# LIGHT+ MATTER

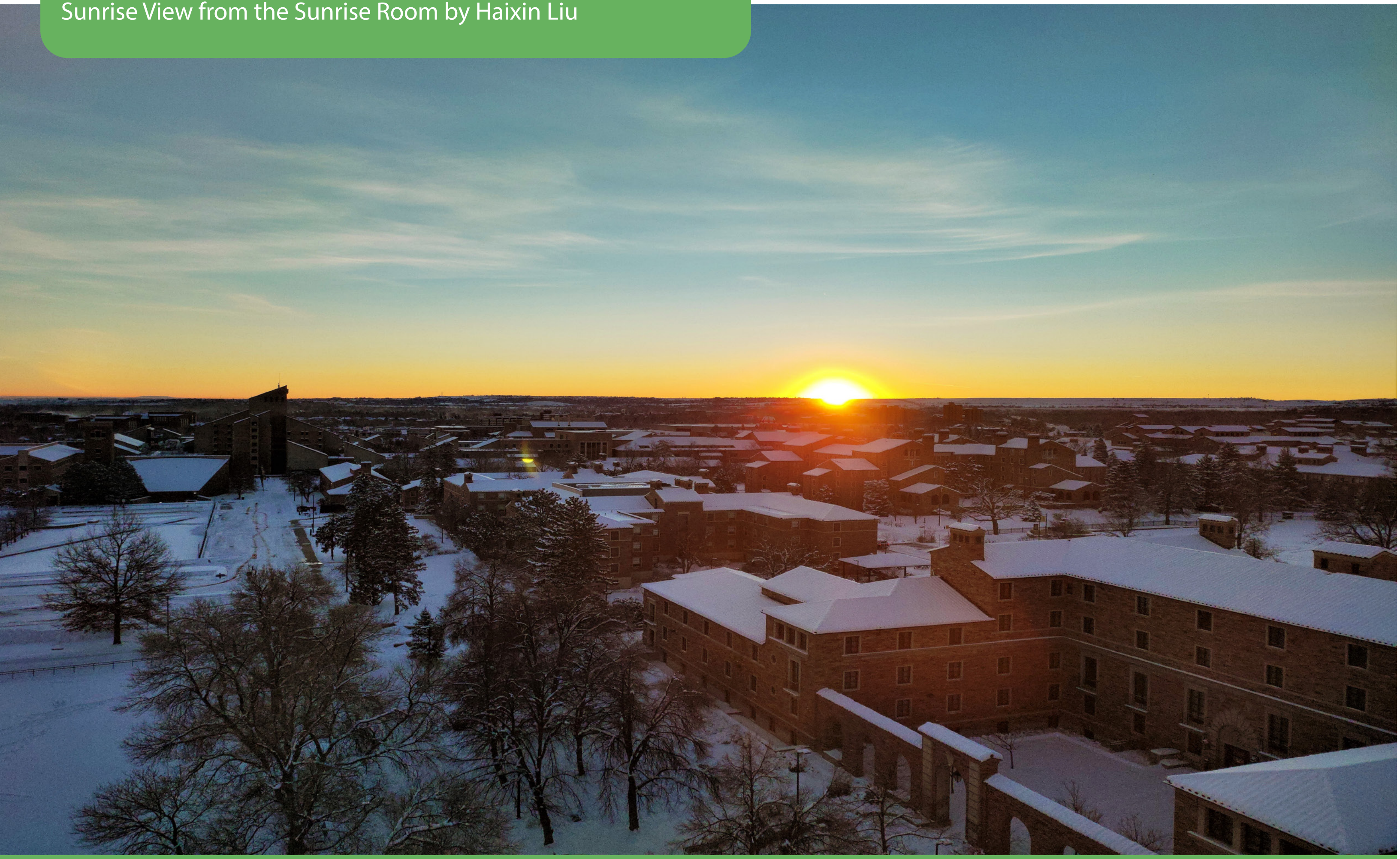
Spring 2022 | jila.colorado.edu

JILA
CU Boulder and NIST

AMO Physics Mural pg. 15

Winner of the 2022 JILA Photo Contest:

Sunrise View from the Sunrise Room by Haixin Liu



JILA Light & Matter is published quarterly by the ScientificCommunications Office at JILA, a joint institute of the University of Colorado and the National Institute of Standards and Technology.

The science communicators do their best to track down recently published journal articles and great research photos and graphics. If you have an image or a recent paper you'd like to see featured, contact us at:
sco@jila.colorado.edu
Please check out this issue of JILA Light & Matter online at
https://jila.colorado.edu/publications/jila-light-matter-quarterly

Steven Burrows, Project Manager, Artwork
Kristin Conrad, Design & Production
Kenna Castleberry, Science Writing, Design, Editor-in-Chief
Gwen Dickinson, Editor
Guest Authors: Laura Ost, NIST Science Writer

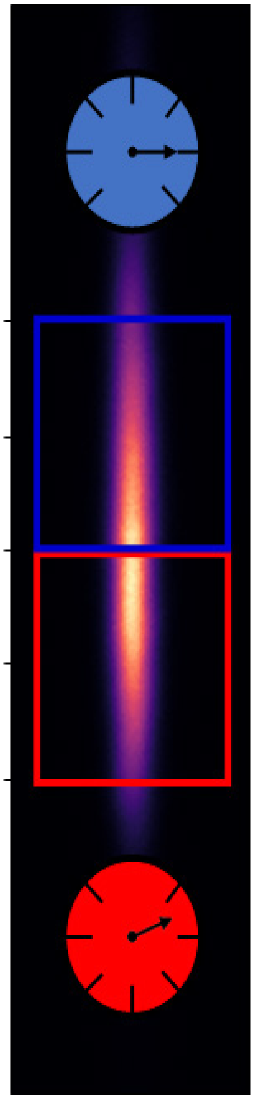
# Research Highlights

# Feature Articles

# JILA Atomic Clocks Measure Einstein's General Relativity at Millimeter Scale

JILA physicists have measured Albert Einstein's theory of general relativity, or more specifically, the effect called time dilation, at the smallest scale ever, showing that two tiny atomic clocks, separated by just a millimeter, or the width of a sharp pencil tip, tick at different rates.

The experiments, described in the February 17, 2022 issue of *Nature*, suggest how to make atomic clocks 50 times more precise than today's best designs and offer a route to perhaps revealing how relativity and gravity interact with quantum mechanics, a major quandary in physics.



JILA is jointly operated by the National Institute of Standards and Technology (NIST) and the University of Colorado Boulder.

"The most important and exciting result is that we can potentially connect quantum physics with gravity, for example, probing complex physics when particles are distributed at different locations in the curved space-time," NIST/JILA Fellow Jun Ye said. "For timekeeping, it also shows that there is no roadblock to making clocks 50 times more precise than today—which is fantastic news."

Einstein's 1915 theory of general relativity explains large-scale effects such as the gravitational effect on time and has important practical applications such as correcting GPS satellite measurements. Although the theory is more than a century old, physicists remain fascinated by it. NIST scientists have used atomic clocks as sensors to measure relativity more and more precisely, which may help finally explain how its effects interact with quantum mechanics, the rulebook for the subatomic world.

According to general relativity, atomic clocks at different elevations in a gravitational field tick at different rates. The frequency of the atoms' radiation is reduced—shifted toward the red end of the electromagnetic spectrum—when observed in stronger gravity, closer to Earth. That is, a clock ticks more slowly at lower elevations. This effect has been demonstrated repeatedly; for example, NIST physicists measured it in 2010 by comparing two independent atomic clocks, one positioned 33 centimeters (about 1 foot) above the other.

The JILA researchers have now measured frequency shifts between the top and bottom of a single sample of about 100,000 ultracold strontium atoms loaded into an optical lattice, a lab setup similar to the group's earlier atomic clocks. In this new case the lattice, which can be visualized as a stack of pancakes created by laser beams, has unusually large, flat, thin cakes, and they are formed by less intense light than normally used. This design reduces the distortions in the lattice ordinarily caused by the scattering of light and atoms, homogenizes the sample, and extends the atoms' matter waves, whose shapes indicate the probability of finding the atoms in certain locations. The atoms' energy states are so well controlled that they all ticked between two energy levels in exact unison for 37 seconds, a record for what is called quantum coherence.

Crucial to the new results were the Ye group's imaging innovation, which provided a microscopic map of frequency distributions across the sample, and their method of comparing two regions of an atom cloud rather than the traditional approach of using two separate clocks.

