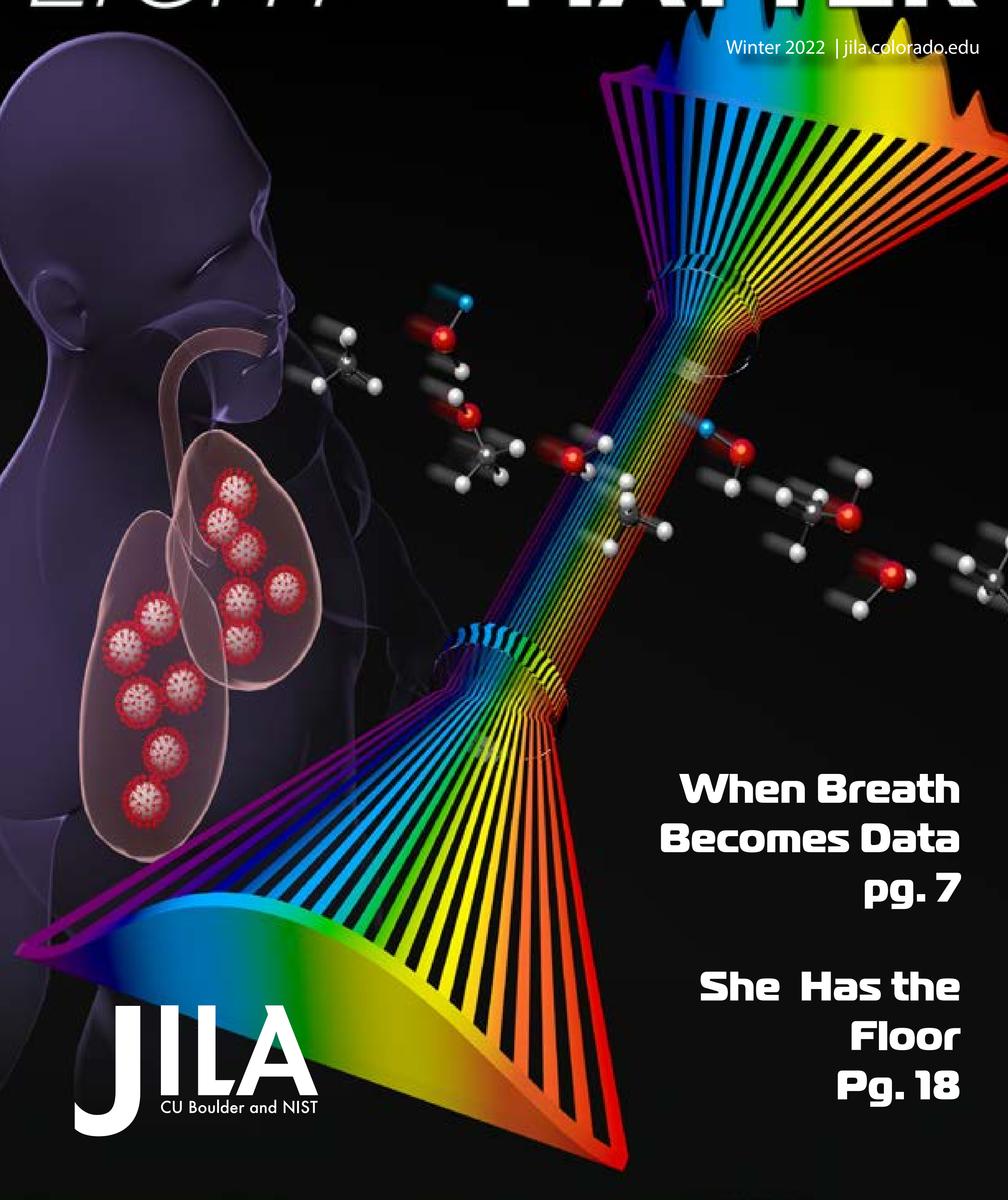
LIGHT + MATTER

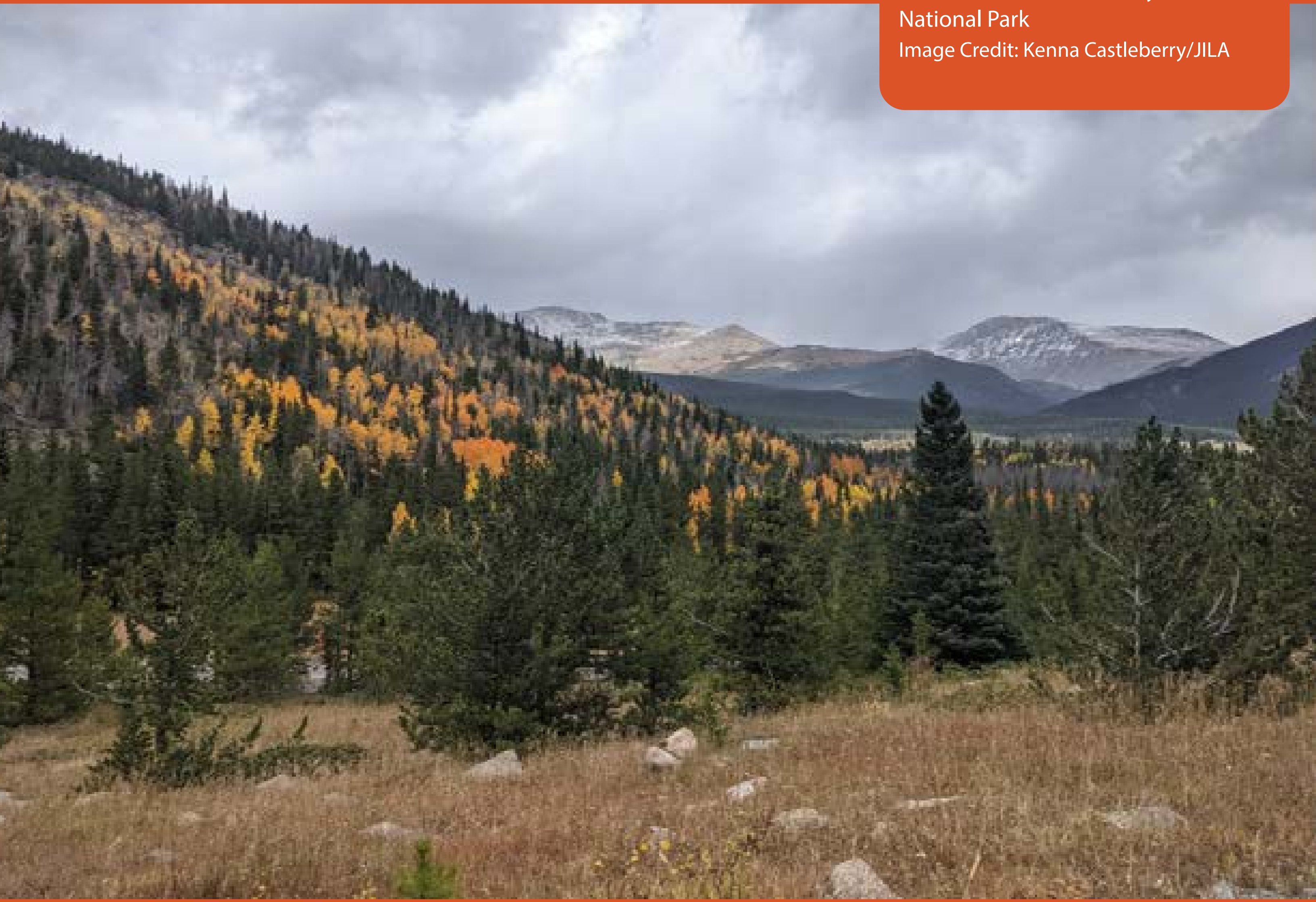
Winter 2022 | jila.colorado.edu



When Breath Becomes Data
pg. 7

She Has the Floor
Pg. 18

JILA
CU Boulder and NIST



2021 Fall colors in Rocky Mountain National Park
Image Credit: Kenna Castleberry/JILA

JILA Light & Matter is published quarterly by the Scientific Communications 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

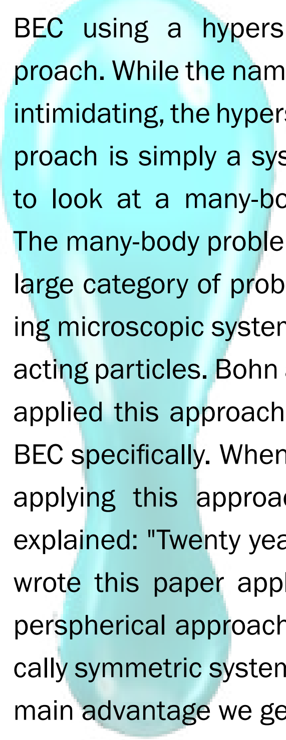
Please check out this issue of JILA Light & Matter online at
https://jila.colorado.edu/publications/jila-light-matter-quarterly

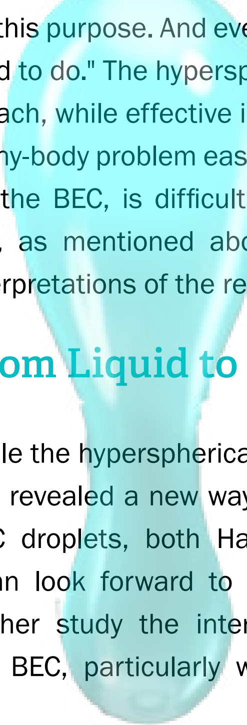
Steven Burrows, Project Manager, Artwork
Kristin Conrad, Design & Production
Kenna Castleberry, Science Writing, Design
Gwen Dickinson, Editor
Guest Author: Daniel Strain, Science Writer for CU Office of Strategic Relations and Communications

Research Highlights

Feature Articles

From Liquid to a Gas





The Bose-Einstein Condensate (BEC) has been studied for decades, ever since its prediction by scientists Satyandra Nath Bose and Albert Einstein nearly 100 years ago. The BEC is a gas of atoms cooled to almost absolute zero. At low enough temperatures, quantum mechanics allows the locations of the atoms in the BEC to be uncertain to the extent that they can’t be located individually in the gas. The BEC has a special history with JILA, as it was at JILA that the first gaseous condensate was produced in 1995 by JILA Fellows Eric Cornell (NIST) and Carl Wieman (University of Colorado Boulder). The original BEC was a gas of rubidium atoms, but using other atoms, such as dysprosium, a BEC can also be produced that will have dipolar interactions. Unlike a normal BEC, the atoms in a dipolar BEC have two opposing poles, similar to the two ends of a magnet. This dipolar BEC has been shown to create self-binding droplets, which cohere even in the absence of an electric potential to hold them together. The non-polar BEC does not create these droplets. The droplets are of interest to physicists who have researched ways to describe the droplet’s energetic excitations.

