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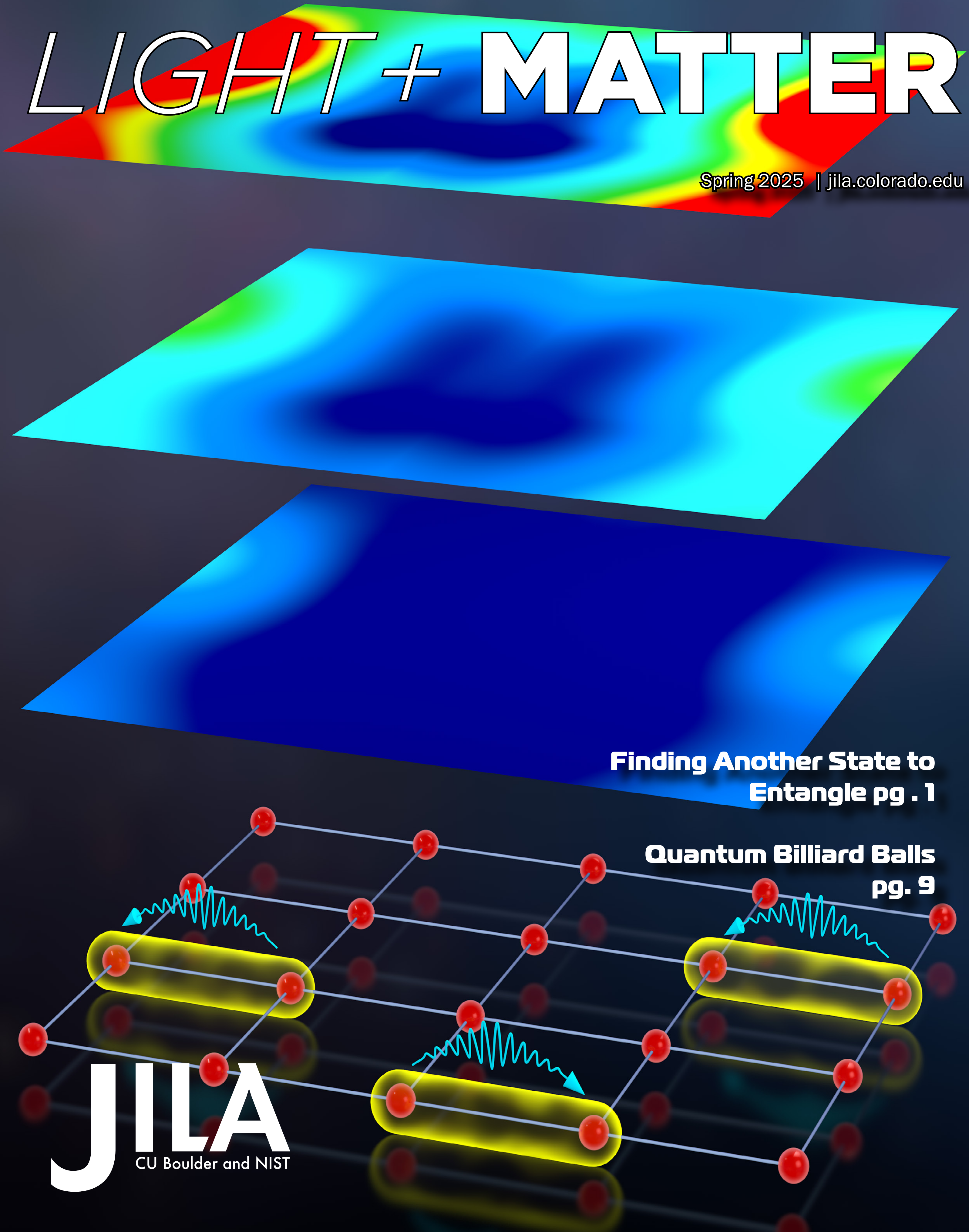

