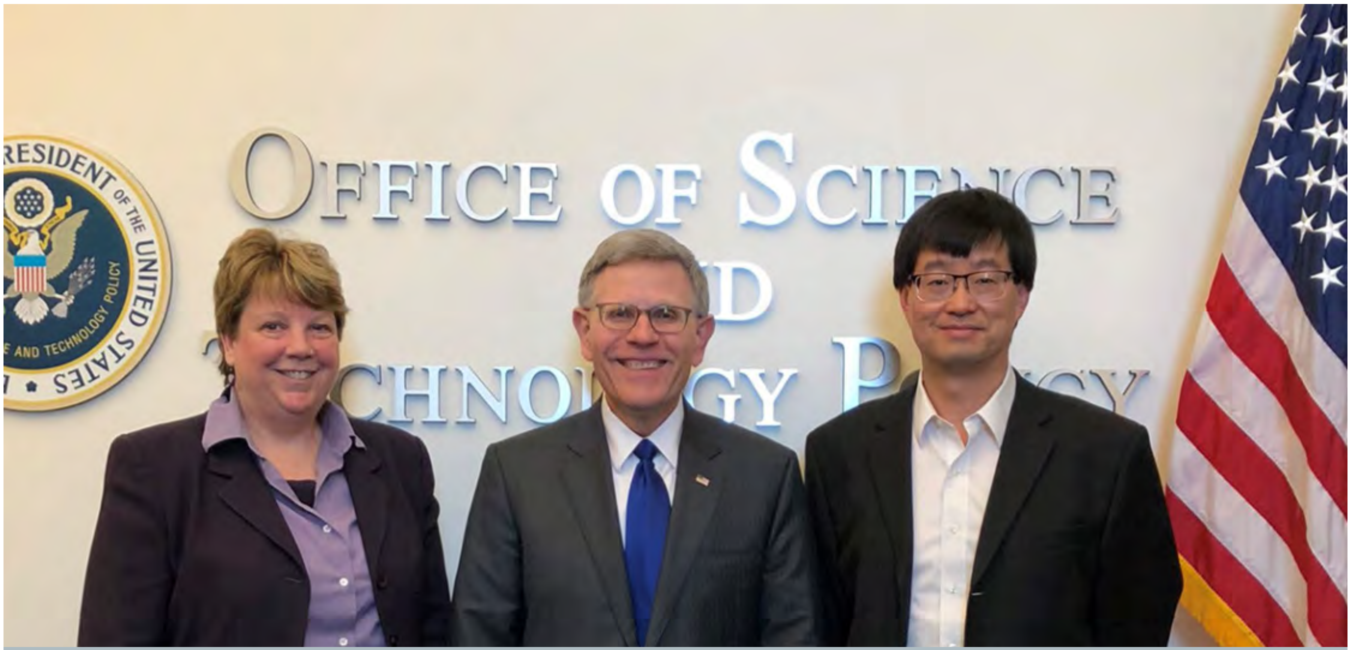
The Regal Group will use the 2020 Cottrell FRED Award to investigate mechanical films suspended in an engineered lattice, sensitive to miniscule forces.
Image Credit: Regal Group/ JILA

The project could lead to new design principles for precision mechanical sensors of force and acceleration, and may even enable 3D nanoscale imaging—which would advance our understanding of the quantum world.

"This funding is designed to enable a big leap in a project that will have a big impact," said RCSA President and CEO Dan Linzer.

"We're delighted to honor such an accomplished scientist and excited to see what Cindy achieves."

Regal will be honored with the FRED Award and will present a talk about her work at the 27th Annual Cottrell Scholars Conference in July 2021.