Since 2005, research on dipolar BEC has continued, using different theories to describe the droplet’s interactions. In a paper recently submitted to *Physical Review A,* first author, and graduate student, Eli Halperin and JILA fellow John Bohn theorize a way to study the BEC using a hyperspherical approach. While the name may sound intimidating, the hyperspherical approach is simply a systematic way to look at a many-body problem. The many-body problem refers to a large category of problems regarding microscopic systems with interacting particles. Bohn and Halperin applied this approach to a dipolar BEC specifically. When speaking of applying this approach, Halperin explained: "Twenty years ago, John wrote this paper applying the hyperspherical approach to a spherically symmetric system...I think the main advantage we get here is this nice linear way of looking at a many-body problem, without too much loss of accuracy." This approach could be used to help researchers describe the energies and wavefunctions of the BEC droplets using relatively straightforward quantum mechanics rather than more sophisticated quantum field theories.

As a theoretical physicist, Bohn was particularly interested in finding ways to describe interactions of the BEC. According to Bohn: "The problem is, whatever one atom is doing affects what all the other atoms are doing. So how do you keep track of them all? The way people normally solve this is to take a representative atom and follow it as it moves around in the background of other atoms that are, basically, exactly like this atom. Our approach with hyperspherical coordinates is to say, ‘There are a lot of atoms there, let's treat them all at once, as opposed to individually.’ So, we have a coordinate, the hyperradius, which is sort of the size of the whole droplet. It accounts for all atoms at the same time, leaves behind this independent particle picture, and tries to look at things in a collective way.” Bohn was not the first to use this approach. "We didn't invent this. Hyperspherical coordinates have been around since the 1930s. They're used all the time in chemistry and nuclear physics," explained Bohn. "And there's a vast literature out there that we basically stole to put to use for this purpose. And even then, it's hard to do." The hyperspherical approach, while effective in making a many-body problem easier to study for the BEC, is difficult to set up, but, as mentioned above, allows interpretations of the results.

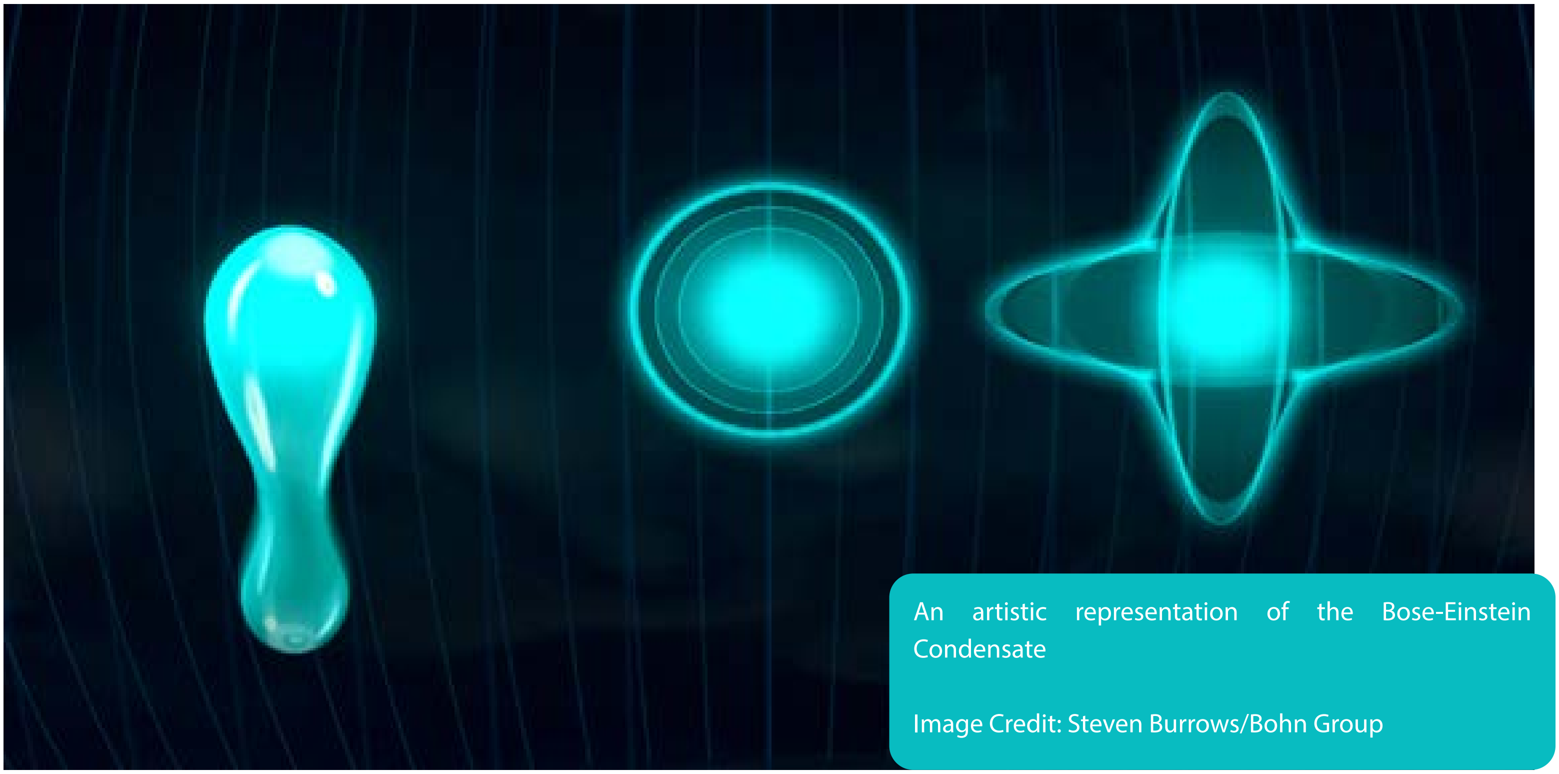
From Liquid to a Gas

While the hyperspherical approach has revealed a new way to look at BEC droplets, both Halperin and Bohn look forward to using it to further study the interactions of the BEC, particularly with its excitations. In clarifying research around the BEC, Bohn stated: "normally in Bose-Einstein condensation, you have a trap where you hold the atoms in place with magnetic fields or optical fields. An experiment done in 2016 showed that if you tuned things just right, the dipoles in the gas align head to tail, which makes them attract each other. It turns out, there's a kind of quantum mechanical fluctuation effect that keeps them from crashing in on themselves. Under the right circumstances, you could turn off the trap, and the thing holds together in the middle of the experiment as a self-bound droplet, like a liquid droplet would. There's a transition that happens where this liquid droplet can transform into a gas. And what we're applying this method to is the transition between liquid to gas." Looking at the transition, both Halperin and Bohn hope to find more about the excitations of the BEC as it changes shape when oscillating between a liquid like droplet and gas.

Halperin explained that it was important to look at the energy states for both the droplet and the the BEC as they had similar energies but different excitations. "We think it might be possible to find a regime where you could get the gas to naturally oscillate between the droplet state and the gas state," Halperin said. "We're interested to see if you can first use the hyper-spherical approach and see this oscillation between the liquid and gas states. And then to test this also in a quantum field theory." Being able to describe the oscillation from liquid to gas using this approach would allow a better understanding of the BEC, specifically at a quantum level. According to Bohn: "You think of liquid and gas as an either-or situation. But in quantum mechanics, why can't it be both?" As the work continues, it will be interesting to see how the quantum interactions within the BEC build on the field of quantum physics.

Eli J. Halperin, and John L. Bohn. "Hyperspherical approach to dipolar droplets beyond the mean-field limit." Physical Review A 104(3): 033324 (2021).