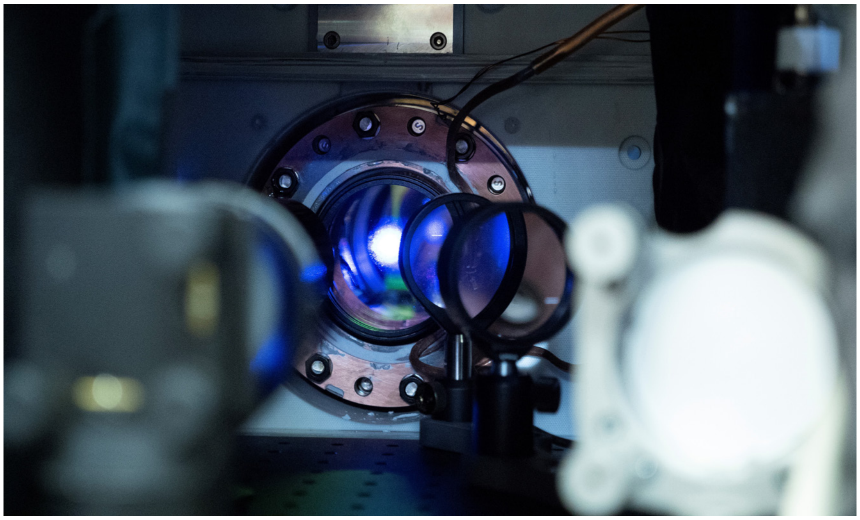
The measured redshift across the atom cloud was tiny, in the realm of 0.0000000000000000001, consistent with predictions. (While much too small for humans to perceive directly, the differences add up to major effects on the universe as well as technology such as GPS.) The research team resolved this difference quickly for this type of experiment, in about 30 minutes of averaging data. After 90 hours of data, their measurement precision was 50 times better than in any previous clock comparison.

“This a completely new ballgame, a new regime where quantum mechanics in curved space-time can be explored,” Ye said. “If we could measure the redshift 10 times even better than this, we will be able to see the atoms' whole matter waves across the curvature of space-time. Being able to measure the time difference on such a minute scale could enable us to discover, for example, that gravity disrupts quantum coherence, which could be at the bottom of why our macroscale world is classical.”

Above: The February 17, 2022 "Nature" cover featuring Ye's research
Below: Part of the experimental set up in the Ye laboratory

Image Credits: Nature, Rebecca Jacobson/NIST

Better clocks have many possible applications beyond timekeeping and navigation. Ye suggests atomic clocks can serve as both microscopes to see minuscule links between quantum mechanics and gravity and as telescopes to observe the deepest corners of the universe. He is using clocks to look for mysterious dark matter, believed to constitute most matter in the universe. Atomic clocks are also poised to improve models and understanding of the shape of the Earth through the application of a measurement science called relativistic geodesy.

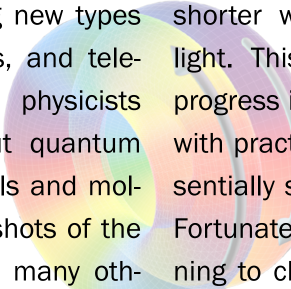


---

Tobias Bothwell, Colin J. Kennedy, Alexander Aeppli, Dhruv Kedar, John M. Robinson, Eric Oelker, Alexander Staron and Jun Ye. "Resolving the gravitational redshift in a millimetre-scale atomic sample." Nature, 602:420-424, (2022).

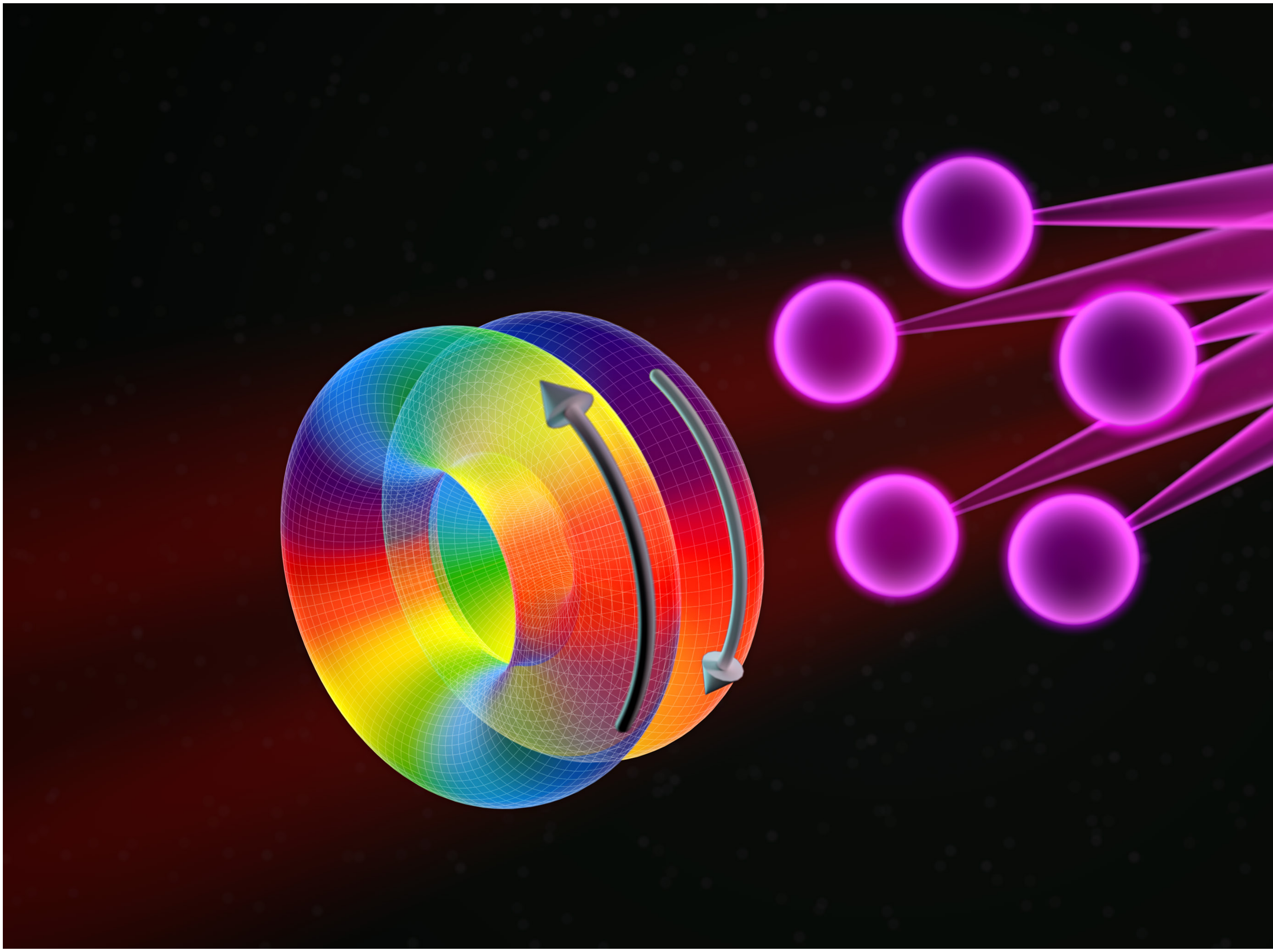
Written by Laura Ost, NIST Writer

# A Necklace Made of Doughnuts

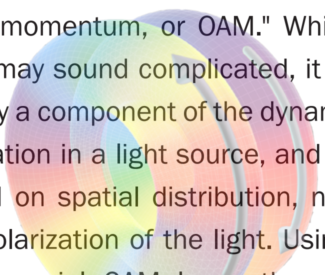


At JILA, physicists develop some of the most cutting-edge technologies, including new types of lasers, microscopes, and telescopes. Using lasers, physicists can learn more about quantum interactions in materials and molecules by taking snapshots of the fastest processes and many other things. While lasers have been used for decades, their applications in technology continue to evolve. One such application is to generate and control x-ray laser light sources, which produce much shorter wavelengths than visible light. This is important because progress in developing x-ray lasers with practical applications had essentially stalled for over 50 years. Fortunately, researchers are beginning to change this by using new approaches. In a paper published in *Science Advances*, a JILA team manipulated laser beam shapes to better control properties of x-ray light.

In order to achieve this feat, the team needed a special type of laser beam. According to graduate student Nathan Brooks, working with JILA Fellows Margaret Murnane and Henry Kapteyn, "This work grew out of a long-term collaboration with the group of Carlos Fernandez- Garcia, at the University of Salamanca in Spain. We have previously done a lot of work with



them studying doughnut-shaped laser beams carrying orbital angular momentum, or OAM." While OAM may sound complicated, it is merely a component of the dynamic rotation in a light source, and is based on spatial distribution, not the polarization of the light. Using their special OAM laser, the researchers studied the process of high harmonic generation (HHG). HHG works by illuminating a target (usually a gas sample) with an intense femtosecond (10-15 sec) laser pulse. Using HHG, the team projected the OAM laser pulses on argon and helium gas to produce special shapes. Brooks explained: "By imprinting a certain type of structure onto the visible laser, we can transfer some of those properties in a unique and useful way onto the emitted extreme ultraviolet or x-ray light." In manipulating the shape of the beams, the team could change the spectrum (i.e., colors) and divergence (i.e., spreading) of the emitted x-ray beams.