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JILA
CU Boulder and NIST

JILA postdoctoral researcher Rachael Merritt teaches a workshop on "Finding your Place in Physics" at the January 2025 Conference for Undergraduate Women and Gender Minorities sponsored by the American Physical Society.
Credit: Kenna Hughes-Castleberry/JILA

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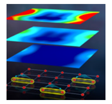
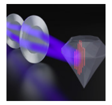
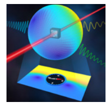
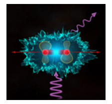
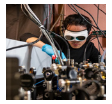










Feature Articles

Making a Leap by Using "Another State to Entangle"

Interactions between atoms and light rule the behavior of our physical world, but, at the same time, can be extremely complex. Understanding and harnessing them is one of the major challenges for the development of quantum technologies.

To understand light-mediated interactions between atoms, it is common to isolate only two atomic levels, a ground level and an excited level, and view the atoms as tiny antennas with two poles that talk to each other. So, when an atom in a crystal lattice array is prepared in the excited state, it relaxes back to the ground state after some time by emitting a photon. The emitted photon does not necessarily escape out of the array, but instead, it can get absorbed by another ground-state atom, which then gets excited. Such an exchange of excitations, also referred to as dipole-dipole interaction, is key for making atoms interact, even when they cannot bump into each other.

"While the underlying idea is very simple, as many photons are exchanged between many atoms, the state of the system can become correlated, or highly entangled, quickly," explains JILA and NIST Fellow and University of Colorado Boulder physics professor Ana Maria Rey. "I cannot think of a single atom as an independent object. Instead, I need to keep track of how its state depends on the state of many other atoms in the array. This is intractable with current computational methods. In the absence of an external drive, the generated entanglement typically disappears since all atoms relax to the ground state."

Atoms can, however, have more than two atomic levels. Interactions in the system can change drastically if more than two internal levels are allowed to participate in the dynamics. In a two-level system (weak excitation) with only one photon and, at most, one excited atom in the array, one just needs to track the single excited atom. While this is numerically tractable, it is not so helpful for quantum technologies since the atoms could be thought of more as classical antennas.

In contrast, by allowing just one additional ground level per atom, even with a single excitation, the number of configurations accessible to the system grows exponentially, drastically increasing the complexity. Understanding atom-light interaction in multi-level settings is an extremely difficult problem, and up to now it has eluded both theorists and experimentalists.

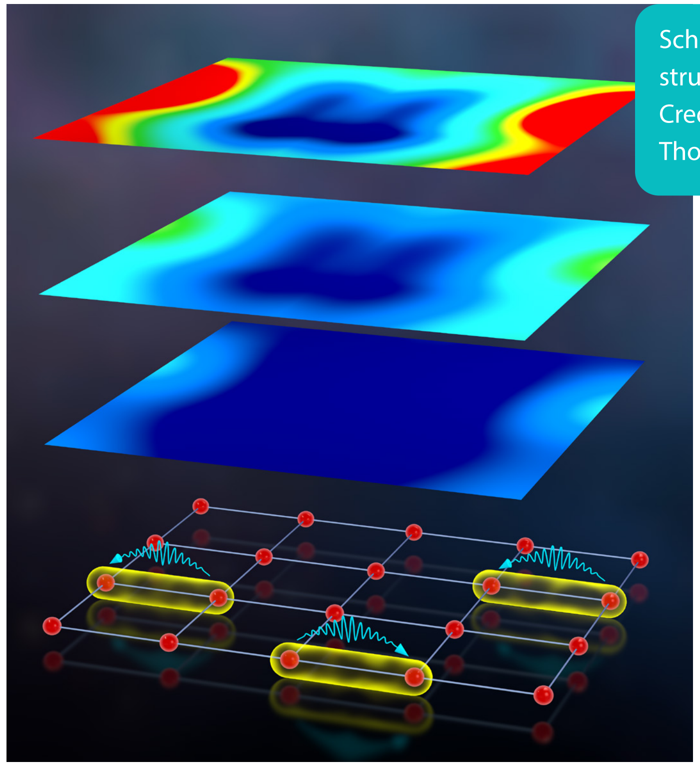
Rey explains, "However, it can be extremely useful, not only because it can generate highly entangled states which can be preserved in the absence of a drive since atoms in the ground levels do not decay.''