Written by Kenna Castleberry



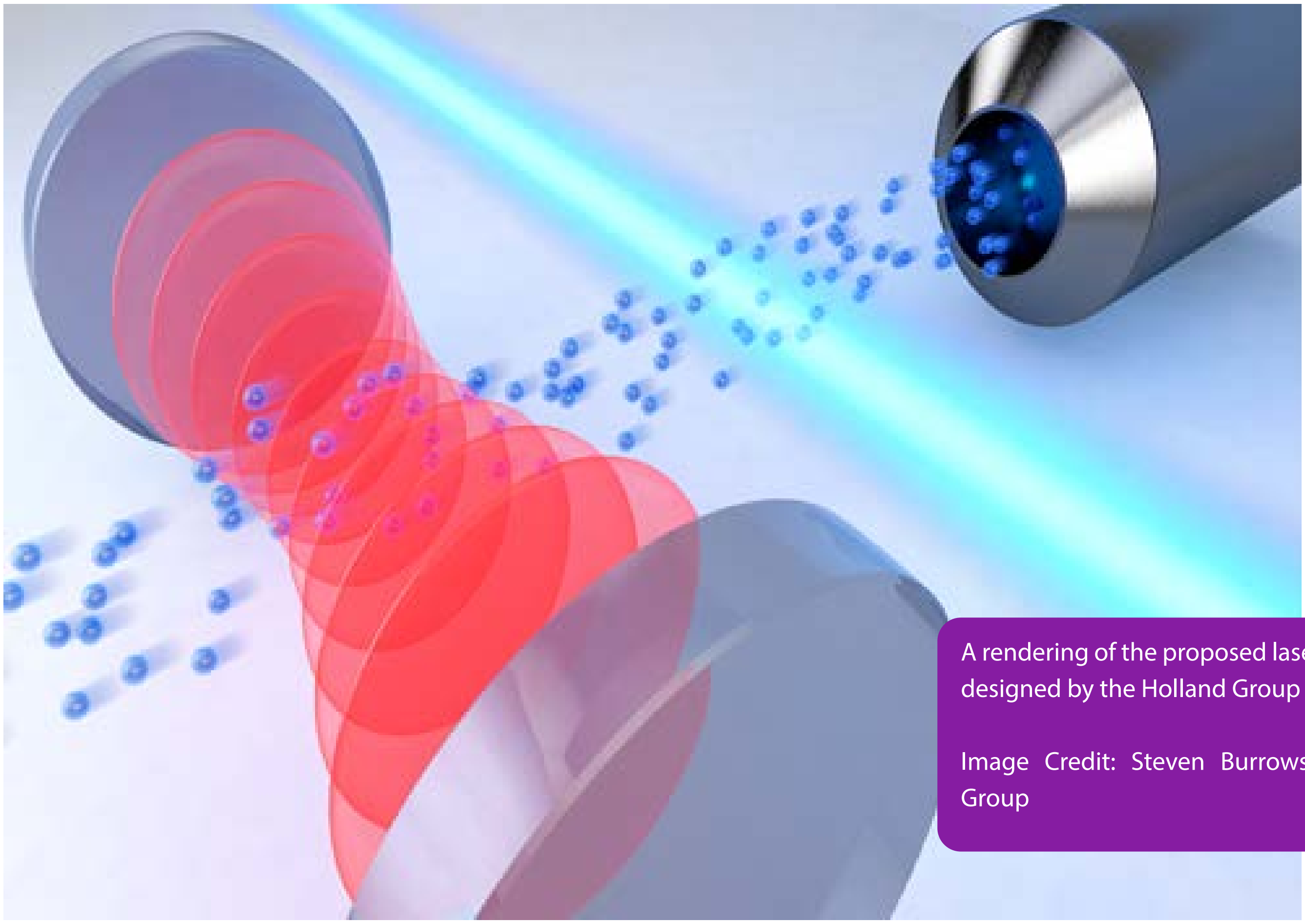
An artistic representation of the Bose-Einstein Condensate

Image Credit: Steven Burrows/Bohn Group

Laser Cavities and the Quest for the Holy Grail

Atomic clocks have been heavily studied by physicists for decades. The way these clocks work is by having atoms, such as rubidium or cesium, that are "ticking" (that is, oscillating) between two quantum states. As such, atomic clocks are extremely precise, but can be fragile to shaking or other perturbations, like temperature fluctuations. Additionally, these clocks need a special laser to probe the clock. Both factors can make atomic clocks imprecise, difficult to study, and expensive to make.

A team of physicists are proposing a new type of laser that could change the future path of atomic clocks. In this team, JILA Fellow Murray Holland and Research Associate Simon Jäger theorized a new type of laser system in a paper recently published in *Physical Review Letters.* The designed laser system utilizes a dense beam of excited atoms that cooperatively lose their energetic excitations by collective emission into an optical cavity. The design put forth by Holland and Jäger relies on excitation of the atoms outside of the laser cavity, making the equipment more robust and less sensitive to cavity shaking. In studying their new laser design, the Holland group collaborated with the Nicholson Laboratory at the Center for Quantum Technologies in Singapore. The team hoped to use this stronger and more robust laser to develop an active atomic clock. Holland explained that “an active atomic clock produces its own stable light. And that is something of a Holy Grail for us theoretical physicists. This would combine light and matter into a single



A rendering of the proposed laser system designed by the Holland Group

Image Credit: Steven Burrows/Holland Group device, making an integrated coherent source, which is something that could eventually replace conventional atomic clocks.” The impact of making better atomic clocks is of widespread benefit to society as it may lead to new discoveries in quantum physics, and new applications of quantum information science for industry and technology.

This new, more robust laser system would also be able to be implemented in other fields. In their paper, the team suggested that this system could be used to improve space technology, geodesy, and astrophysical measurements. With this more robust laser system, more accurate measurements could be made of some of our Earth’s properties, such as its composition and magnetic fields, as well as properties of other planets in our solar system.

A New Method for Entanglement

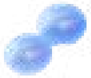
In designing this new laser system, the researchers found that their laser system could have two regimes, one of superradiance and one of subradiance. “Superradiant light is made by basically taking a lot of atoms, and putting them inside an optical cavity. And inside the cavity they talk to each other,” Holland said. “And these atoms can synchronize together and generate this extremely pure light. The other side of the coin is subradiance. It's the same set up consisting of atoms placed inside an optical cavity, but instead of all emitting light in phase together, they sort of conspire against each other. And that destructive lack of reinforcement causes very little light to come out, but it also causes the atoms to become correlated in a quantum entangled way.” Jäger and Holland explained that this laser system has a critical threshold for subradiance, and that close to this threshold, their laser actually produces a huge number of entangled atoms. Their research on subradiance was published in a second paper in *Physical Review Letters.*

Pushing further, the team emphasized that quantum entanglement emerges in this laser system due to the interplay between driving, dissipation, and long-range interactions. As the laser system contained many different controls and parameters, finding the right ones were vital for their research. “One of these parameters is the beam flux—how many atoms there are inside the laser system,” commented Holland. “Lasers have a sort of critical threshold. So, if you crank up the parameters, eventually there’s a sort of phase transition to producing laser light, and it happens quite suddenly.” By varying the parameters, the team was excited to find a controllable boundary that separated the production of ultra-stable light and the generation of vast quantities of entangled atoms.

Finding a new method for generating quantum entanglement would not only be valuable to processes like quantum communications, but could help with further study of condensed matter and quantum information science. The research team, including Holland and Jäger, were extremely excited to see experimental groups being interested in both the superradiant and subradiant regimes of this cavity setup. “There are multiple groups around the world that are very actively putting the numbers together and trying to think about whether a real engineering model could be developed from this theory,” Holland stated. Jäger, for his part, added: “It is, I think, a very nice feeling when people are actually so interested in a theory that one creates."

Haonan Liu, Simon B. Jäger, Xianquan Yu, Steven Touzard, Athreya Shankar, Murray J. Holland, and Travis L. Nicholson. “Rugged mHz-Linewidth Superradiant Laser Driven by a Hot Atomic Beam.” Physical Review Letters 125(25): 253602 (2020).

Written by Kenna Castleberry



From Plane Propellers to Helicopter Rotors

For laser science, one major goal is to achieve full control over the spatial, temporal, and polarization properties of light, and to learn how to precisely manipulate these properties. One property of light, called the Orbital Angular Momentum (OAM), depends on the spatial distribution of the phase (or crests) of a doughnut-shaped light beam. More recently, a new variant of OAM was discovered—called the spatial-temporal OAM (i.e., ST-OAM)—with much more elusive properties, since the phase/crests of light evolve both temporally and spatially. A collaboration led by senior scientist Dr. Chen-Ting Liao, working with graduate student Guan Gui and JILA Fellows Margaret Murnane and Henry Kapteyn, explored how such beams change after propagating through nonlinear crystals that can change their color. “Over the past few years, we have been studying pure spatial OAM and its variations such as spin-orbit coupled OAM beams [1] and time-varying OAM beams (also called self-torqued beams).”Dr. Chen-Ting Liao stated. The team’s new results, published in *Nature Photonics* in 2021, uncovered the conservation laws underpinning how such an ST-OAM beam undergoes frequency doubling in a process known as Second Harmonic Generation (SHG).

Planes and Helicopters

SHG is considered one of the most fundamental non-linear processes, wherein two photons with the same energy interact with a nonlinear material and combine together. This generates a new photon that has double the energy of the original two photons. The team first used a pulse shaper to form ST-OAM light in the infrared region of the spectrum, and then focused it into a nonlinear crystal. Then they carefully characterized the output blue SHG light in space and time, to see how the spatial and temporal shape and phase/crests evolved over time.

Liao explained the differences in shapes between standard spatial OAM and spatio-temporal OAM light sources. Spatial OAM moves like a plane propeller, where its angular momentum is parallel to the propagation of the light. In contrast, the ST-OAM moves like a helicopter rotor, where its angular momentum moves perpendicular to the direction of propagation of the light. Because of the differences between these two light sources, their charges, and energies of the sources, are different. In studying ST-OAM light using the SHG process, the team wanted to understand how the energy of the ST-OAM light flowed into the BBO (barium borate) crystals upon interaction with the crystals. To study this, Liao explained, the team needed to “experimentally extract...energy density flux of the spatial-temporal OAM beams in space and time to better understand what's going on in this process.” From their data, the team found that the changes in the phases/crests of the blue ST-OAM light had increased compared with the red light, essentially doubling the topological charge, which is the quantity used to quantify the complex OAM shapes and phase patterns. Using the analogy, the helicopter rotors spin twice as fast as the plane propeller. Thus, they uncovered the conservation of topological charge of ST-OAM during frequency doubling, since the charge of each red photon was combined. Other possible applications for using ST-OAM waves from other nonlight sources include acoustic waves and matter waves.

Representation of the transformation of OAM when interacting with BBO crystals
Image Credit: Steven Burrows/The Murnane and Kapteyn Groups

The next steps for using ST-OAM waves seem pretty straightforward. “We're trying to see if there are any potential applications for spatial-temporal OAM, because over the past three decades, the pure spatial-OAM has been used for optical tweezers, super-resolution imaging, and telecommunications,” Liao said. “We can also use spatial-OAM for quantum entanglement and information, as well as defect inspection in the semiconductor industry, as we recently proposed [1].” While spatial-OAM is used for many processes, spatial-temporal OAM's applications are not so clear. With time, perhaps ST-OAM will have as many applications as spatial-OAM.

References

[1] K. Dorney, L. Rego, N. Brooks, J. San Román, C.-T. Liao, J. Ellis, D. Zusin, C. Gentry, Q. Nguyen, J. Shaw, A. Picón, L. Plaja, H. Kapteyn, M. Murnane, and C. Hernández-García, “Controlling the polarization, divergence and vortex charge of attosecond high-harmonic beams via simultaneous spin-orbit momentum conservation,” Nature Photonics, 13, 123 (2019).