Terri Fiez (Vice Chancellor for Research & Innovation, CU Boulder), Kelvin Droegemeier (Director, White House Office of Science and Technology Policy), Jun Ye (Director, CUbit Quantum Initiative at CU Boulder; JILA Fellow) met in mid-April 2019 about quantum information science.
Image Credit: White House OSTP

JILA's Jun Ye named to National Quantum Initiative Advisory Committee

The White House Office of Science and Technology Policy (OSTP), and the U.S. Department of Energy (DOE) have announced that JILA and CU Boulder's Jun Ye will be one of the members of the National Quantum Initiative Advisory Committee (NQIAC). NQIAC was established as part of the National Quantum Initiative Act in 2018 and will counsel the administration on ways to ensure continued American leadership in quantum information science (QIS).

Quantum science has the potential to further revolution technology in several fields, from computing and precision measurement to secure communication. DOE has already announced blueprint strategy for developing a national quantum internet, bringing the United States to the forefront of the global quantum race and ushering in a new era of communications.

Ye has been internationally recognized for his work on light-matter interactions, particularly in optical atomic clocks. As a JILA and NIST Fellow, Ye's lab has set numerous first- and best-in-the-world records for optical atomic clocks. These clocks are even poised to redefine standards of timekeeping and are used to study phenomena of the quantum world. In 2019 Clarivate Analytics recognized Ye as one of the most highly cited researchers in physics for the sixth year in a row.

His scientific accomplishments have made him a leader in the field. Ye is the director for CUbit, a collaboration between CU Boulder, NIST Quantum Physics Division and Front Range companies to advance quantum science. He was recently chosen to lead Q-SEnSE, a new $25 million National Science Foundation quantum science and engineering research center. Ye is also leading CU's participation in Quantum Systems Accelerator (QSA), one of five new quantum research centers funded by the DOE.

The NQIAC consists of 23 scientists and experts from universities, federal laboratories and industry. The committee will be co-chaired by Charles Tahan, OSTP assistant director for quantum information science and director of the National Quantum Coordination Office, and Kathryn Ann Moler, dean of research at Stanford University.

"Today, the White House is proud to join DOE to announce the members of the NQIAC, an important step forward for the National Quantum Initiative. We look forward to engaging with the entire U.S. innovation ecosystem to advance quantum research and innovation for the betterment of our Nation," said U.S. Chief Technology Officer Michael Kratsios.

The first NQIAC meeting was tentatively scheduled for October 2020, with additional details to come.

JILA, located on the CU Boulder campus.

New $115 Million Quantum Systems Accelerator to Pioneer Quantum Technologies for Discovery Science

The Department of Energy has awarded $115 million over five years to the Quantum Systems Accelerator (QSA), a new research center that will include CU Boulder.

The center, which is led by Lawrence Berkeley National Laboratory in California, will forge the technological solutions needed to harness quantum information science for discoveries that benefit the world. It will also energize the nation's research community to ensure U.S. leadership in quantum research and development and accelerate the transfer of quantum technologies from the lab to the marketplace.

Total planned funding for the center is $115 million over five years, with $15 million in Fiscal Year 2020 dollars and outyear funding contingent on congressional appropriations. The center is one of five new Department of Energy National QIS Research Centers announced in August. Jun Ye will lead CU Boulder's participation in the center, which will compliment the university's work through the CUbit Quantum Initiative and Quantum Systems through Entangled Science and Engineering (Q-SEnSE).

"The QSA's focus on the development of scalable quantum systems for meaningful applications will likely lead to major scientific discoveries and technology breakthroughs," said Ye, a fellow in JILA, a partnership between CU Boulder and the National Institute of Standards and Technology.

Steve O'Neil, Director of Operations for Q-SEnSE, which is funded by NSF, added: "This DOE Quantum Systems Accelerator center will have a major research program that is complementary to that of the CU-led Q-SEnSE, and together the two centers confirm Boulder as a national jewel for research in quantum science and engineering."

The Quantum Systems Accelerator brings together dozens of scientists who are pioneers of many of today's quantum capabilities from 15 institutions: Lawrence Berkeley National Laboratory, Sandia National Laboratories, MIT Lincoln Laboratory, CU

Boulder, Caltech, Duke University, Harvard University, Massachusetts Institute of Technology, Tufts University, UC Berkeley, University of Maryland, University New Mexico, University of Southern California, UT Austin and Canada's Université de Sherbrooke.