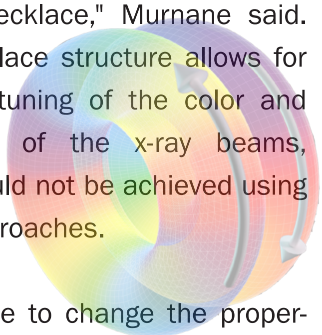


A rendering of the OAM laser pulses that produce special shapes when pulsing on argon or helium gas.

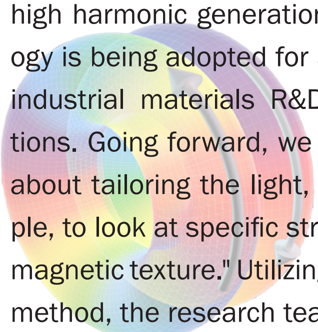
Image Credit: Steven Burrows/Kapteyn and Murnane Laboratories

## Necklaces and Donuts

The first step was to create a necklace-shaped laser beam by combining two distinct OAM laser beams together. Normally OAM laser beams are shaped like donuts. But there's one little twist—if you'll excuse the pun!—the phase structure is not constant, but rather changes or wraps around the doughnut. “We make the necklace laser beam by interfering two different doughnut laser beams together with different phase structure, and this combination gives that beautiful necklace structure. This in turn allows us to control the properties of the generated x-rays, simply by changing the properties of the necklace," Murnane said. The necklace structure allows for the fine tuning of the color and spectrum of the x-ray beams, which could not be achieved using other approaches.



Being able to change the properties of x-ray beams on demand can have significant consequences. "Widespread applications demand precise control over light," explained Murnane. "Sometimes one needs a focused laser beam, sometimes one needs different colors, polarizations, phases, or shapes. And so, this is one more tool we have available to control x-ray light." Controlling x-ray light can help further research within optics and laser physics. But it also has more real-world applications in spectroscopy or imaging processes. According to Murnane: "It's really only in the last three years that high harmonic generation technology is being adopted for advanced industrial materials R&D applications. Going forward, we can think about tailoring the light, for example, to look at specific structural or magnetic texture." Utilizing this new method, the research team is hoping to probe further into improving the control of x-rays and extreme ultraviolet light. The researchers look forward to the development of these tools for demanding applications in a wide variety of sciences and technology, for example, in bioscience and nanoscience.



---

Laura Rego, Nathan J. Brooks, Quynh L. D. Nguyen, Julio San Román, Iona Binnie, Luis Plaja, Henry C. Kapteyn, Margaret M. Murnane, and Carlos Hernández-García. "Necklace-structured high-harmonic generation for low-divergence, soft X-ray harmonic combs with tunable line spacing." Science Advances, 8(5): eabj7380 (2022).

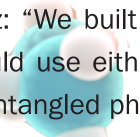
---

Written by Kenna Castleberry

# The Prime Suspect: Hot Band Absorption

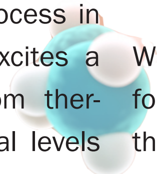
The hunt was afoot within the laboratory of JILA and NIST Fellow Ralph Jimenez as his team continued to unravel the mystery of entangled two-photon absorption. Entangled photons are pairs of light particles whose quantum states are not independent of each other, so they share aspects of their properties, such as their energies and angular momenta. For many years, these photons have been studied by physicists who are trying to create quantum networks and other technologies. The Jimenez lab has been researching whether entangled photons can excite molecules with greater, even super, efficiency as compared with normal photons.

In a new paper published in the *Journal of Physical Chemistry Letters*, Jimenez and his team report a new experimental setup to search for the cause of a mysterious fluorescent signal that appears to be from entangled photon excitation. According to Jimenez: “We built a setup where you could use either a classical laser or entangled photons to look for fluorescence. And the reason we built it is to ask: ‘What is it that other people were seeing when they were claiming to see entangled photon-excited fluorescence?’ We saw no signal in our previous work published a year ago, headed by Kristen Parzuchowski. So now, we're wondering, people are seeing something, what could it possibly be? That was the detective work here.” The results of their new experiments suggested that hot-band absorption (HBA) by the subject molecules, could be the potential culprit for this mysterious fluorescent signal, making it the prime suspect.



## Case Notes on HBA

HBA is a classical one-photon absorption process. According to graduate student Kristen Parzuchowski, “[HBA is a] process in which a single photon excites a one-photon transition from thermally populated vibrational levels of the ground electronic state.” Normally, this doesn’t happen for less energetically vibrating molecules, which require two infrared photons to be excited and transition to a higher state.



In order to determine if HBA was the source of the mysterious fluorescence, Jimenez and his team tested two different molecules: Rhodamine 6G (Rh6G) and LDS798 (a fluorophore or fluorescent chemical compound that can re-emit light upon light excitation) dissolved in solvents. “A 1060-nanometer laser was used to directly excite the sample,” Jimenez explained. “The excited molecules emit red light, which is measured by a photomultiplier tube.” To create entangled photons, Jimenez added: “We used a 532-nanometer laser and focused it into a ppKTP [periodically poled potassium titanyl phosphate] crystal where one in a million photons is turned into an entangled pair of 1064-nanometer photons...which can excite the sample. This way we have a classical and a quantum side of the experiment to compare.”

With their setup, the researchers focused on the “cross section” of the absorption process. “The cross section tells you how much area a molecule presents for being hit by a photon pair,” Jimenez stated. The cross section size has a history of being somewhat controversial, as Parzuchowski explained that: “Right now there is significant controversy about the size of entangled two-photon absorption

Opposite: Looking at the LDS798 molecule experiencing HBA

Image Credit:
Steven Burrows/Jimenez Group

(E2PA) cross sections.” Jimenez added: “Other groups claimed that the E2PA cross-section was almost as large as that for a single photon, which implies very strong absorption.” The Jimenez group’s previous work showed that other investigators were over-estimating cross-sections by a factor of 10,000 or more. The team was eager to see if their experiment could validate previous observations, or if it would offer something new.

In looking at the cross-sections of the Rh6G and LDS798 molecules, Jimenez pointed out some important parameters. “For regular two-photon absorption, the cross-section is very small. That's why people need to use high-powered lasers with short pulses of light to get a signal,” he stated. “So, the implication was that big cross-sections for entangled two-photon absorption would allow ultralow-power imaging.” But this was where the HBA became important. “If the signal is from hot band absorption, that doesn't allow you to do two-photon imaging, which is 3D.” Jimenez explained that: “For at least one of the molecules we showed here, the signal could be pretty much entirely due to this hot band absorption. The other molecule we looked at did not show this absorption.”

## The Evidence Points to Overestimating

In seeing HBA happen in the LDS798 molecule, the researchers realized this small signal may have big implications for the study of entangled photons interacting with molecules. “What we found is that if you calculate the hot band absorption cross-section, it can account for most of the overestimated cross-section that people were reporting for entangled two-photon absorption,” Jimenez said. “We're showing that HBA can mimic what people think is entangled two-photon absorption, so additional tests are needed to verify which process is occurring. We don't know if that's happening with every molecule that others have studied.” Jimenez hopes that others will take this new factor into account when looking at entangled two-photon absorption. In observing the similarities between the entangled two-photon absoprtion and HBA, Parzuchowski noted that: “These two processes share one signature: a linear scaling with excitation photon flux [absorption]. This is an exciting finding because some researchers who claim to measure E2PA only look for evidence of this one signature. They may have been measuring HBA all along!”

## The Case Isn't Closed

While the researchers found a potential explanation, they still want to understand how to generate a bona fide entangled photon absorption signal. According to Jimenez: “ Now, we know that the real signal is going to be around 10,000 times smaller than what people claimed to see before. But it could still be hundreds or thousands of times stronger than a classical signal under the same conditions.” The team is hoping to tweak their experimental setup to better their chances to find the signal. “There are various ways you can think of doing this experiment,” Jimenez added. “Either by using a different type of quantum light source that provides stronger excitation or by building your experiment in such a way that you get a much stronger interaction between the photons and the sample.” The researchers hope that with their new setup, and results from their previous research they can definitively identify the source of the mystery fluorescent signal, and find a real fluorescence signal from tangled photon excitation. That would be case closed.

---

Alexander Mikhaylov, Ryan N. Wilson, Kristen M. Parzuchowski, Michael D. Mazurek, Charles H. Camp Jr., Martin J. Stevens, and Ralph Jimenez. "Hot-Band Absorption Can Mimic Entangled Two-Photon Absorption." Journal of Physical Chemistry Letters, 13(6): 1489-1493, (2022).