[2] B. Wang, M. Tanksalvala, Z. Zhang, Y. Esashi, N. Jenkins, H. Kapteyn, M. Murnane, and C.-T. Liao*. “Coherent Fourier scatterometry using orbital angular momentum beams for defect detection.” Optics Express 29, 3342 (2021). DOI: https://doi.org/10.1364/OE.414584

Guan Gui., Nathan J. Brooks, Margaret Murnane., Henry Kapteyn, and Chen-Ting Liao. "Second-harmonic generation and the conservation of spatiotemporal orbital angular momentum of light." Nature Photonics. 15(1): 608–613 (2021).

Written by Kenna Castleberry

When Breath Becomes Data

There are many ways to diagnose health conditions. One of the most common methods is blood testing. This sort of test can look for hundreds of different kinds of molecules in the body to determine if an individual has any diseases or underlying conditions. Not everyone is a fan of needles, however, which makes blood tests a big deal for some people. Another method of diagnosis is breath analysis. In this process, an individual's breath is measured for different molecules as indicators of certain health conditions. Breath analysis has been fast progressing in recent years and is continuing to gain more and more research interest. It is, however, experimentally challenging due to the extremely low concentrations of molecules present in each breath, limited number of detectable molecular species, and the long data-analysis time required. Now, a JILA-based collaboration between the labs of NIST Fellows Jun Ye and David Nesbitt has resulted in a more robust and precise breath-testing apparatus. In combining a special type of laser with a mirrored cavity, the team of researchers was able to precisely measure four molecules in human breath at unprecedented sensitivity levels, with the promise of measuring many more types of molecules. The team published their findings in the *Proceedings of the National Academy of Sciences (PNAS).*

Mirrors and Lasers

In order to make an effective breath-testing apparatus, the team of researchers needed a way to "code" the different molecules found in breath into usable data. They did this through a "fingerprinting" process. Using a laser known as a frequency comb, the team could shine over 10,000 different colors of infrared light at the breath sample. According to first author Qizhong Liang, the variation in color was important: "Molecules absorb infrared light in a selective manner. They give different absorption strengths to light at different optical frequencies. How the absorption pattern looks is governed by the molecular rotational and vibrational properties." Since each molecule in the breath absorbed light at a different frequency, this "fingerprinted" each molecule, associating it with a unique absorption pattern, making it easier for the researchers to measure and analyze the data. Liang added that "measuring the optical absorption signals over a broad spectral range, one can simultaneously determine what molecular species are present." As many other devices take tens of minutes, or could only test one molecule species at a time, this new apparatus increased the number of analyzed molecules in breath-testing significantly by analyzing breath in real-time—a reduction in analysis time and presumably, cost.

The implementation of the frequency comb was essential for the apparatus to work. The colors within this special type of laser are evenly spaced in frequency, making them easier to fine-tune than other lasers. In order for the frequency comb to work properly, it has to be coupled to the mirrored cavity by matching the cavity's resonance—a specific frequency that corresponds to the longitudinal mode of that cavity. Depending on the size and shape of the cavity, the resonance may vary. Matching the cavity resonance frequency to the laser frequency helped the team to better measure molecules. "By controlling and matching the light frequency to a specific cavity resonance frequency, one can measure ultrasensitive molecular absorption signals over a broad frequency range in a simultaneous manner," Liang explained. "In our experiment, we can measure absorption signals at 15,000 isolated optical frequencies in just three minutes. This allows us to detect multiple molecular species in a highly time-efficient manner." The increased efficiency made the apparatus capable of measuring and analyzing data in almost real-time.

In building their effective apparatus, the researchers realized that some molecules in breath had very weak light absorption. To boost this absorption, the team built a cavity with a pair of high-reflectivity mirrors. The mirrors enhanced the interaction length between the laser light and breath molecules by a factor of several thousand in order to make the absorption stronger in just one breath. The mirrored cavity increased the sensitivity of the apparatus, furthering its precision.

Testing the Breath: Bananas and...Booze?

After the apparatus was constructed, the researchers needed to test its effectiveness. They decided to look at methanol as a target molecule. In order to see possible changes in methanol levels, they had a test subject consume foods and drinks in an effort to change the methanol levels in their breath. "We actually started with alcohol, because there are some literature reviews in the past that suggest some change in the methanol levels of breath," Liang grinned. "This sounds like a fun experiment because your test subject gets the opportunity to drink alcohol. We tried brandy, whisky, and soju, a South Korean wine. It turns out none of these alcohols actually gave some obvious change in molecular concentrations." Though drinking alcohol in the name of science would have been a rather whimsical endeavor, the team ultimately had to abandon the idea.

Instead, they turned to fruit, and found that collecting data in 15-minute intervals while their test subject ate ripe bananas resulted in a gradual increase of methanol concentration in the breath. Liang found the entire process to be: "... very impressive. We could monitor several other molecules simultaneously, like methane and partially-deuterated water. We could confirm their concentrations did not change over the time after the banana consumption."

COVID-19 Ready

After seeing success in their apparatus, the team of researchers is shifting their focus towards diagnosing COVID-19 in people. According to postdoctoral researcher Jutta Toscano: "We are currently conducting a campus-wide study to understand how much the molecules present in people's breath can tell us about the state of their health, including the presence of various conditions that could be affecting them, such as COVID-19, diabetes, and asthma, among others." Having a less invasive method to diagnose COVI9-19 will not only make it easier to contain the virus, but can also be a cheaper and faster option for the government in the long run. Toscano found that: "Collaborating and learning from people in other fields of research (from engineering to physiology) has been a very exciting part of this project. Building bridges across disciplines and sharing expertise to reach a common scientific goal is both fulfilling and formative." Such collaborations as this can result in timely and beneficial real-world applications, like the breath-analyzer apparatus, which may change the way COVID-19 infections are analyzed and treated.

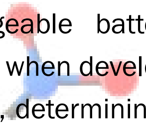
Qizhong Liang, Ya-Chu Chan, Brian P. Changala, David Nesbitt, Jun Ye, Jutta Toscano. "Ultrasensitive multispecies spectroscopic breath analysis for real-time health monitoring and diagnostics." Proceedings of the National Academy of Sciences, 118 (40) e2105063118 (2021).

Written by Kenna Castleberry

Opposite: A depiction of the frequency comb used in the breath-testing apparatus
Image Credit: Steven Burrows/Ye and Nesbitt Laboratories

Seeing with the "Nano" Eye

Understanding the chemical and physical properties of surfaces at the molecular level has become increasingly relevant in the fields of medicine, semiconductors, rechargeable batteries, etc. For example, when developing new medications, determining the chemical properties of a pill's coating can help to better control how the pill is digested or dissolved. In semiconductors, precise atomic level control of interfaces determines performance of computer chips. And in batteries, capacity and lifetime is often limited by electrode surface degradation. These are just three examples of the many applications in which the understanding of surface coatings and molecular interactions are important.

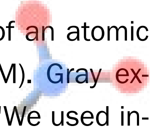


The imaging of molecular surfaces has long been a complicated process within the field of physics. The images are often fuzzy, with limited spatial resolution, and researchers may not be able to distinguish different types of molecules, let alone how the molecules interact with each other. But it is precisely this—molecular interactions—which control the function and performance of molecular materials and surfaces.

In a new paper published in Nano Letters, JILA Fellow Markus Raschke and graduate student Thomas Gray describe how they developed a way to image and visualize how surface molecules couple and interact with quantum precision. The team believes that their nanospectroscopy method could be used for molecular engineering to develop better molecular surfaces, with controlled properties for molecular electronic, photonic, or biomedical applications.

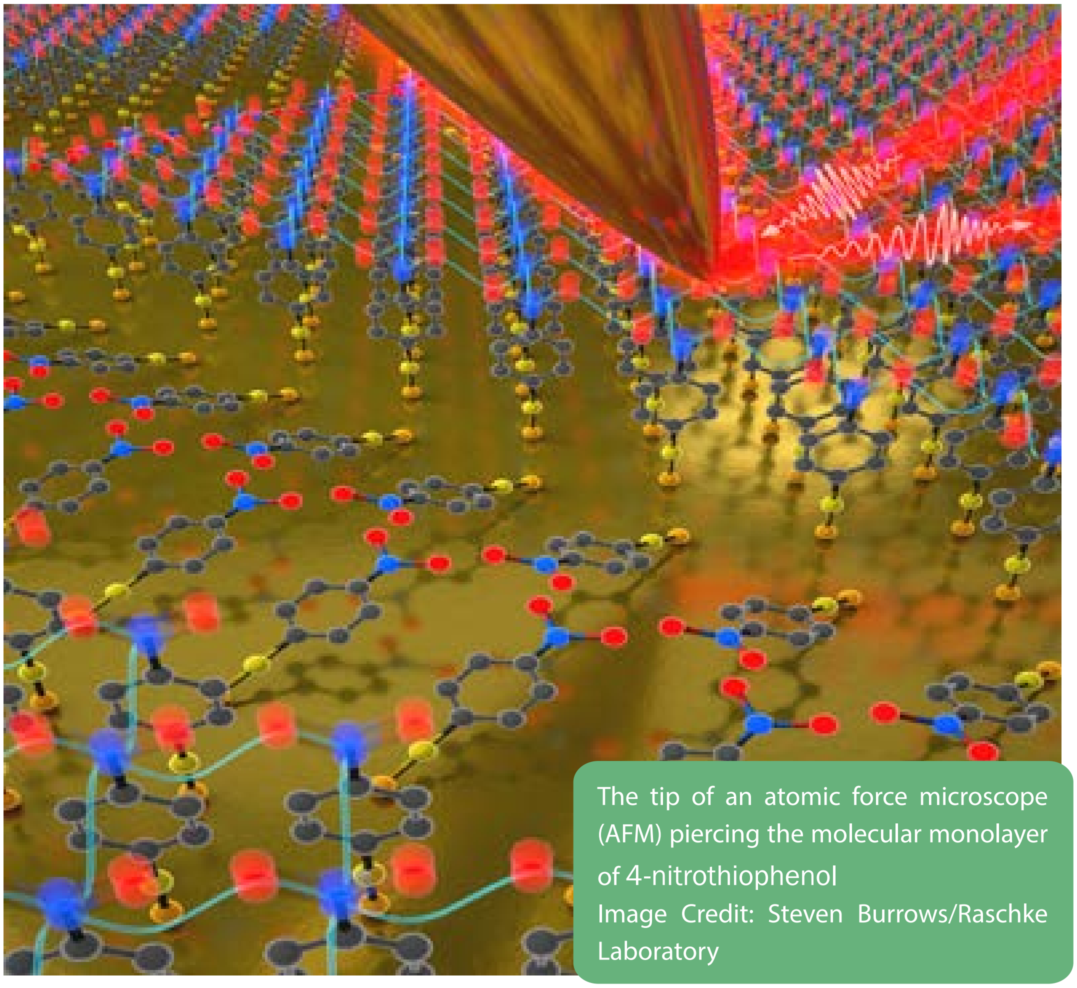
Imaging Monolayers with an Infrared Nano-Eye