Now, in a recent study published in *Physical Review Letters,* Rey and JILA and NIST Fellow James K. Thompson, along with graduate student Sanaa Agarwal and researcher Asier Piñeiro Orioli from the University of Strasbourg, studied atom-light interactions in the case of effective four-level atoms, two ground (or metastable) and two excited levels arranged in specific one-dimensional and two-dimensional crystal lattices.

"We know that including the full multilevel structure of atoms can give us richer physics and new phenomena, which are promising for entangled state generation," says Agarwal, the paper's first author. With quantum technologies like computing and secure communications requiring entanglement, understanding how to create stable, interconnected atomic systems has become a priority.

From Two to Four Internal States

For this study, the researchers focused on isolating four energy levels in strontium atoms, arranged in either one-dimensional (1D) or two-dimensional (2D) configurations where the atoms are loaded in a special configuration in which they are closer to each other than the wavelength of the laser light used to excite them.



Schematic of the multi-level atomic array structure used in this study. Credit: Steven Burrows/Rey and Thompson groups

The study concentrated on a set of internal levels with a much smaller energy separation than typical optical transitions. Instead of using truly ground-state levels, they proposed using metastable levels where atoms can live for a very long time.

This very interesting set of levels has not been explored much before since it requires a special laser with a very long wavelength, but Thompson plans to have this laser in his lab.

"We plan to build the necessary capabilities in our lab to first knock the atom into an excited state that lives for a really long time," Thompson says. "This will let us use a 2.9-micron wavelength transition between this so-called metastable-state excited-state 3P2 in strontium and another excited-state 3D3 state. This wavelength is about eight times longer than the usual separation between nearby atoms trapped in an optical lattice in our lab. By having a transition wavelength much longer than the trapping light wavelength, we will be able to realize strong and programmable interactions via this photon exchange that happens when the atoms are jammed in close to each other."

Agarwal adds, "The atoms need to be very close, as interactions weaken with distance, eventually becoming lost due to other sources of decoherence [noise]. Keeping atoms close allows interactions to dominate, preserving the growth of entanglement."

The team focused on the weak and far-from-resonance regime where atoms are allowed to virtually "trade" photons, i.e., moving them between ground states without permanently occupying an excited state.

"By exchanging photons, atoms are effectively only moving between different configurations in the ground state levels, which simplifies our calculations by reducing the number of states accessible to the system," Agarwal adds. "It's easier to eliminate the excited states and focus on the metastable state dynamics, where we observe growing correlations, which furthermore can be preserved when the laser is turned off.

Creating a Spin Model for Entanglement

In the regime where the excited levels are only "virtually" populated, and only atoms can occupy the metastable state levels, the four-level problem can be reduced back to a two-level system at the cost of dealing with much more complex interactions, which involves not only pair-wise interactions but multi-atom interaction.

Rey explains, "We focused in the far from a resonant regime where to leading order, only two atoms interact at a given time. In this case, the Hamiltonian describing the metastable state dynamics maps back to a well-characterized spin model."

The team used this well-known model to study what are called “spin waves”—coordinated low-energy excitations of atomic spins—across the lattice arrangement. Moreover, by controlling the polarization and propagation direction of the photons of the laser exciting the atoms, the researchers could determine which “spin-wave pattern” became dominantly entangled. The entanglement observed was spin-squeezing, a specific form of entanglement that has increased sensitivity to external noise, and is thus useful for metrology.