"The global race is on to build quantum systems that fuel discovery and make possible the next generation of information technology that greatly improves our lives," said Berkeley Lab's Irfan Siddiqi, the director of the Quantum Systems Accelerator. "The Quantum Systems Accelerator will transform the enormous promise of quantum entanglement into an engineering resource for the nation, forging the industries of tomorrow."

The center's multidisciplinary expertise and network of world-class research facilities will enable the team to co-design the solutions needed to build working quantum systems that outperform today's computers. The goal is to deliver prototype quantum systems that are optimized for major advances in scientific computing, discoveries in fundamental physics and breakthroughs in materials and chemistry. In addition to furthering research that is critical to DOE's missions, this foundational work will give industry partners a toolset to expedite the development of commercial technologies.

The Quantum Systems Accelerator will strengthen the nation's quantum research ecosystem and help ensure its international leadership in quantum research and development by building a network of national labs, industry, and universities that addresses a broad spectrum of technological challenges. The center will train the workforce needed to keep the nation at the forefront of quantum information science, share its advances with the scientific community and serve as a central clearinghouse for promising research.

Other CU Boulder and NIST participants in the effort include John Bollinger, Adam Kaufman, Cindy Regal, Ana Maria Rey, Graeme Smith and James Thompson.

Written by Daniel Strain

Welcome Newest JILA Fellow, Shuo Sun

JILA is proud to introduce our newest Fellow—Shuo Sun.

Sun's research focuses on light-matter interactions at the quantum limit, where single photons and single atoms can strongly interact. These interactions will expand our knowledge of quantum interactions, but Sun is particularly interested in how quantum light-matter interactions can be used for quantum information technologies.

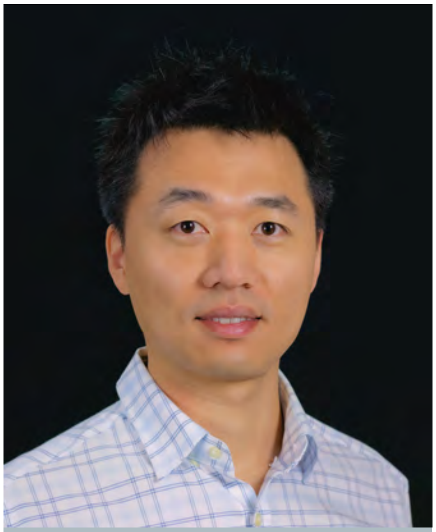
There are many possible platforms scientists are exploring to build quantum computers, a quantum internet, and new quantum sensors, such as trapped ions or superconducting qubits. Optical photons are the only qubits that can travel long distances with small losses, which makes them indispensable for quantum communication channels in quantum networks and distributed quantum computers, Sun explained.

"We are interested in exploring more quantum information processing capabilities with photons, including optical quantum computing and quantum simulation, by employing the quantum nonlinear effect created by strong atom-photon interactions," he added.

The Sun Lab is also pursuing several research projects to convert quantum information to optical photons, or using photons to mediate remote entanglement. Sun and his group are studying how to generate, control, and manipulate solid-state artificial atoms, which are made of semiconductor nanocrystals or atomic defects and impurities, and use them to store and process quantum information.

One interesting feature about these artificial atoms is that they can be conveniently coupled with optical photons through engineered nanophotonic structures defined in their host materials, explained by Sun.

Sun joins JILA after a postdoc and research scientist position at Stanford University. He received his master's degree and Ph.D. in electrical engineering from University of Maryland, College Park, and his bachelor's degree in optics from Zhejiang University. He's become fond of driving and road trips since driving from Maryland to Stanford. When he's not in the lab, he also enjoys hiking, skiing, and premier league soccer.



New JILA Fellow Shuo Sun
Image credit: Steven Burrows

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

University of Colorado **Boulder**

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

About JILA

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