---

Written by Kenna Castleberry

# Electrifying Molecular Interactions

Worldwide, many researchers are interested in controlling atomic and molecular interactions. This includes JILA and NIST fellows Jun Ye and Ana Maria Rey, both of whom have spent years studying interacting potassium-rubidium (KRb) molecules, which were originally created in a collaboration between Ye and the late Deborah Jin. In the newest collaboration between the experimental (Ye) and theory (Rey) groups, the researchers have developed a new way to control two-dimensional gaseous layers of molecules, publishing their exciting new results in the journal *Science.*

## Electricity as a Tuning Knob

Building off their previous work, the researchers created ultracold KRb molecules in a stack of two-dimensional layers. This time, they applied an electric field gradient to manipulate the energies of the molecules and the interactions between layers. First author and Ye group graduate student William Tobias explained the setup of the experiment: “It's a one-dimensional optical lattice, which arranges molecules like a stack of pancakes. The molecules can each move in a two-dimensional plane, but not between layers.” Because the molecules within these layers are polar (having positive and negative poles), they can be influenced by electric fields which act on the charges that these poles have. “Polar molecules are particularly interesting because they have dipolar interactions, which are typically longer ranged than interactions between atoms and are anisotropic, which means that the interaction varies based on the relative orientation of the molecules,” he added. Dipolar interactions occur when the charged poles on these molecules interact, causing them to attract or repel each other.

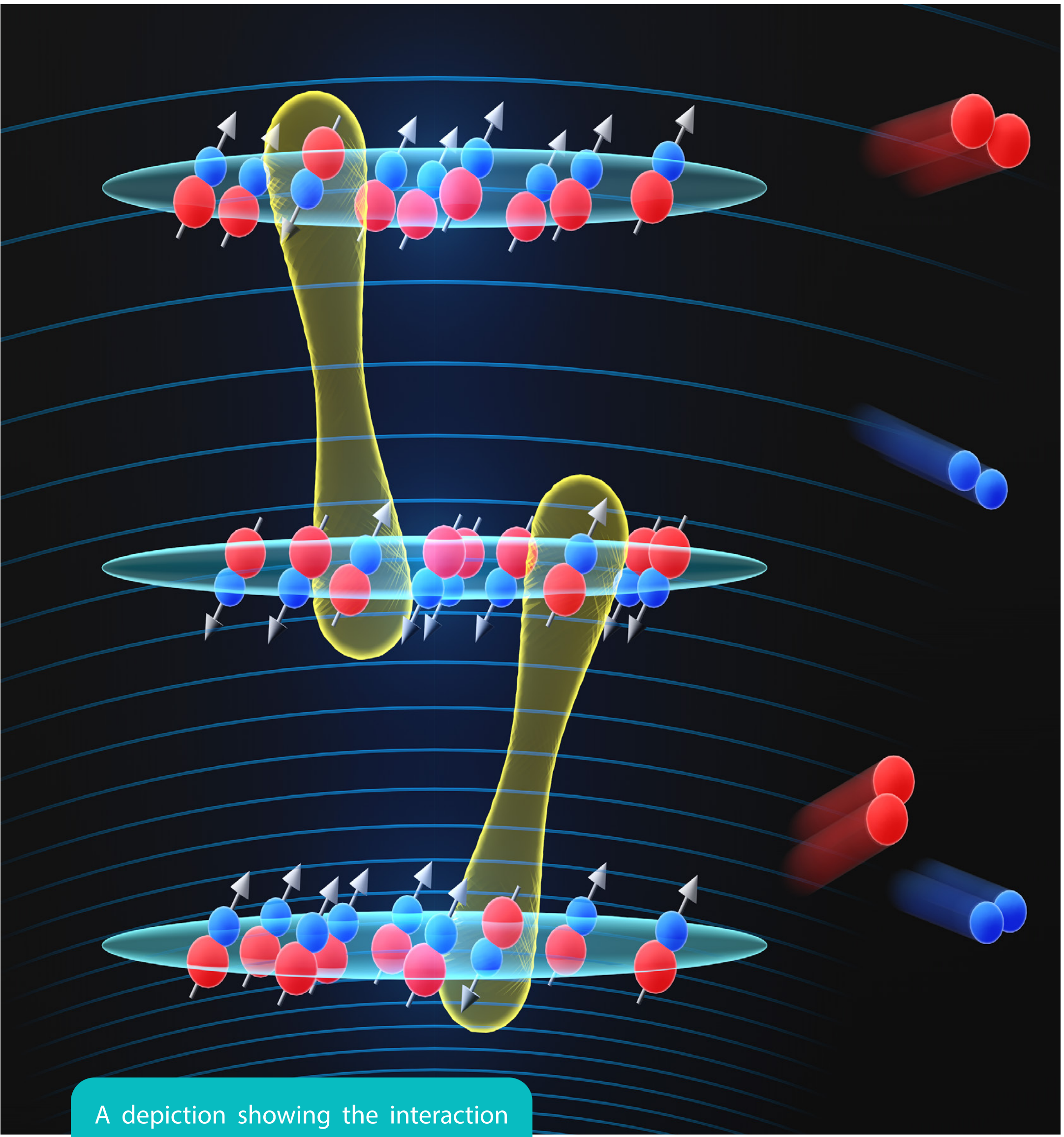
Using these charged poles, the team manipulated the dipolar interactions via an electric field. “Our new method uses electric fields to select individual layers of molecules and prepare them in specific rotational states,” Tobias stated. Molecules in different rotational states, which are energy levels determined by the speed of rotation, respond differently to electric fields. “Starting from an initial condition of many layers containing molecules, we can reduce the system to only one or two layers by probing the molecules with microwaves and prepare quantum systems with controlled densities and interactions.” This extra level of electric field control worked like a fine-tuning knob, where the researchers could probe each layer individually and study the molecular interactions more closely.

## A New Molecule-Scale Microscope

The researchers were even able to use their molecules as an electric field microscope by manipulating the energy of the molecules using the electric field. “If you stabilize the molecules very carefully with respect to the electric field.” Tobias said, “you can either apply a known electric field to control the molecules or use the molecules to measure an unknown electric field distribution. We showed that we could measure electric fields with a spatial precision on the order of tens of nanometers.” This was especially important when the researchers were studying a molecular phenomenon called “spin exchange.”

## Spinning Into Different Energy States

When looking at molecular interactions, rotation is important—interacting molecules can trade their rotational states,



A depiction showing the interaction between ultra cold compressed 2D gas layers of KRb molecules

Image Credit: Steven Burrows/Ye and Rey Groups

swapping energy levels in a process called "spin exchange." This can even happen between the different layers within the researchers' experiments. "Once you're able to select the individual layers of the lattice, if you prepare molecules in two layers in different rotational states, you find that they exchange rotational states between layers," Tobias noted. This exchange affects the energy levels of these molecules. "Exchanging states conserves energy if there is no difference in the electric field between layers," Tobias added. "But if we introduce an electric field difference [a variation in field between neighboring layers], it costs some energy for the molecules to make that exchange. We found in the experiment that when the molecules trade rotational states, they also have to give up or gain kinetic energy as well, equal to the change in the electric potential energy." The Rey group, for their part of the collaboration, worked to help calculate the dependence of the spin exchange rate on the electric field difference. From their calculations and the experiments from the Ye group, the researchers found that a larger electric field difference minimized the spin-exchange rate, allowing for better control of the system.

With their "fine-tuning knobs", the researchers could better understand and control the molecular interactions within the compressed layers. This new precision allowed the team to develop other aspects of these interactions to study. According to Tobias: "One project we're working on right now is to measure energy shifts from thousands of polar molecules in single and multiple layers using the tools we've developed for layer selection. In the longer term, although we would need to be at much lower temperatures, there are a variety of proposals for using pairing of molecules between layers to study superfluidity and other quantum phenomena." The researchers are hopeful other physicists will use their methods to further explore molecular interactions.