“The spin squeezing in our system can be experimentally measured and serves as a witness of quantum entanglement. Our setup also has possible applications in simulating many-body physics,” Agarwal says.

This finding is especially significant, as it implies that quantum systems could maintain entanglement over long periods, without needing constant intervention to prevent decoherence.

Limitations in Simulations

While the team’s model offered promising insights, it also faced limitations in accurately simulating the system over time. One of the key limitations arose from the dipole-dipole interactions, which, unlike simpler interactions, involve long-range forces that couple atoms both near and far in the lattice. Furthermore, these couplings are anisotropic and depend on the relative orientation of the atomic dipoles, making the system more complex. Each atom interacts differently with its neighbors spaced along different directions in the lattice, leading to varying interaction strengths and signs across the array.

Other popular simulation techniques designed for short-range interactions fail when applied to long-range interactions, as they aren’t equipped to handle the many correlations that develop over time. Although some other methods are more appropriate for long-range atomic interactions, they are constrained to small atom numbers due to their computational complexity, limiting the researchers’ ability to observe the long-time progression of correlations in a large system.

Diving Further into Internal States

The team’s findings could open new avenues in quantum information science and quantum computing, offering a potential path for the development of highly entangled and scalable quantum systems.

“We’re inching closer to systems that could sustain entanglement reliably, which is a crucial step for future quantum applications,” says Agarwal.

Looking forward, the research team plans to explore how more extensive multilevel systems might enhance entanglement potential.

“In atoms like strontium, with as many as 10 ground and excited levels each, the complexity grows significantly, and we want to see how this impacts entanglement,” Agarwal says. “Furthermore, while we have focused here on interactions between atoms in free space, one excited extension is to understand how these interactions can interplay with additional photon-mediated interactions [that are] built when atoms are instead placed inside an optical cavity or in nanophotonic devices,” she adds

“The competition between the infinite range interactions mediated by the cavity photons and the dipole-dipole interactions described here can open fantastic opportunities to harness light-mediated quantum gates, entanglement distribution, and programmable quantum many-body physics,” says Thompson.

Sanaa Agarwal, Asier Piñeiro Orioli, James Thompson, and Ana Maria Rey. "Entanglement Generation in Weakly Driven Arrays of Multilevel Atoms via Dipolar Interactions." Physical Review Letters, 133(23), 233003, 2024.

Written by Kenna Hughes-Castleberry

Diamonds are Forever—But Not in Nanodevices

Ultrawide-bandgap semiconductors—such as diamond—are promising for next-generation electronics due to a larger energy gap between the valence and conduction bands, allowing them to handle higher voltages, operate at higher frequencies, and provide greater efficiency compared to traditional materials like silicon. However, their unique properties make it challenging to probe and understand how charge and heat move on nanometer-to-micron scales. Visible light has a very limited ability to probe nanoscale properties, and moreover, it is not absorbed by diamond, so it cannot be used to launch currents or rapid heating.

Now, researchers at JILA, led by JILA Fellows and University of Colorado physics professors Margaret Murnane and Henry Kapteyn, along with graduate students Emma Nelson, Theodore Culman, Brendan McBennett, and former JILA postdoctoral researchers Albert Beardo and Joshua Knobloch, have developed a novel microscope that makes examining these materials possible on an unprecedented scale. The team’s work, recently published in *Physical Review Applied,* introduces a tabletop deep-ultraviolet (DUV) laser that can excite and probe nanoscale transport behaviors in materials such as diamond. This microscope uses high-energy DUV laser light to create a nanoscale interference pattern on a material’s surface, heating it in a controlled, periodic pattern. Observing how this pattern fades over time provides insights into the electronic, thermal, and mechanical properties at spatial resolutions as fine as 287 nanometers, well below the wavelength of visible light.

Murnane states that this new probe capability is important for future power electronics, high-frequency communication, and computational devices based on diamond or nitrides rather than silicon. Only by understanding a material's behavior can scientists address the challenge of short lifetimes observed in many nanodevices incorporating ultrawide-bandgap materials.