In order to test their new nanospectroscopic imaging method, the researchers used a so called self-assembled monolayer of small organic molecules of 4-nitrothiophenol. The monolayer was then placed under the tip of an atomic force microscope (AFM). Gray explained the process-: "We used infrared light, which has a very long wavelength, limiting spatial resolution to the order of microns, or thousands of molecules across. The way we get the nanometer spatial resolution is using the extremely sharp tip of an atomic force microscope, which is only tens of molecules across. It acts as a lightning nod, just for light, and can focus it to the nanoscale. This allows us to image and perform spectroscopy on the nanoscale with sensitivity as high as just a few molecules." Gray emphasized that because of its low energy, the infrared light directly probes molecular structure, as it could indicate if the 4-nitrothiophenol molecules interacted or coupled with each other.



Molecular Interactions and Quantum Sensors

Principal investigator Raschke was excited about seeing these molecular interactions, and postulated that these interactions could be used for quantum sensing. In order to test their hypothesis of successful quantum sensing, the team looked at the coupling to determine the size of the surface domains. Gray categorized the type of coupling as "a vibrational exciton delocalized across many molecules." He added that: "When people hear the term exciton they think of electronic excitations. Our vibrational exciton is the conceptual analogue just for molecular vibrations." Using their new imaging systems, the team could see these vibrational excitons on their natural length scales extending



The tip of an atomic force microscope (AFM) piercing the molecular monolayer of 4-nitrothiophenol
Image Credit: Steven Burrows/Raschke Laboratory

localized infrared light of their imaging system improved their view of these excitons because "the tip itself already provides localization and spatial resolution down to a few tens of nanometers — that is already one ten-thousandth [the width of]of a human hair. The vibrational exciton quantum sensor provides another improvement of spatial resolution by a factor of ten into the true molecular scale. And with a sensitivity where we can distinguish if two, three, or four molecules would be interacting, meaning sharing their wavefunction, or colloquially, speaking to each other in a quantum sense." This new nanospectroscopic approach of vibrational exciton nanoscopy could be used to improve and engineer molecular materials from the from the start and better predict their properties.

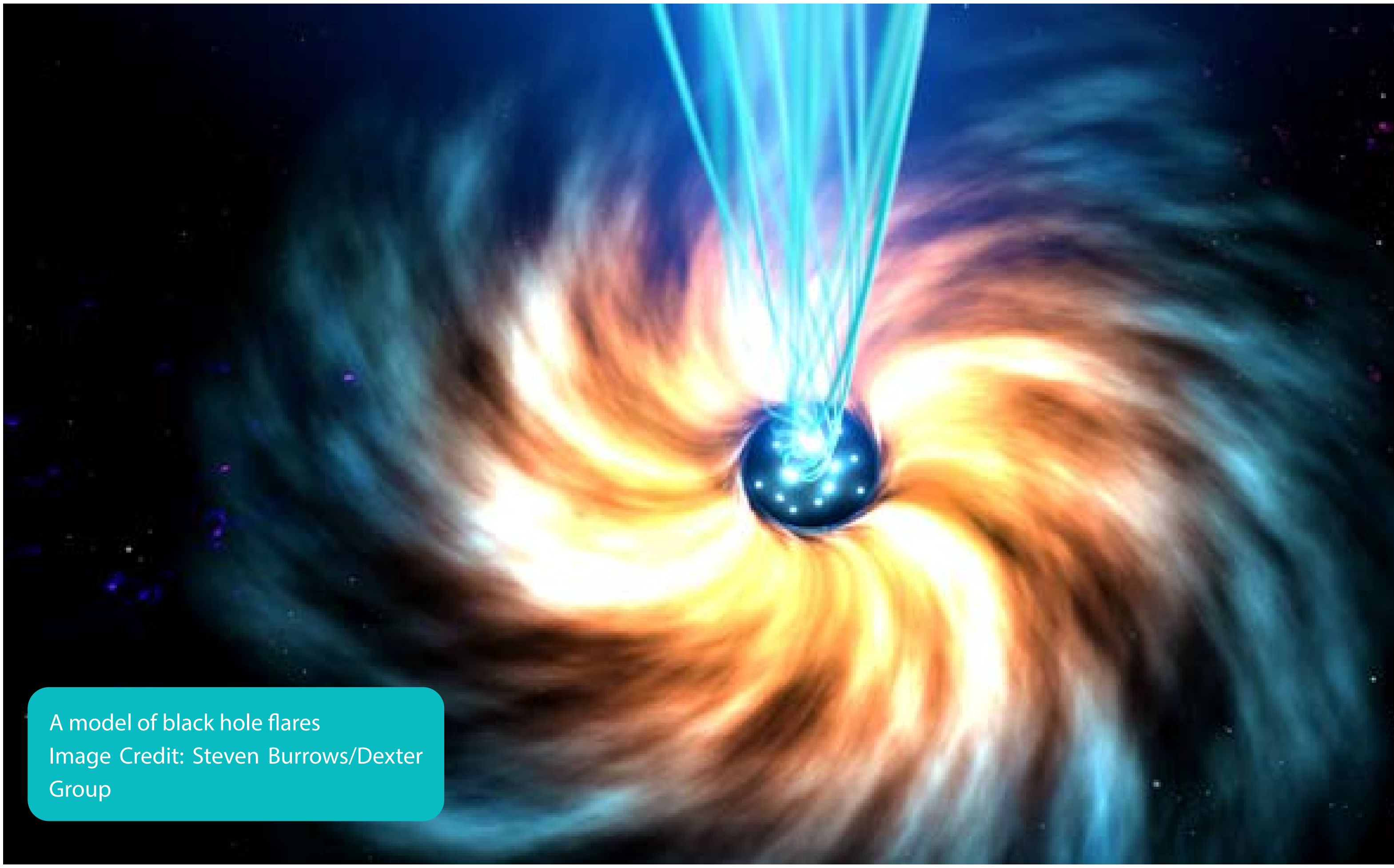
Should the vibrational excitons become a successful quantum sensor, this might have implications for quantum technology more generally. "Some people have theorized quantum state transfer for quantum information applications based on these vibrational excitons," Gray stated. "And the reason it would be nice is because a vibrational exciton is potentially stable at room temperature and you wouldn't have to go down to these low temperatures typically required for quantum sensing or computing." Taking quantum technology out of the cold temperatures usually required for most quantum devices would make them more affordable and more widely accessible.

Having found success with their new imaging system, by taking advantage of vibrational excitons as a super-resolution imaging quantum sensor, Gray and Raschke are expanding their research focus. "We are now extending this work from molecular monolayers to molecular crystals used, for example, in molecular electronics or in light-emitting diodes," said Gray. While this new imaging system is helping to improve quantum technology it is also expanding knowledge about the interactions of molecules at the quantum level that will help in designing, improving, and controlling molecular materials in general.

Thomas P. Gray, Jun Nishida, Samuel C. Johnson, and Markus B Raschke. "2D Vibrational Exciton Nanoimaging of Domain Formation in Self-Assembled Monolayers." Nano Letters 21(13): 5754–5759 (2021).

Written by Kenna Castleberry

The Mystery of Black Hole Flares



A model of black hole flares
Image Credit: Steven Burrows/Dexter Group

In 2019, a team of researchers used an international network of radio telescopes—called the Event Horizon Telescope—to take the first photo of a supermassive black hole in the center of the elliptical galaxy Messier 87 (M87). On that team of researchers was JILA Fellow Jason Dexter. Since then, Dexter has been studying M87's black hole further using simulations, with code written by researchers at the University of Illinois. As described in a new paper published in the *Monthly Notices of the Royal Astronomical Society*, Dexter, and his team of graduate students and postdoctoral researchers, collaborated with researchers at the Los Alamos National Laboratory and the University of Illinois to create a new simulation studying the edge of a black hole.

The researchers specifically focused on the phenomenon of flaring that occurs around the black hole. Flares, also called jets, are outputs of hot gas. The source of these flares, and the explanations for their behavior are still unknown. These unanswered questions intrigued first author Philippe Z. Yao, who led this study as a CU Boulder undergraduate student. "I started talking to Jason Dexter about what we can do to help us better understand the processes around black holes. And since we also

see these very high-energy flares that come from M87, we do not know what processes really trigger them" said Yao. Dexter echoed this uncertainty about where the flares around the black hole occur: "The brightness changes can occur in about the same amount of time it would take for light to cross roughly the size of the event horizon of the black hole. So, it's possible that the flares happen close to the black hole." The event horizon is the term for the edge of the black hole. The telescope images that showed the flares were confusing to the researchers, as the flares could have been either close to the event horizon, or farther away, just flaring at a faster rate.

In order to better understand where these flares were occurring, the researchers created General Relativistic Magneto-Hydro-Dynamic (GRMHD) simulations, which naturally follow how gas flows along magnetic fields that thread through a black hole. The GRMHD simulations looked at accretion flow of the gas, where the gas spinning around the black hole slowly moves toward the black hole, and eventually falls in. Dexter explained this accretion flow in the simulation by describing the gas as: "an ionized fluid made of protons and electrons. The reason the gas falls into the black hole is that the charged particles conduct magnetic fields and the magnetic fields actually cause the gas to become unstable and turbulent. The turbulence causes collisions which knock the gas off of stable orbits around the black hole and cause it to fall in through the event horizon. And the magnetic fields also end up launching the jet that we see." In studying how the gas moves toward the event horizon of the black hole, the researchers hoped to find an explanation for the cause of the flares as well as their positions relative to the black hole.