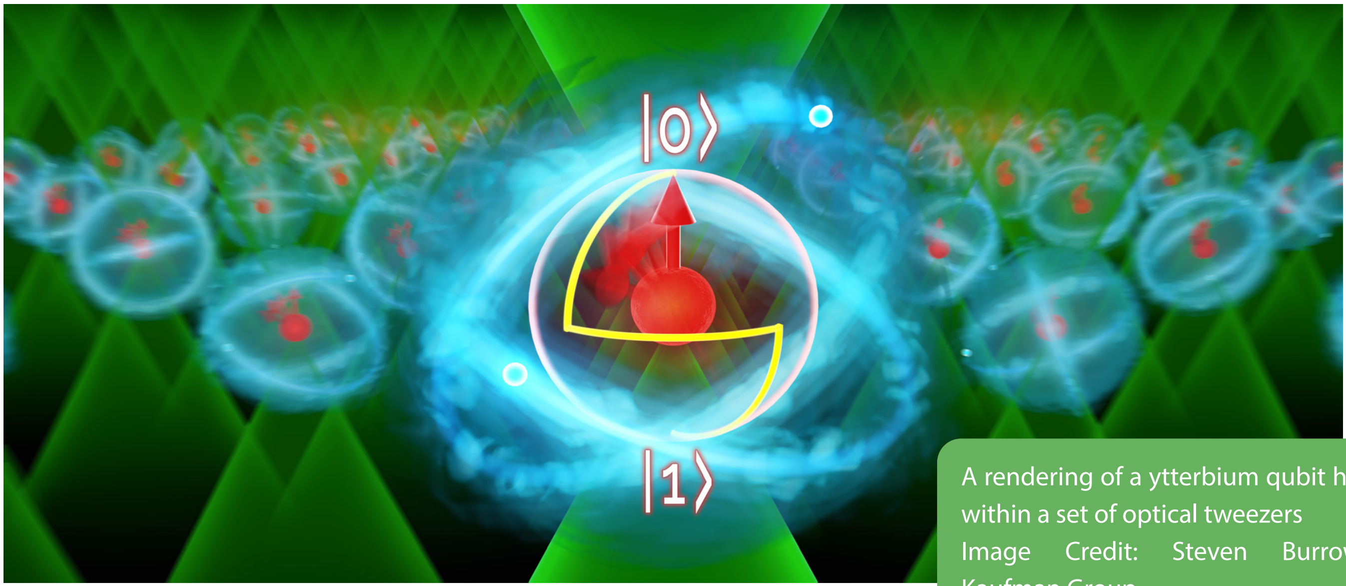
---

William G. Tobias, Kyle Matsuda, Jun-Ru Li, Annette N. Carroll, Thomas Bilitewski, Ana Maria Rey, and Jun Ye. "Reactions between layer-resolved molecules mediated by dipolar spin exchange." Science, 375(6586): 1299-1303, (2022).

---

Written by Kenna Castleberry

# Tweezing a New Kind of Qubit



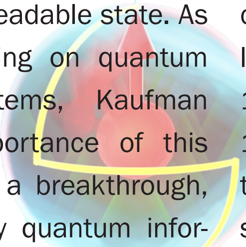
A rendering of a ytterbium qubit held within a set of optical tweezers
Image Credit: Steven Burrows/ Kaufman Group

JILA has a long history in quantum research, advancing the state of the art in the field as its Fellows study various quantum effects. One of these Fellows is Adam Kaufman. Kaufman and his laboratory team work on quantum systems that are based on neutral atoms, investigating their capacities for quantum information storage and manipulation. The researchers utilize optical tweezers—arrays of highly focused laser beams which hold and move atoms—to study these systems. Optical tweezers allow researchers exquisite, single-particle experimental control. In a new paper published in *Physical Review X,* Kaufman and his team demonstrate that a specific isotope, ytterbium-171 (171Yb), (1) has the capacity to store quantum information in decoherence-resistant (i.e., stable) nuclear qubits, (2) allows for the ability to quickly manipulate the qubits, and (3) permits the production of such qubits in large, uniformly filled arrays.

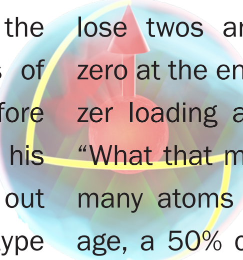
## A New Kind of Qubit?

A qubit, or "quantum bit," is the basic unit of quantum information. A qubit, thanks to its quantum properties, can be a 0, 1, or a combination of both. This makes it an essential building block for those working on quantum computing. The researchers had anticipated that their 171Yb isotope would allow access to a new kind of qubit, one based on the isotope's nuclear spin. "The nice thing about this particular species of ytterbium is that it has this kind of natural qubit in it," co-first author and postdoctoral researcher Alec Jenkins said. "It has a spin one-half. It's a very isolated sort of ideal two-level system within the nucleus of ytterbium, which is good for quantum applications." Not only is the nuclear qubit novel, but it also affords unprecedented coherence (stability), making it an ideal system to work with.

Maintaining qubit coherence is a daunting challenge for any prospective quantum information platform. Although quantum computers allow capabilities inaccessible to classical computers, this comes at a cost because of the notorious fragility of qubits. For this purpose, the nuclear qubit, decoupled almost completely from the electron cloud and thus insensitive to outside interactions like noise, is nearly ideal. For this reason, Kaufman finds the nuclear qubit exciting. "What's special about this nuclear spin—compared to the spin in other atoms like rubidium which have historically been used in tweezers—is that, in certain quantum states, it can be completely isolated from the remainder of the atom," he elaborated. This means that the high-intensity tweezer light doesn't disturb the qubit, allowing for a longer coherence time when the qubit is in a readable state. As a scientist working on quantum information systems, Kaufman realized the importance of this stability. "This is a breakthrough, because in many quantum information platforms with neutral atoms, these so-called 'light shifts' can significantly degrade qubit performance," he explained.



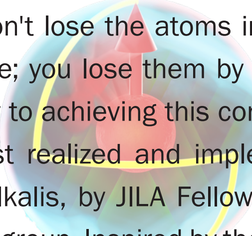
Not only are the nuclear qubits long-lived and noise-resistant, they can also be manipulated very quickly, allowing for a more efficient process. "In this work, adding to the second scale quantum memory feature, we found we can do fast 100-nanosecond-scale qubit manipulations with an unconventional single-beam Raman transition method," said graduate student Aruku Senoo. "We also showed the manipulation is quite low noise, only at the part in a thousand level." The combination of long coherence time and fast control promises to enable the implementation of thousands of individual manipulations before the qubit is lost. Kaufman and his team hope to continue finding out what is possible with this new type of qubit, which, if proven feasible for quantum computation, could have big implications for quantum information studies.



## Loading Tweezers can be Tricky

To study the qubit, the team used a tweezer system, running into the challenge that preparing a uniformly filled array can present. Using 171Yb, the team set up a special 10×10 tweezer array. According to the co-first author and graduate student Joanna Lis: "The tweezers are made by focusing a light beam through an objective lens. The atoms sit in these traps and emit light, which we collect with the same objective and focus on a camera, which we use for imaging." However, if multiple atoms are loaded into a tweezer, they will interfere strongly with each other, interfering with coherence times and adding to the overall noise levels. To prevent multiply-occupied tweezers, light-assisted collisions can be used to cause the atoms to be lost pairwise from the trap. According to postdoctoral researcher Will McGrew, "One important part about that process is that you always lose the ytterbium atoms in twos. So, if you happen to load an even number of atoms, you would lose twos and then you'd have zero at the end." This makes tweezer loading a statistical process. "What that means is, as you load many atoms you've got, on average, a 50% chance of loading an odd number and a 50% chance of loading an even number," McGrew added. "After the light-assisted collision process is completed, you end up with a 50% chance of filling your tweezer with a single atom."

Instead of using the light-assisted collision process, which only gives a 50% chance of a full array, the researchers instead used a method called blue-shielded collisions. In this process, the atom gains some energy, but does not immediately get lost in the trap. "You can cycle this multiple times, and eventually lead to one atom leaving the trap but not the other," McGrew said. "You don't lose the atoms in twos anymore; you lose them by ones." The key to achieving this condition was first realized and implemented in alkalis, by JILA Fellow Cindy Regal's group. Inspired by these results, the Kaufman group explored using the narrow spectroscopic lines in ytterbium to isolate a similar cooling feature, needed to promote these blue-shielded collisions. In achieving this, it changed the statistical numbers game the researchers were playing with their tweezers, allowing them a higher percentage of filling the array. In using the 171Yb isotope with this technique, the researchers found that they could fill on average nearly 93 tweezers in the 10 ×10 array. This increased efficiency for optical tweezers allows for more qubits to be manipulated, which the researchers plan to use to continue studying quantum information processing.



---

Alec Jenkins, Joanna W. Lis, Aruku Senoo, William F. McGrew, and Adam M. Kaufman. " Ytterbium Nuclear-Spin Qubits in an Optical Tweezer Array." Phyical Review X , 12(2): 021027 (2022).