A Challenge from an Industry Partner

For Nelson and the other JILA researchers, this project began with an unexpected challenge from materials scientists from one of their industry collaborators: 3M.

“3M approached us to study an ultrawide material sample that wasn’t compatible with our existing microscopes,” Nelson says. The team then collaborated with 3M scientists Matthew Frey and Matthew Atkinson to build a microscope that could image transport in this material.

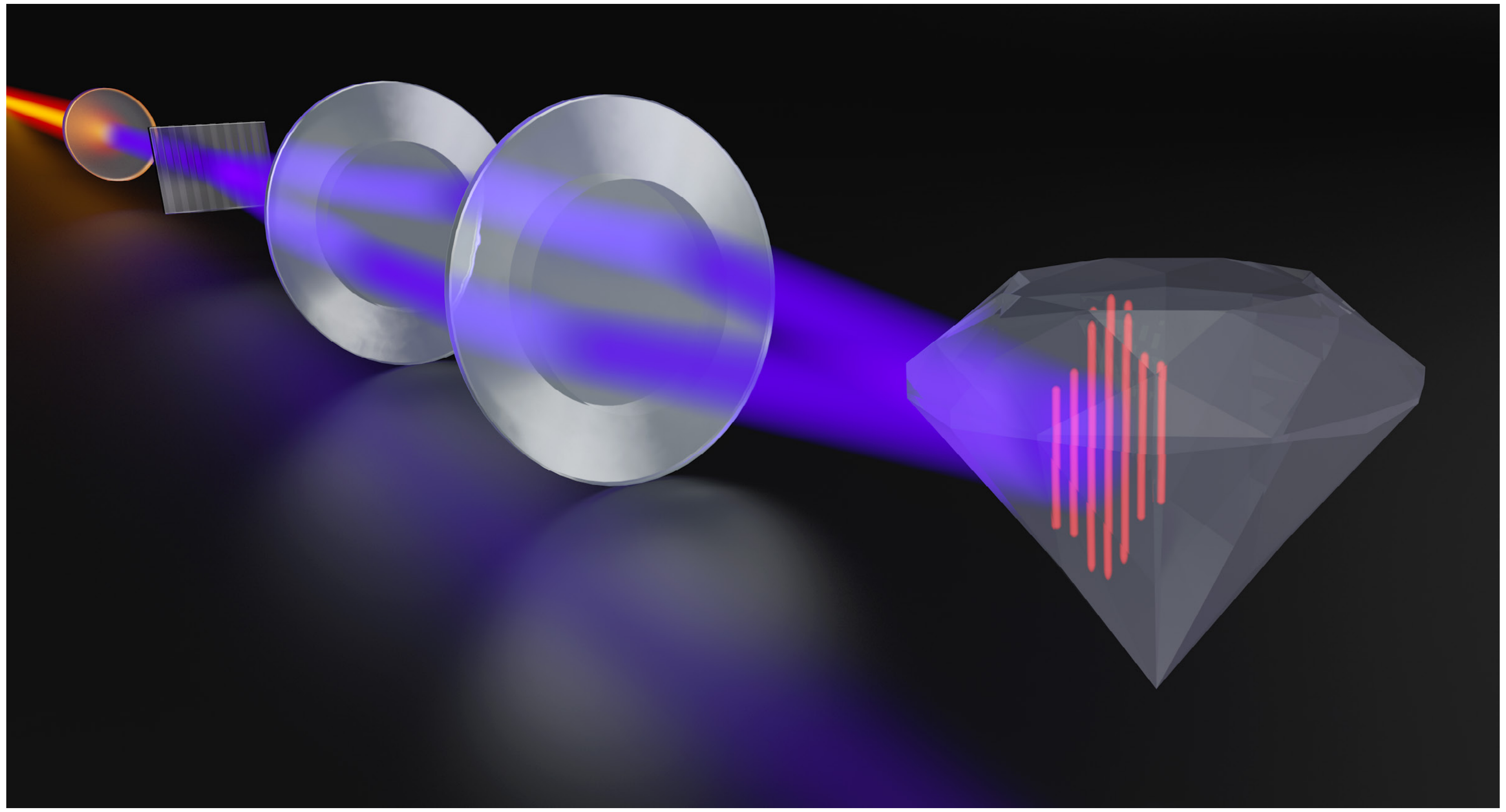
Traditional imaging methods rely on visible light to see the microscopic composition and transport behaviors in semiconductors and other materials, which is effective for studying materials with smaller bandgaps.