Gas and Light

The simulation not only modeled the flow of this gas, but also how it interacted with light particles, called photons. According to Dexter, the gas cools by radiating light and gamma rays. "The gas heats up, and then we can track its cooling," Dexter said. "That puts us in a unique position, because all the mechanisms for how you might produce flares close to the black hole rely on how photons interact with matter. We're able to realize what we think is a physically realistic description of the gas and the photons near the black hole." The study of the photons in the gas shed new light (no pun intended) on more processes occurring at the edge of a black hole. This simulation is also important because it builds on previous black hole research. "Previous work on the flares have made simplifying assumptions about the low-energy photons near the black hole," said postdoctoral researcher Alexander Chen, who had worked on flare models before this paper. "One of the results of this work is that we have a much better understanding of how these low-energy photons are distributed." The team is planning to continue building on these simulations to find ways to answer questions about the black hole flares. "Our calculations provide new background conditions for calculations of the flaring process itself," Dexter stated. "What we find is that how the light is moving inside the jet is not at all uniform, with photons moving mostly inwards close to the black hole and away from it as well." Chen, for his part, is excited to continue the research: "We can now take this result and compute more accurately the gamma-ray flares, and compare with data. This is what we're going to do next."

Philippe Z. Yao, Jason Dexter., Alexander Y. Chen, Benjamin R. Ryan, George N. Wong. "Radiation GRMHD simulations of M87: funnel properties and prospects for gap acceleration," Monthly Notices of the Royal Astronomical Society, 507(4): 4864–4878 (2021).

Written by Kenna Castleberry

Gravitational ‘Kick’ May Explain the Strange Shape at the Center of Andromeda

When two galaxies collide, the supermassive black holes at their cores release a devastating gravitational “kick,” similar to the recoil from a shotgun. New research led by CU Boulder suggests that this kick may be so powerful it can knock millions of stars into wonky orbits.

The research, published Oct. 29 in *The Astrophysical Journal Letters,* helps solve a decades-old mystery surrounding a strangely-shaped cluster of stars at the heart of the Andromeda Galaxy. It might also help researchers better understand the process of how galaxies grow by feeding on each other.

“When scientists first looked at Andromeda, they were expecting to see a supermassive black hole surrounded by a relatively symmetric cluster of stars,” said Ann-Marie Madigan, a fellow of JILA, a joint research institute between CU Boulder and the National Institute of Standards and Technology (NIST). “Instead, they found this huge, elongated mass.”

Now, she and her colleagues think they have an explanation.

In the 1970s, scientists launched balloons high into Earth’s atmosphere to take a close look in ultraviolet light at Andromeda, the galaxy nearest to the Milky Way. The Hubble Space Telescope followed up on those initial observations in the 1990s and delivered a surprising finding: Like our own galaxy, Andromeda is shaped like a giant spiral. But the area rich in stars near that spiral’s center doesn’t look like it should—the orbits of these stars take on an odd, ovalish shape like someone stretched out a wad of Silly Putty.

And no one knew why, said Madigan, also an assistant professor of astrophysics. Scientists call the pattern an “eccentric nuclear disk.”

In the new study, the team used computer simulations to track what happens when two supermassive black holes go crashing together —Andromeda likely formed during a similar merger billions of years ago. Based on the team’s calculations, the force generated by such a merger could bend and pull the orbits of stars near a galactic center, creating that telltale elongated pattern.

“When galaxies merge, their supermassive black holes are going to come together and eventually become a single black hole,” said Tatsuya Akiba, lead author of the study and a graduate student in astrophysics. “We wanted to know: What are the consequences of that?”

Bending Space and Time

He added that the team’s findings help to reveal some of the forces that may be driving the diversity of the estimated two trillion galaxies in the universe today—some of which look a lot like the spiral-shaped Milky Way, while others look more like footballs or irregular blobs.

Mergers may play an important role in shaping these masses of stars: When galaxies collide, Akiba said, the black holes at the centers may begin to spin around each other, moving faster and faster until they eventually slam together. In the process, they release huge pulses of “gravitational waves,” or literal ripples in the fabric of space and time. “Those gravitational

Graphic showing stars orbiting supermassive black holes
Image Credit: Steven Burrows/Madigan Group

waves will carry momentum away from the remaining black hole, and you get a recoil, like the recoil of a gun," Akiba said.

He and Madigan wanted to know what such a recoil could do to the stars within 1 parsec, or roughly 19 trillion miles, of a galaxy's center. Andromeda, which contains about twice the number of stars as the Milky Way, stretches 67,000 parsecs from end to end.

It gets pretty wild.

Galactic Recoil

The duo used computers to build models of fake galactic centers containing hundreds of stars—then kicked the central black hole to simulate the recoil from gravitational waves.

Madigan explained the gravitational waves produced by this kind of disastrous collision won't affect the stars in a galaxy directly. But the recoil will throw the remaining supermassive black hole back through space—at speeds that can reach millions of miles per hour, not bad for a body with a mass millions or billions of times greater than that of Earth's sun.

"If you're a supermassive black hole, and you start moving at thousands of kilometers per second, you can actually escape the galaxy you're living in," Madigan said.

When black holes don't escape, however, the team discovered they may pull on the orbits of the stars right around them, causing those orbits to stretch out. The result winds up looking a lot like the shape scientists see at the center of Andromeda.

Madigan and Akiba said they want to grow their simulations so they can directly compare their computer results to that real-life galaxy core—which contains many times more stars. They noted their findings might also help scientists to understand the unusual happenings around other objects in the universe, such as planets orbiting mysterious bodies called neutron stars.

"This idea—if you're in orbit around a central object and that object suddenly flies off—can be scaled down to examine lots of different systems," Madigan said.

Tatsuya Akiba, Ann-Marie Madigan. "On the Formation of an Eccentric Nuclear Disk following the Gravitational Recoil Kick of a Supermassive Black Hole." The Astrophysical Journal Letters. 921(1) L12 (2021).

Written by Daniel Strain, Science Writer for CU Boulder Strategic Relations and Communications

HELP WANTED: HOW TO BUILD A PREPARED AND DIVERSE QUANTUM WORKFORCE

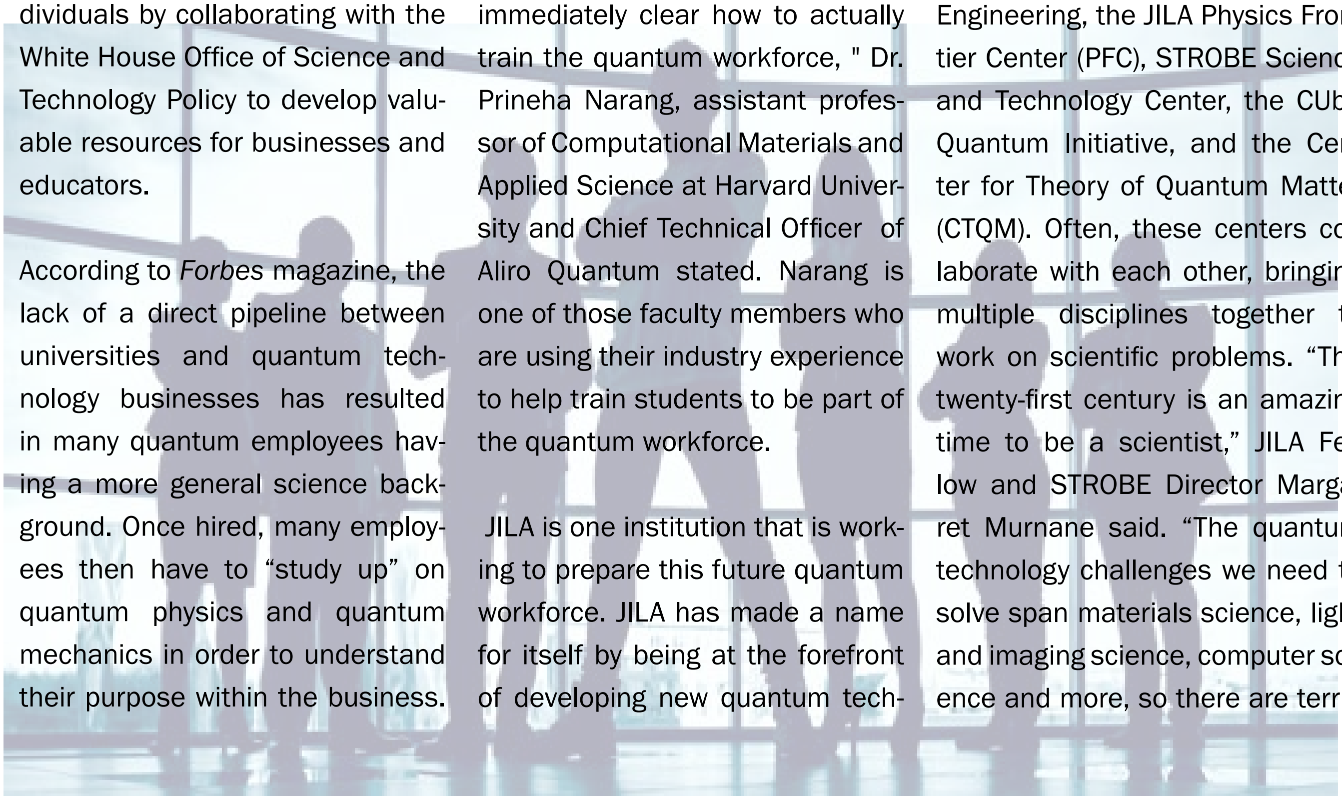
The second quantum revolution is underway, a period marked by significant advances in quantum technology, and huge discoveries within quantum science. From tech giants like Google and IBM, who build their own quantum computers, to quantum network startups like Aliro Quantum, companies are eager to profit from this revolution. However, doing so takes a new type of workforce, one trained in quantum physics and quantum technology. The skillset required for this occupation is unique, and few universities expose students to real-world quantum technology. This in turn leads to a tiny talent pool of qualified job candidates for a rapidly expanding industry. Realizing this growing problem, the NSF has taken strides to better train individuals by collaborating with the White House Office of Science and Technology Policy to develop valuable resources for businesses and educators.