Written by Kenna Castleberry

# Running in a Quantum Corn Maze and Getting Stuck in the Dark

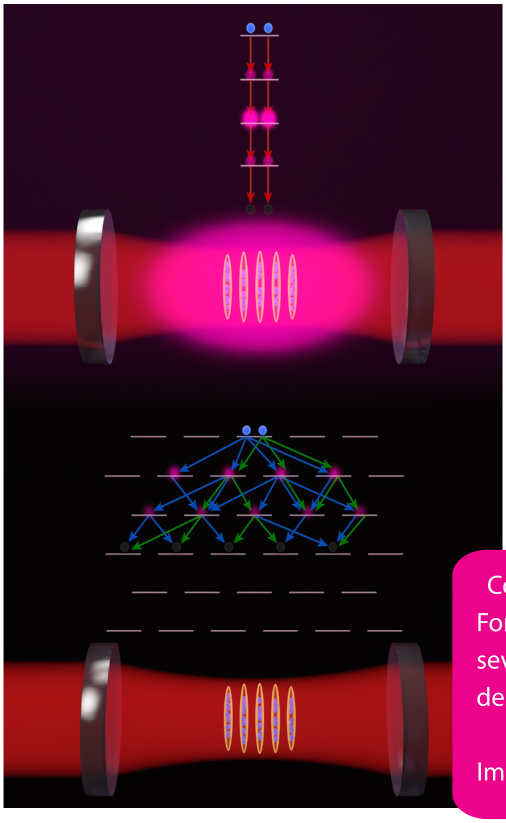
Light is emitted when an atom decays from an excited state to a lower energy ground state, with the emitted photon carrying away an energy. The spontaneous emission of light is a fundamental process that originates from the interaction between matter and the modes of the electromagnetic field—the background "hiss" of the universe that is all around us. However, spontaneous emission of light can limit the utility of atomic excited states for a wide array of scientific and technological applications, from probing the nature of the universe to inertial navigation. Understanding ways to alter or even engineer spontaneous emission has been an intriguing topic in science. JILA Fellows Ana Maria Rey and James Thompson study ways to control light emission by placing atoms in an optical cavity, a resonator made of two mirrors between which light can bounce back and forth many times. Together, with JILA postdoc and first author Asier Piñeiro Orioli, they have predicted that when an array of multi-level atoms is placed in the cavity the atoms can all cooperate and collectively suppress their emission of light into the cavity. These findings were recently published in *Physical Review X.*

## The Paths of Emission

As an atom goes through spontaneous emission, it follows a certain decay path, i.e., the different energy levels an atom passes through on the process of decaying. This process can be modified if many atoms are placed inside a cavity where atoms become highly sensitive to the light emitted by the other atoms. For two-level atoms—atoms with only two internal levels: a ground and an excited state—the decay path is rather straightforward. When an atom decays from the excited state to the ground state it stimulates other atoms to do the same, i.e., the decay paths interfere constructively. As a consequence, all atoms collectively emit light at a faster rate, a process known as superradiance, a phenomenon that has been observed in experiments performed by the Thompson Group. However, for multi-level atoms, things can get a bit complicated. "What happens is that when an excited multilevel atom starts to radiate there are multiple paths it can go through," explained Rey. This is different from a two-level atom which has only one path. "Interestingly, there are many situations where the various paths interfere destructively, causing a cancellation in the decay process," Rey added. "When that happens, atoms get stuck in a particular state and stop emitting light into the cavity." This state is called a quantum dark state, or, in contrast to superradiance, a subradiant state. As Thompson describes, "It is kind of like a corn maze with many paths from entrance to exit. If you go down a single path, you will always reach the exit. But in quantum mechanics, the atoms will try to follow each path through the maze simultaneously, and they can cancel each other's ability to ever exit the maze—super weird, right?"

One way to visualize this quantum corn maze is by imagining an atom as an arrow that points down when it is in the ground state and up when it is in the excited state. In this scenario, the light emission process can be seen as a rotation of the arrow from up to down, where the rotation speed depends on the sum of all the arrows. When you have two-level atoms in the cavity, all arrows synchronize in rotation resulting in a very big "arrow". However, multilevel atoms are different, according to Piñeiro Orioli: "Imagine we can visualize each multilevel atom, not as a single arrow, but instead as a collection of arrows which are associated with the different decay transitions available. During the emission process the arrows start to rotate back down towards the ground state but this time you can encounter a situation where the arrows point in fdifferent directions such that their sum kind of cancels out. When this happens, the arrows stop rotating and the atoms get stuck. This is what we call a quantum dark state."

A quantum dark state may offer many benefits for quantum technology, including quantum clocks, which many JILAns study. Not only is the quantum dark state intriguing, but the researchers found that the state itself was inherently entangled. As Rey noted, "To be dark, these states must have some correlations. These particles need to know what other particles are doing to avoid the decay process." Thompson adds, "By using many internal levels, the extra paths allow for correlations that could even move beyond classical correlations and involve quantum entanglement between the atoms." The entangled properties of the dark states make them even more attractive for future quantum technologies.



Comparison of 2-level and 6-level atom decay paths. For 6-level systems, each state can potentially decay into several states and some of them might be dark due to destructive interference.

Image Credit: Steven Burrows/Rey and Thompson Groups

## Preparing Dark States

In order to observe these dark states, the team of researchers proposed an experiment that utilizes strontium atoms in an optical cavity, an experimental setup that exists in the Thompson laboratory. Strontium atoms, Rey explained, have: "...a narrow transition with 10 excited levels and a spontaneous emission decay rate that can be longer than 100 seconds. This allows the strontium atoms to have multiple decay paths, permitting them to give rise to quantum dark states. According to Rey: "To create these dark states, we would first drive the cavity, which means we inject light in the cavity with certain polarization. We add coherent light into the cavity for some time. Then we stop the driving process and let the atoms evolve until they all decay to the ground stay or get stuck in a quantum dark state."

For realistic implementations of their proposed experiment, the team of researchers provides a more nuanced view on the power of their findings. "The dark states we have found are not perfect," Piñeiro Orioli said. "They are only dark when they decay into the cavity, which is by far the dominant decay channel. However, they will still decay through spontaneous emission into free space, i.e., photons will be emitted into other directions. But, if we choose a narrow transition, this free space decay will be very slow and we will be able to see the benefit from the cavity's dark nature of the state."

Moving forward, the researchers are hoping to further improve their quantum dark states. "In the future, we want to figure out ways to create large-scale entangled states while retaining the darkness in the cavity decay," added Piñeiro Orioli. "I believe this is possible because the large number of dark states available gives us the freedom to combine them in many different ways. Some preliminary results make me optimistic, but this is still a work in progress and we will have to wait."

---

Asier Pineiro Orioli, James K. Thompson, and Ana Maria Rey. "Emergent Dark States from Superradiant Dynamics in Multilevel Atoms in a Cavity." Physical Review X, 12(1): 011054 (2021).

Written by Kenna Castleberry

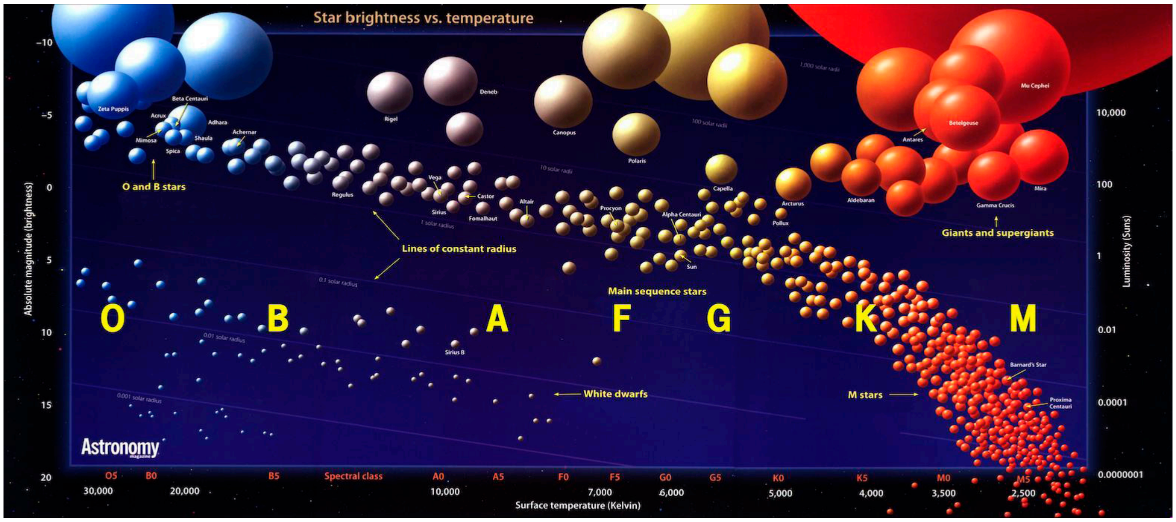
# New Insights into Magnetic Fields of Red Dwarfs