However, materials like diamond, often used in electronic components, have a much larger energy gap between their valence and conduction bands—typically exceeding 4 electron volts (eV)—making them transparent to lower-energy visible and infrared light. Higher-energy photons in the ultraviolet (UV) range or beyond are required to interact with and excite electrons in these materials.

Visible-light setups also struggle with spatial resolution, as their longer wavelengths limit the ability to probe the nanoscale dimensions relevant to modern devices.

These limitations inspired the team to think outside the box for their imaging setup.

“We brainstormed a new experiment to expand what our lab could study,” says Nelson.



A diffractive optic creates two DUV beams, which are focused and interfered on a sample surface (diamond) using a 4f imaging system to generate a microscopic sinusoidal excitation profile. Credit: Steven Burrows/Kapteyn and Murnane groups

The result was a multi-year effort to develop a compact microscope that uses DUV light to generate nanoscale heat patterns on a material's surface without altering the material itself.

Diving into the Deep Ultraviolet Regime

To generate the DUV light, the team first started with a laser emitting pulses at an 800-nanometer wavelength. Then, by passing laser light through nonlinear crystals and manipulating its energy, the team converted it step-by-step into shorter and shorter wavelengths, ultimately producing a powerful, deep-ultraviolet light source at around 200 nanometers wavelength.

Each step required precise alignment of laser pulses in space and time within the crystals to achieve the desired wavelength efficiently.

"It took a few years to get the experiment working during the pandemic," says Nelson, describing the trial-and-error process of aligning light through three successive crystals. "But once we had the setup, we could create patterns on a scale never before achieved on a tabletop."

To produce the periodic pattern, called a transient grating, the researchers split the DUV light into two identical beams using a diffraction grating. These beams were directed onto the material's surface at slightly different angles, where they overlapped and interfered with each other, forming a precise sinusoidal pattern of alternating high and low energy. This interference pattern acted as a nanoscale "grating," temporarily heating the material in a controlled way and generating localized energy variations.

This process allowed the team to study how heat, electrons, or mechanical waves—depending on the material—spread and interacted across the nanoscale grating. The periodicity of the grating, which defined the distance between these high-energy peaks, was closely related to the wavelength of the light source, allowing researchers to get shorter periods by using higher energy (and shorter wavelength) light. The periodicity could be tuned by adjusting the angles of the beams, enabling detailed studies of transport phenomena at microscopic scales. For example, in this experiment, the team achieved grating patterns as delicate as 287 nanometers, a record for laser tabletop setups.

Testing the New DUV Microscope

Once the DUV transient grating system was operational, the team focused on validating its accuracy and exploring its capabilities. Their first test involved thin gold films, which served as a benchmark material due to their well-understood properties. The researchers used their system to generate nanoscale heat patterns, launching acoustic waves at the film's surface. By analyzing the frequency and behavior of these waves, they extracted material properties such as density and elasticity.

To confirm their results, Nelson developed computer models simulating how the gold film would behave under similar conditions. The experimental data matched her predictions closely, providing a strong validation of the system's precision.

"Seeing the experiment work and align with the models we created was a relief and an exciting milestone," Nelson says.