According to *Forbes* magazine, the lack of a direct pipeline between universities and quantum technology businesses has resulted in many quantum employees having a more general science background. Once hired, many employees then have to “study up” on quantum physics and quantum mechanics in order to understand their purpose within the business. Surprisingly, many quantum technology companies are not looking for physics students with PhDs but rather engineering students. This has caused some engineering students to take physics classes to learn about quantum science and technology, even when not required for their major.

Universities are beginning to realize that their curricula need to change in order to create properly trained candidates. This process is difficult, as not every faculty member has background in the quantum industry from a business perspective. Even for those who do, the challenge of teaching a quantum workforce can be overwhelming. "There's a strong pull for people to come into this field. And yet, it's not immediately clear how to actually train the quantum workforce, " Dr. Prineha Narang, assistant professor of Computational Materials and Applied Science at Harvard University and Chief Technical Officer of Aliro Quantum stated. Narang is one of those faculty members who are using their industry experience to help train students to be part of the quantum workforce.

JILA is one institution that is working to prepare this future quantum workforce. JILA has made a name for itself by being at the forefront of developing new quantum technology and discovering new things within quantum science. According to JILA and NIST Fellow Jun Ye: “One area we are working on is to create more opportunities for students of diverse background to have hands-on training in quantum technologies and related technical areas and enhance interactions between these students and the existing quantum experts. Another important area is to extend the workforce pipeline to cover pre-college students and existing industry workforce with no prior quantum background.”

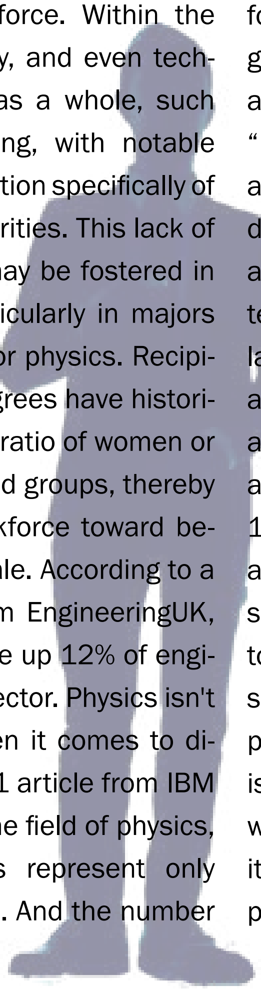
JILA has several centers within itself for specific research within quantum science. These include Q-SEnSE: Quantum Systems through Entangled Science and Engineering, the JILA Physics Frontier Center (PFC), STROBE Science and Technology Center, the CUbit Quantum Initiative, and the Center for Theory of Quantum Matter (CTQM). Often, these centers collaborate with each other, bringing multiple disciplines together to work on scientific problems. “The twenty-first century is an amazing time to be a scientist,” JILA Fellow and STROBE Director Margaret Murnane said. “The quantum technology challenges we need to solve span materials science, light and imaging science, computer science and more, so there are terrif-



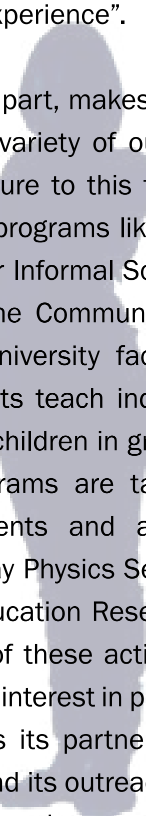
ic opportunities to work as part of transdisciplinary teams. There are many opportunities for discoveries at the boundaries between these fields, and so many ways that we can help and learn from each other.” These JILA centers are helping to set aside time and funding to better prepare students for their future careers in the quantum industry.

Quantum’s Lack of Workforce Diversity

While the training of a quantum workforce is a long and ongoing process, it provides an opportunity to increase employee diversity within this workforce. Within the quantum industry, and even technology industry as a whole, such diversity is lacking, with notable under representation specifically of women and minorities. This lack of representation may be fostered in universities, particularly in majors like engineering or physics. Recipients of these degrees have historically had a lower ratio of women or other marginalized groups, thereby skewing the workforce toward being White and male. According to a 2016 survey from EngineeringUK, women only made up 12% of engineering for any sector. Physics isn't much better when it comes to diversity, as a 2021 article from IBM stated that: "In the field of physics, Black Americans represent only 1% of total PhD’s. And the number of Black students graduating with a physics PhD, has been decreasing since 2012." These statistics, while not surprising to some, show that the college majors typically supplying the quantum workforce may play a significant role in the under representation of these minorities.



Another theory on to the origins of this under representation is postulated by Dr. Tina Brower-Thomas, Assistant Research Professor, Howard University Graduate School and Executive Director Center Integrated Quantum Materials Brower-Thomas believes the stage is already set for a lack of diversity within the quantum workforce and it is indelibly tied to the gap in resources and infrastructure at minority serving institutions. “If allowed to persist, we will face a twenty-first century “quantum, digital divide”, said Brower-Thomas. She further explained that the term digital divide, coined in the late twentieth century, refers to the acknowledged lack of reliable and affordable internet access in rural and low-income communities: “K—12 schools, community colleges and universities that serve underserved communities need access to the tools of education and research that allow youth an early exposure to quantum. Early exposure is essential to preparing the future workforce. I firmly believe that ability is certainly a necessary factor in preparing the quantum workforce, but we cannot underestimate access and experience”.



JILA, for its part, makes sure to offer a wide variety of outreach for early exposure to this technology. JILA hosts programs like The Partnerships for Informal Science Education in the Community (PISEC), in which university faculty, staff, and students teach inquiry-based science to children in grades K—8. Other programs are targeted for older students and adults, like the Saturday Physics Series or the Physics Education Research (PER) Group. All of these activities work to foster an interest in physics. JILA also utilizes its partnerships with CU to expand its outreach, such as with CU Wizards, a program that has entertained and informed children about the wonders of science for over 30 years. These programs are helpful in bridging the digital divide in the Boulder area and surrounding regions, and allows for resources to be shared to inspire interests that can lead to a more properly trained quantum workforce.

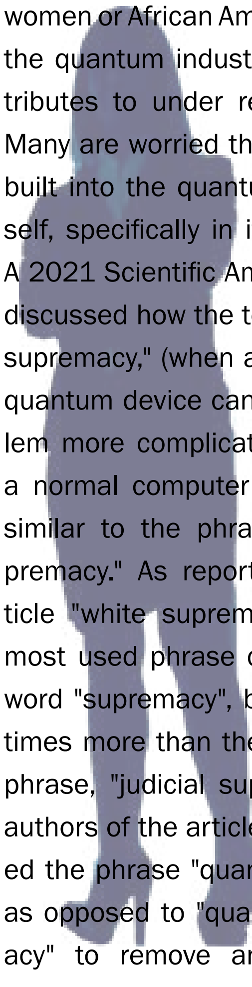
Increasing Diversity Through Training

JILA is stepping up to not only train future generations of the quantum workforce, but to emphasize diversity. According to Mike Bennet, JILA PFC Director of Educational Outreach and Research:

"It's imperative that efforts to recruit into the quantum workforce don't just cater to well-prepared students at large R1 universities [Research 1 Universities, a designation indicating participation in the highest levels of research], but are designed from the ground up for students from a diverse set of backgrounds and experience levels as well. Creating a truly representative quantum workforce is both a matter of expanding our vision for who gets to participate and a matter of ensuring that we create cultures and environments that diverse populations of students want to join." JILA is ensuring that diversity is implemented with groups like Justice Excellence in Diversity and Inclusivity (JEDI). The JEDI groups encourages conversations about diversity and works to support a community of inclusivity within JILA. Being more inclusive leads to a larger talent pool that JILA Fellows can partner with to properly train the incoming quantum workforce. These Fellows help students go to quantum technology conferences, and/or network with the many quantum technology businesses in the U.S.

While these partnerships are beneficial, others, like Brower-Thomas, believe increasing diversity will take "dedication and a paradigm shift". "We have to get rid of this myth that certain things are only for certain people," Brower-Thomas explained. "I think it's a change of mentality, not only for people who are trying to figure out what they want to do with the rest of their lives, but also for leaders in technology and business, who by now recognize the importance of increasing the numbers and diversity in Science Technology Engineering and Math (STEM)." JILA emphasizes this inclusion through its JEDI program, which helps to encourage individuals from all backgrounds to pursue a career in quantum science, breaking the stereotype-creating myth-.

Brower-Thomas alludes to the history of bias against minorities like women or African Americans within the quantum industry, which contributes to under representation. Many are worried that that bias is built into the quantum science itself, specifically in its vocabulary. A 2021 Scientific American article discussed how the term "quantum supremacy," (when a programmed quantum device can solve a problem more complicated than what a normal computer can solve) is similar to the phrase "white supremacy." As reported in the article "white supremacy" was the most used phrase containing the word "supremacy", being used 15 times more than the next highest phrase, "judicial supremacy." The authors of the article recommended the phrase "quantum primacy" as opposed to "quantum supremacy" to remove any perception of potential bias. Currently, the phrase "quantum advantage," is also used, removing this bias.



But this may not be enough, as JILA Fellow Heather Lewandowski explained: "We need to stop talking about how quantum is strange and spooky. This is not motivating for everyone. Often, this language communicates that you have to be special to understand these concepts and quantum has no connection to real life. Quantum-enabled technology can be understood and used to impact real world applications." Putting the technology into a more accessible and familiar perspective can keep students motivated and aligned for better career positions in the quantum workforce.

To ensure diversity as the quantum workforce develops, it will be important to consider who has—and does not have—access to federally funded resources. "We, as a community, have to buy into the idea that we're all better off if more have opportunities to contribute to quantum," said Brower-Thomas. "Whether that is engaging diverse communities and exposing citizens to quantum, providing teachers resources to quantum educate, investing in infrastructure, reeducating the current workforce, or improving ways to help the existing quantum community engage others. Let's open the door."