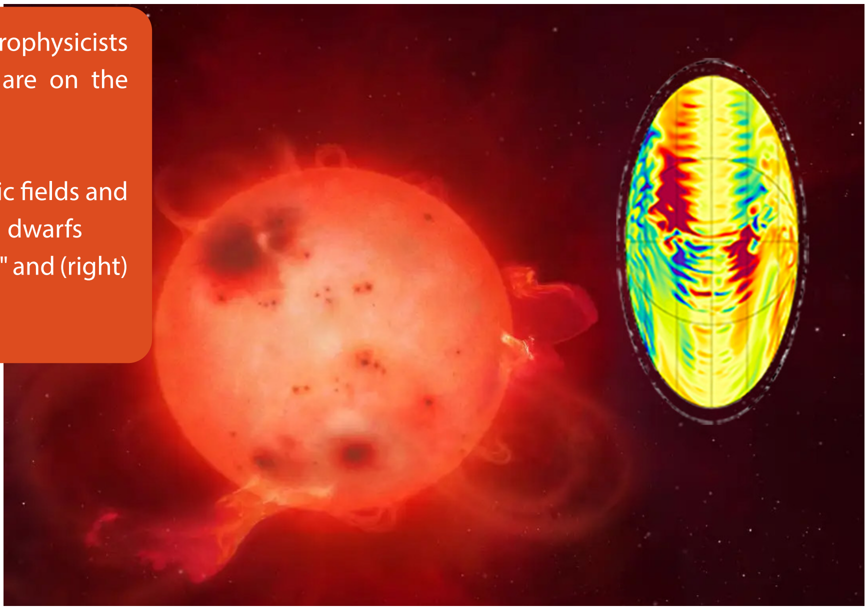
Of the many different objects in the solar system, M-dwarf stars, also known as red dwarf stars, are of particular interest to astrophysicists. These small objects are the most common type of star in the universe and have unique properties. “If you lay out all of the different types of stars [in a plot of stellar color versus brightness] we can see, based on what color they are and how bright they are, [that] most stars fall on a line we call the ‘main sequence’,” explained graduate student Connor Bice. “That's where they are born, and they stay in that same spot for most of their lives. Down at the tail end of that [line] are red dwarfs. They're the least massive, the coldest, and the smallest type of main-sequence stars.” Bice is a researcher in JILA Fellow and astrophysicist Juri Toomre's group, and both he and Toomre have been looking at some of a red dwarf's unique properties, mainly their magnetic fields and convective flows. In a new paper published in the *Astrophysical Journal*, Bice and Toomre have found a link between the star’s convective cycles, or the heat cycles in a star’s atmosphere, and its magnetic fields, using fluid dynamics simulations.

## The Smallest and Coldest

Red-dwarf stars may be the least massive and coldest, but according to Bice, “When we actually sit down and watch some of them, we find that a huge proportion are strikingly violent magnetically, and it really sets them apart. They put off flares constantly, and many of them are brighter than any flares we've seen on the Sun,” Bice continued. “Since they have to power that magnetic activity somehow, as small and dim as they are, it raises some very interesting questions about how they're able to do it.”

Both Toomre and Bice were intrigued by this magnetic violence and wanted to research the cause of this behavior. In order to study this magnetic activity, Bice and Toomre used an open-sourced software program called Rayleigh to run a series of massively parallel 3D simulations on NASA’s Pleiades supercomputer. The simulations studied the dynamics in the interiors of three virtual red dwarfs. The researchers wanted to better understand how the star’s dynamo action, the fluid processes by which it generates magnetic fields, might differ from those of more massive stars. When analyzing the influence of the convective flows, the researchers focused in on a phenomenon called a convective nest. According to Bice, the convective nest is a concentration of the star’s vertical heat transport, from the core of the star to its atmosphere, into a





Left: The Main Sequence graph used by astrophysicists to organize star types. Red dwarf stars are on the bottom right of the graph.

Right: Bice and Toomre studied the magnetic fields and the convective flows on three simulated red dwarfs
Image Credits: (left) "The Astronomy Journal" and (right) Kenna Castleberry and Connor Bice

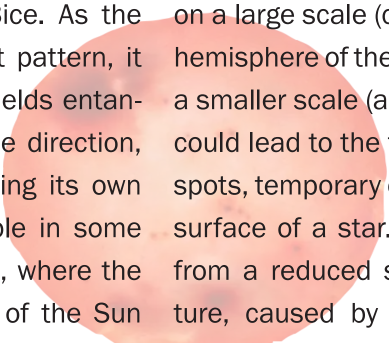
large structure at the star's equator that continually travels around the star. Since the convective nest is an area of particularly vigorous flows, the researchers were hopeful the nest could provide insight into the cause of the violently magnetic behavior observed in many red dwarf stars.

## The Secrets of the Nest

When looking at the interactions between the convective nests and the magnetic fields in the simulations, the researchers found a couple of interesting things. “First, we're seeing that turbulent induction [a circular movement] by the nest tends to cause the magnetic fields within it to reverse their direction,” explained Bice. As the nest spun in a distinct pattern, it caused the magnetic fields entangled within it to reverse direction, similar to a snake eating its own tail. “This is comparable in some ways to the solar cycle, where the global magnetic fields of the Sun reverse direction every 11 years, though that's by a very different mechanism,” Bice added. In one of the simulations, the magnetic field reversal expanded to the rest of the star, showing a larger effect beyond the convective nest. From these results, the researchers concluded that the convective nest had a direct influence on the magnetic field of the red dwarf.

The other interesting result had to do with the outward movement of the magnetic field from the star’s convection zone. “Above this convective nest, at the surface of the star, we're seeing the outward magnetic fields get amplified,” Bice said. This amplification, where the magnetic field got stronger, not just on a large scale (covering an entire hemisphere of the star), but also on a smaller scale (a more local area), could lead to the formation of starspots, temporary dark areas on the surface of a star. Starspots come from a reduced surface temperature, caused by strong magnetic fields preventing cooled material from sinking back below the surface. In studying this amplification further, Bice and Toomre hoped to build on previous research showing that starspots can affect stellar rotation measurements, by examining the starspot origin process.

For Bice and Toomre, this study of convective nests is just a part of a much bigger picture. “These three simulations were actually drawn from a larger survey of models that we're looking to publish a paper on this summer,” Bice said. “It's shaping up as a broader take on several of the behaviors we've seen a lot since turning to red dwarfs, that you don't really see when modeling Sun-like stars.” Understanding more about how the convective nests shape magnetic fields not only allows the researchers to learn more about properties of red dwarfs, but can also help astrophysicists better calculate stellar rotation and other properties of these unique stars.



---

Connor P. Bice and Juri Toomre. "Longitudinally Modulated Dynamo Action in Simulated M-dwarf Stars." The Astrophysical Journal, 928(51): (2022).

---

Written by Kenna Csatleberry

# WHERE SCIENCE MEETS ART : A MURAL ON AMO PHYSICS

JILA Fellow Cindy Regal has helped consult on a new mural placed in Washington Park in Denver, Colorado. The mural, titled *Leading Light*, loosely alludes to AMO (Atomic, Molecular, and Optical) physics, which Regal studies by using laser beams. With bright yellows and vivid pinks, the mural depicts four women interacting with different blue spheres, representing electrons. One woman wears sunglasses, modeled on the laser goggles that JILAns wear for lab safety. The artist, Amanda Phingbodhipakkiya, found Regal's work captivating. “We share a vision to not only uplift women in STEM and to bring science and our society closer together, but also to foster dynamic and organic relationships with science in everyone, whether or not they choose to become scientists," the artist said.

Regal and Phingbodhipakkiya were originally connected through the Heising-Simons Foundation. The Foundation funds Phingbodhipakkiya's mural series, called FINDINGS, a public art series dedicated to celebrating women and science. The mural not only uses shadows to distinguish important motifs, but also incorporates bold colors to capture the attention. "We all need portals for discovery that invite us to follow our curiosity, and FINDINGS murals, like *Leading Light* do just that—with a vortex of color, movement, and figures of color harnessing their power to manipulate matter, just as scientists like Cindy are using light to manipulate matter," Phingbodhipakkiya explained. This mural not only offers a whimsical and beautiful masterpiece to consider but also includes augmented reality (AR) aspects that a user can look at using the special FINDINGS app on their phone. The app causes pieces of the mural to digitally move, teaching the viewer about the background of the mural.

For her part, Regal enjoyed helping her research be translated into an artistic medium. "I went down there in August when it was in process, and I met with Amanda and a small art group, and I even got to paint some tiny bits of the mural. I think I managed to stay in the lines," Regal joked.

Regal worked closely with Phingbodhipakkiya to make sure the accuracy came through in the painting. "Amanda's process is to collaborate with scientists to incorporate bold ideas from different fields of science into the murals," Regal explained. "And it was exciting to hear that atomic and quantum science in general could be brought to life in her current work." According to Phingbodhipakkiya: "I consult my scientific partners first, before I that we create a narrative together and the work maintains its scientific rigor while also sparking curiosity, imagination, and discovery." In *Leading Light,* viewers can see atoms in 2D and 3D lattices, similar to ones studied by JILA Fellows like Regal.

Since being finished in August of 2021, the mural has gotten positive reviews, and raised interesting questions. "The response has been overwhelmingly positive," Phingbodhipakkiya said. "So many folks have expressed how moving it is to see figures like them represented so powerfully. But because FINDINGS murals also center on women of color, there are always the occasional 'Where are the men?' and other racist comments. This tension is important because without these questions and conversations about equity and justice, there is no change. And I am proud that we are bringing these conversations into communities where they need to happen."