Next, the team used their new DUV microscope to look at diamond, a material prized for its exceptional electronic and thermal properties. Previous techniques for studying diamond often required physical alterations, such as adding nanostructures or coatings, which inadvertently changed its properties. The DUV system eliminated this need, enabling the team to study diamond in its pristine state.

Using their new setup, the researchers observed how charge carriers—electrons and holes—diffused across the diamond after being excited by the DUV light. This process revealed new insights into the nanoscale transport dynamics of diamonds, particularly at nanometer scales.

Beyond validating the system and exploring diamond's properties, the team's findings shed light on broader questions of nanoscale heat transport. At such small scales, heat doesn't always behave as predicted by traditional physical models, which assume a smooth, continuous flow. Instead, nanoscale transport can involve ballistic and hydrodynamic effects, where energy carriers like phonons can travel in a straight line without scattering or can spread like water flowing through channels.

As researchers continue to refine these techniques and explore new materials, this advancement could play a crucial role in the development of high-performance power electronics, efficient communication systems, and quantum technologies. In the quest to push the boundaries of modern devices, diamonds may not last forever—but their impact on nanoscience certainly will.

Emma E. Nelson, Brendan McBennett, Theodore H. Culman, Albert Beardo, Henry C. Kapteyn, Matthew H. Frey, Matthew R. Atkinson, Margaret M. Murnane, and Joshua L. Knobloch. "Tabletop deep-ultraviolet transient grating for ultrafast nanoscale carrier-transport measurements in ultrawide-band-gap materials." Physical Review Applied, 22(5), 054007, 2024.

Written by Kenna Hughes-Castleberry

Tiny Compasses Could Improve Navigation, Brain Imaging, and More

A team of physicists and engineers at the CU Boulder has discovered a new way to measure the orientation of magnetic fields using what may be the tiniest compasses around—atoms.

The group's findings could one day lead to a host of new quantum sensors, from devices that map out the activity of the human brain to others that could help airplanes navigate the globe. The new study, published this month in the journal *Optica*, stems from a collaboration between physicist Cindy Regal and quantum engineer Svenja Knappe.

It reveals the versatility of atoms trapped as vapors, said Regal, professor of physics and fellow at JILA, a joint research institute between CU Boulder and the National Institute of Standards and Technology (NIST).

"Atoms can tell you a lot," she said. "We're data mining them to glean simultaneously whether magnetic fields are changing by extremely small amounts and what direction those fields point."

These fields are all around us, even if you never see them. Earth's iron-rich core, for example, generates a powerful magnetic field that surrounds the planet. Your own brain also emits tiny pulses of magnetic energy every time a neuron fires.

But measuring what direction those fields are pointing, for precise atomic sensors in particular, can get tricky. In the current study, Regal and her colleagues set out to do just that—with the aid of a small chamber containing about a hundred billion rubidium atoms in vapor form. The researchers hit the chamber with a magnetic field, causing the atoms inside to experience shifts in energy. They then used a laser to precisely measure those shifts.

"You can think of each atom as a compass needle," said Dawson Hewatt, a graduate student in Regal's lab at JILA. "And we have a billion compass needles, which could make for really precise measurement devices."