Written by Kenna Castleberry

JEDI PROJECTS: "SHE HAS THE FLOOR"

When it comes to inspiring young people pursuing a career within the sciences, you can't start too early. At least, that's what the JILA Excellence in Diversity and Inclusivity (JEDI) group believed when they collaborated with the Colorado non-profit organization Pretty Brainy to develop a speaker series. The series, designed for girls from ages 11 and up, featured the voices of several women JILAns, all focusing on their work and sharing tools for success to this younger generation. Over the course of 8eightweeks, women of all ages could tune-in virtually to hear some of the brightest female minds from JILA discuss the importance of mentorship, perseverance, failure, and of course, some of the newest findings within physics.

In the first event, held on October 5th, 2021, JILA Fellow Ann-Marie Madigan spoke on her research within the field of astrophysics, and her day-to-day life as a scientist. "I'll go to work where I'll have a group meeting," Madigan said. "In there, we will discuss our latest results, we might read scientific papers, we might present to each other if we're going to give a talk. It's really good fun. This is a joy in my life, as I'm with really smart people." Madigan elaborated about how fulfilling this job was to her. "It's a really fun job and sometimes it doesn't feel like a job. Sometimes, I'm just walking around, reading, and talking to great people all day."

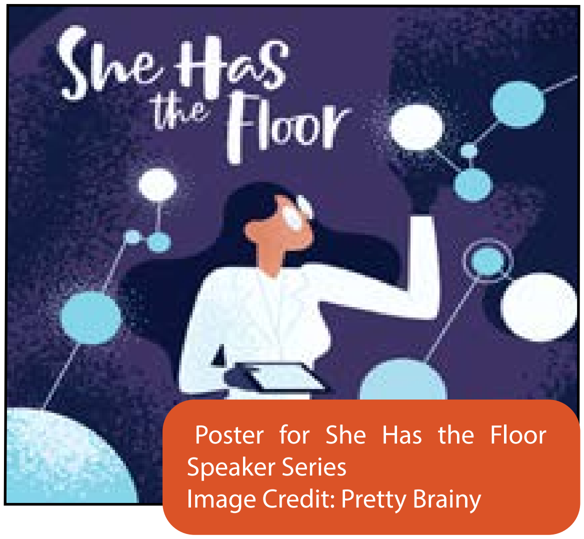
The next two talks were given by JILA graduate students. Ph.D. student Olivia Krohn, from JILA Fellow Heather Lewandowski's group, discussed her work on molecular collisions in cold, low-pressure environments. "I always knew I liked science and math," Krohn stated. She went on to emphasize finding passions to study for these students. Similarly, graduate student Rebecca Hirsch of JILA Fellow J. Mathias Weber's laboratory spoke on her research around cold, gaseous molecules in outer space. Both of these talks, given by younger female scientists, inspired many of the young women in the audience, who gave significant positive feedback after each event.

The last two talks of the speaker series were given by JILA staff members: Chief Operating Officer (COO) Beth Kroger, and Science Communicator Kenna Castleberry. Kroger discussed the importance of perseverance for female scientists. “Each of you has already persevered,” Kroger explained. “It helps me to remember that it’s just a bad day, and it won’t always be this way.” In contrast, Castleberry focused on the importance of failing forward. "It's important to use your past mistakes as lessons to learn from, for your future successes," she explained. "We as female scientists take a lot on, and that can cause us to get overwhelmed and to focus more on our failures. It's important to take a step back and to say no if we have too much going on. No doesn't have to be a scary word."

From the feedback and impact the speaker series had on young women and their families, it was deemed to be a success. No doubt this is just the beginning of a collaboration between JILA JEDI and Pretty Brainy, as both work to inspire powerful young leaders within the scientific community.

You can find out more about Pretty Brainy by clicking here.

Written by Kenna Castleberry



Poster for She Has the Floor Speaker Series
Image Credit: Pretty Brainy

LIFE AFTER JILA

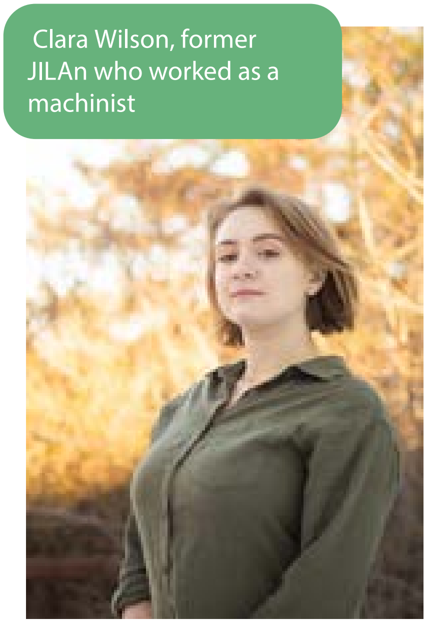
There are many places within JILA that are special to alumni. For many, it may be the JILA tower, or a particular laboratory, or the spiral staircase. For others, like Clara Wilson, it is the machine shop. "I was at JILA for a little over a year and a half," Wilson said. "I worked in the machine shop as a student assistant, which basically meant that I kept the space clean and operable and was able to shadow and learn everything I could from the various machinists there...I helped build things. I think that as a student assistant, one of my main jobs was to ask questions and learn." Wilson gained valuable knowledge and experience working within the machine job at JILA.

Wilson didn't originally expect to work in the machine shop. "I had never been exposed to machining or manufacturing before, even though I was an undergraduate in mechanical engineering at the time. And I remember just being completely in awe, when I visited the first time, and it felt like a playground. I hadn't been exposed to that before, It really showed me what I wanted to do, and that was creation and machining." Wilson flourished in her time at JILA, helping researchers design and build customizable tools for their experiments.

In transitioning from JILA, Wilson became a staff engineer in the machine shop of the physics department of Columbia University. Wilson credited her connections at JILA for helping her get the position. "JILA and JILAns were directly responsible for getting me this job. Not only in the application process, but in the initial connections. I listed several machinists as references for when I applied for my current job. It is something I am going to always be really grateful for."

Wilson was able to use the skills she acquired at JILA to succeed in her current job. She helped transition Columbia's machine shop into something more user-friendly. "What we're doing now is we're transitioning from a machine shop space, much like what JILA has, where the researchers request a tool and machinists will work with them from start to finish on designing to manufacturing, and manufacture it for them. Instead, we're transitioning to a makerspace. This is a space where researchers can come in and actually create their own pieces, and I am just facilitating the student and researcher use of the space. So, I will show them how not to kill themselves on the heavy machinery and then just say: 'Go forth, and don't kill yourself.'" From Wilson's expertise, researchers were able to learn how to craft customizable tools for their work.

In Wilson's own experience, she found that networking can help current JILAns find successful future careers. "Network like crazy," Wilson emphasized. "It is really beneficial because you're actually speaking to people and people generally want to help." She also mentioned: "Don't be afraid of job applications or qualification expectations that you don't meet. Definitely talk to people who have worked with you in the past, like old professors, as they've usually more than likely interested in helping you out. And I mean, obviously, reach out to people in JILA, because JILAns are spread across the country." Wilson alluded to the importance of the community of JILA alumni for networking and career opportunities. This community continues to grow, providing more alumni to help support and encourage current JILAns who are still early in their careers.


Clara Wilson, former JILAn who worked as a machinist

News and Awards

CUbit Director Philip Makotyn speaking at Colorado Congress.
Image Credit: CU Boulder

Philip Makotyn, executive director of the CUbit Quantum Initiative, spoke on September 9, 2021, before the Colorado General Assembly's Joint Technology Committee. Makotyn was one of several people who spoke before the committee on the quantum ecosystem within Colorado, including CU's role in quantum research and the impact the quantum industry has on the Colorado economy.

Awards

JILA and JIST Fellow Jun Ye has been awarded the 2022 Breakthrough Prize in Fundamental Physics for his pioneering research on atomic clocks. Ye has been a physicist at JILA, a joint institute of NIST and CU Boulder, for more than 20 years. The prize selection committee cited him for “outstanding contributions to the invention and development of the optical lattice clock, which enables precision tests of the fundamental laws of nature.”

JILA Fellow Shuo Sun has been awarded an NSF Quantum Interconnect Challenges for Transformational Advances in Quantum Systems (QuIC-TAQS) grant. The grant's purpose is to support interdisciplinary teams exploring innovative and unique ideas for applying and developing quantum engineering, computing, and science in the specific area of quantum interconnection. Quantum interconnection is a part of quantum communications. This grant is part of a larger program by the NSF called the "Quantum Leap."

JILA Fellows Thomas Perkins and Graeme Smith have are recipients of 2021 Oustanding Postdoc Mentor Awards by CU's Office of Postdoctoral Affairs. This award recognizes mentors who have gone above and beyond to support their postdocs.

The NSF has renewed for five years and more than $22 million the cutting-edge Science and Technology Center on Real-Time Functional Imaging (STROBE). STROBE is developing the microscopes of tomorrow, and is a partnership between six institutions: University of Colorado Boulder, UCLA, UC Berkeley, Florida International University, Fort Lewis College, and UC Irvine.

JILA Fellow Dana Anderson won the 2021 Willis E Lamb award for Laser Science and Quantum Optics. The award recognizes Dana's, "excellent contributions to quantum optics and electronics". The Anderson Group is currently involved in state of the art ultracold atom research with applications in atomtronics, atom interferometry and neutral atom quantum computing.

JILA and NIST Fellow Jun Ye has been awarded the Niels Bohr Institute Medal of Honor for 2021. The medal is awarded annually to a particularly outstanding researcher who is working in international cooperation and exchange of knowledge, two qualities exemplified by Bohr himself. Ye was awarded this honor due to his seminal and creative contributions to a remarkably wide range of subjects within atomic, molecular and optical physics.

JILA Fellow Andreas Becker is one of the 11 University of Colorado Boulder faculty to be awarded a 2021 Distinguished Professor title, the highest honor awarded to faculty across the CU systems' four campuses. CU Distinguished Professors are tenured faculty members who give outstanding work in research or creative work and have a reputation of excellence in promoting learning and student engagement in the research process as well as dedicated to the profession, the university, and its

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