Above: Regal helps explain the science behind the mural in Washington Park

Image Credit: Amanda Phingboddhipakkiya

Below: The mural in proccess

Image Credit: Amanda Phingboddhipakkiya

Written by Kenna Castleberry

# JEDI PROJECTS:
# WOMEN IN QUANTUM PANEL

Colorado has a reputation for being a quantum ecosystem hotspot, and a recent panel discussion further bolstered this image. It was hosted by JILA, a world-leading physics institute created by a partnership between the University of Colorado Boulder and NIST, and the CUbit Quantum Initiative, a CU Boulder research center. The panel, titled "Women in Quantum: What Does It Take," consisted of individuals from both quantum research and the quantum industry. With panelists from some of the biggest names in the quantum industry, including ColdQuanta, Maybell Quantum, Quantinuum, and Vescent, the discussions about the industry itself were relevant and engaging.

The panelists ranged in ages and positions, from engineers to researchers. The panelists included Judith Olson (ColdQuanta), Ana Maria Rey (JILA), Sara Campbell (Quantinuum), Star Fassler (Vescent), and Dr. Johanna Zultak (Maybell Quantum). During the discussion, the panelists spoke about their backgrounds and day-to-day activities. “I work with a lot of fibers,” said Fassler, who highlighted the common debugging issues with quantum, as things often “went wrong, so I need to walk away when I get upset, or else I’ll break the fibers. It’s good to learn to walk away when you need to,” she joked.

While all of the panelists had backgrounds in research, they all followed different paths to get to their current positions. As women within both academia and industry, all had experienced the need for more diversity in a field that has a male majority. “When I was doing my Ph.D., there were no women professors in physics,” Zultak explained. “Now there are a few, so we’ve made a bit of progress.” In discussing how to improve this diversity, each of the speakers offered their own suggestions. “Role models are very important,” highlighted Rey. Olson added to that sentiment, saying that she advocated for other women in her company, making them feel welcome, and wanted to encourage others to do the same. As the quantum industry is still relatively new, and growing significantly, many companies are taking this opportunity to make a point to be more inclusive and diverse. For example, ColdQuanta hosted its own panel of women in the quantum industry, showing that key players in the industry are taking this issue very seriously.

While this panel not only helped bring more awareness to the current lack of diversity in the industry, it also showcased the rich quantum ecosystem within Colorado. CUbit, one of the panel's producers, has worked hard to foster that community by developing a partnership network between CU Boulder and Colorado quantum companies. This partnership allows university students to better network with these companies as well as experience a seemingly endless range of career opportunities. Campbell highlighted the importance of the time she spent as a graduate student at JILA, giving her time to meet role models and mentors within the industry. With this ecosystem continuing to grow, it will be no surprise that Colorado will continue to remain a global hotspot for both quantum research and quantum technology.

Written by Kenna Castleberry

Panelists from left to right: Ana Maria Rey (JILA and NIST), Judith Olson (ColdQuanta), Johanna Zultak (Maybell Quantum, Star Fassler (Vescent), and Sara Campbell (Quantinuum). Moderator Brittany Mazin, Director of Engagement at ColdQuanta

# LIFE AFTER JILA

"It's hard to imagine my career without JILA," explained Mike Martin, staff scientist at Los Alamos National Laboratory. Martin first arrived at CU in 2006, as a graduate student. "I began working with [JILA and NIST Fellow] Jun Ye in 2007," he said. "My work was in frequency metrology for precision measurement and timekeeping." During Martin's stint at JILA, he explained that he helped work on the early development of the frequency comb. As time continued, his work expanded to include studying the strontium lattice clock. "At the time there was only one strontium apparatus in Jun's lab," he said. "And around 10 people or so were all studying it." This allowed him to collaborate with many other colleagues on the science behind the clock.

During his time at JILA, Martin learned important techniques that he continues to utilize in his job. Once physicist Ana Maria Rey (a NIST and JILA Fellow) came to Boulder, Martin found his research expanded as the Rey and Ye groups collaborated to study the quantum dynamics and many-body problems of optical lattice clocks. "The collaboration was very impactful for me," Martin added. "I also enjoyed the quality of mentorship within the JILA community, as I found I had a chain of mentors, not just my PI. I think that's one of the things that makes JILA special: their awareness and dedication to training young scientists." From this community, Martin found support for his scientific interests in quantum science. When he graduated from JILA and became a postdoctoral researcher at the California Institute of Technology, he continued to utilize the skills he learned from his mentors and peers at JILA.

Mike Martin, Staff Scientist at Los Alamos National Laboratory

In 2015, Martin joined Sandia National Laboratories as a Harry S. Truman Fellow, then Senior Member of the Technical Staff. Three years later, he moved to Los Alamos National Laboratory, where he currently works as a staff scientist. "It's a broad role," Martin said about his job, "I lead cutting-edge research in neutral atom quantum information science." Working in the field of quantum science allows him to use many of the techniques he learned at JILA. In discussing his position, Martin emphasized how beneficial it was for him to work at a national laboratory. "The Lab supports an array of science, with great depth and breadth of expertise within one organization. Its worldwide reputation helps to establish collaborations," he added.

The National Labs may not be the first thought for many graduating physics students, and Martin thinks he knows one reason why. "I wasn't aware of the type of research career one can have at a National Lab. During my Ph.D., I felt that there were two distinct paths: fundamental research, located mainly in the university setting, and applied science and engineering, which seemed to be mainly driven by industry. However, I found working at a national lab allows me to do a bit of both. The same could be said for my work at JILA," he said. While Los Alamos National Laboratory is a large institution, with thousands of employees, Martin highlighted that it was easy to choose your own path. "You can easily move within a national lab, from engineering-style projects to more fundamental research-focused projects. It's a great place to continue to reinvent yourself over the course of a career, all within the same institution.

Like JILA, Los Alamos National Laboratory contains a high volume of PhDs, which is important to a scientist like Martin. "Both JILA and Los Alamos have such a high depth of knowledge," he added. "This allows us to tackle scientific challenges you wouldn't tackle anywhere else."

# NEWS AND AWARDS

JILA's CUbit Quantum Initative helped create a partnership with the government of Finland as part of a state-wide collaboration between the two locations, offering a quantum-workshop where individuals could discuss the latest technological updates. This included speakers from Atom Computing, ColdQuanta, IQM, Bluefors, and Vescent Photonics.

JILA has been awarded federal funding as part of the $1.5 trillion omnibus bill. The CU Federal Relations team worked with senators Hickenlooper and Bennet to secure $950,000 in funding for JILA through the omnibus bill to give its labs a refresh.According to JILA Chief of Operations Beth Kroger, the funding will pay for much-needed research equipment in the JILA instrument and electronics shops, as well as equipment for CU Boulder's JILA W. M. Keck Metrology and Clean Room Core Facility, which serves the campus and provides important research capabilities.

JILA's W. M. Keck Lab has been selected to receive a CU Green Labs Program Award for the lab's efforts for shared research resources. The annual CU Green Labs Awards Program started in 2015 to reward departments that work to make the campus' eco-sustainability possible. Awardees exemplify CU's continuing efforts to become an eco-sustainable institution.

JILA celebrated World Quantum Day on April 14th, 2022. With around 75% of JILA Fellows researching quantum phenomena, it's no surprise that this institute is a world leader in this field. “Quantum research enables so many applications, varying from new generations of computers, secure communications, to ultraprecise clocks and sensors,” explained JILA Fellow Shuo Sun.

On April 28th, JILA celebrated the dedication of the Debbie Jin Community Rooms, named after reknowned physicist Debbie Jin. JILA Chair Konrad Lehnert and Associate Chair John Bohn spoke at the dedication, reminding JILAns that these rooms are designed for fostering community and encouraging creativity during research.

## Awards

JILA Fellow Heather Lewandowski has been honored in the 2022 President's Teaching Scholars Program (PTSP), which recognizes CU faculty who skillfully integrate teaching and research at an exceptional level.
The title of President's Teaching Scholar recognizes excellence in, and commitment to, learning, and teaching, as well as active, substantial contributions to scholarly work. CU's President Saliman solicits annual nominations of faculty across the four campuses for the designation, which is a lifetime appointment.

JILA and NIST Fellow Ana Maria Rey is to be inducted into the Colombian Academy of Exact, Physical and Natural Sciences (Academia Colombiana de Ciencias Exactas, Fisicas y Naturales). Rey, is a Columbian-American physicist at the University of Colorado, Boulder who "studies the scientific interface between atomic, molecular and optical physics, condensed matter physics and quantum information science."

Above: JILA Associate Chair John Bohn speaks at the dedication of the Debbie Jin Rooms
Image Credit Kenna Castleberry

Below: J. Curtis Beimborn II, Director of the JILA W. M. Keck Lab, receives the sustainability award for the lab.
Image Credit: University of Colorado Boulder

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.

To learn more visit:
jila.colorado.edu