Magnetic World

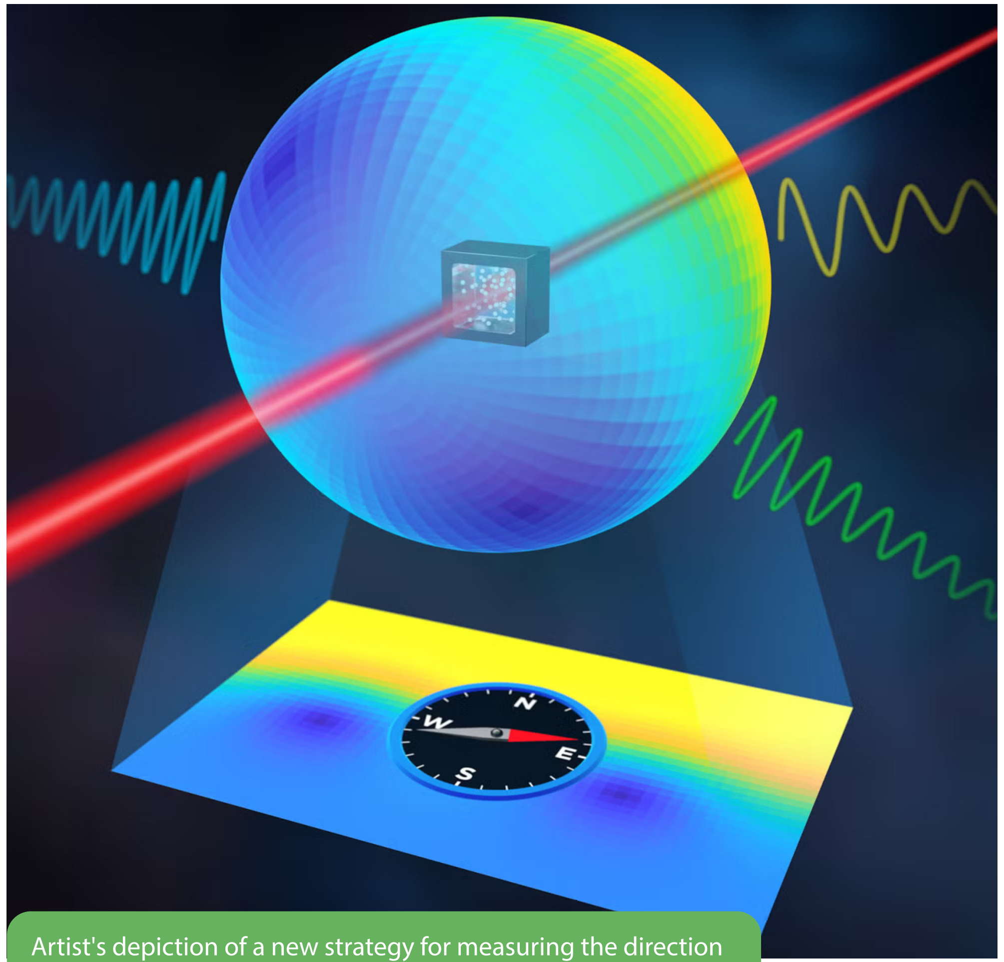
The research emerges, in part, from Knappe's long-running goal to explore the magnetic environment surrounding us.

"What magnetic imaging allows us to do is measure sources that are buried in dense and optically opaque structures," said Knappe, research professor in the Paul M. Rady Department of Mechanical Engineering. "They're underwater. They're buried under concrete. They're inside your head, behind your skull."

In 2017, for example, Knappe co-founded the company FieldLine Inc. that manufactures atomic vapor magnetic sensors, also called optically pumped magnetometers (OPMs). The company builds integrated sensors the size of a sugar cube and fits them into helmets that can map out the activity of human brains.

These OPMs also have a major limitation: They only perform well enough to measure minute changes in magnetic fields in environments shielded from outside magnetic forces. A different set of OPMs can be used outside these rooms, but they are only adept at measuring how strong magnetic fields are. They can't, on their own, record what direction those fields are pointing. That's important information for understanding changes brains may undergo due to various neurological conditions.

To extract that kind of information, engineers typically calibrate their sensors using reference magnetic fields, which have a known direction, as guides of a sort. They compare data from sensors with and without the reference magnetic fields applied to gauge how those sensors are responding. In most cases, those references are small metal coils, which, Knappe said, can warp or degrade over time.



Artist's depiction of a new strategy for measuring the direction of magnetic fields by exposing a cell containing roughly a hundred billion rubidium atoms to a microwave signal.
Credit: Steven Burrows/Regal group

Regal and her team had a different idea: They would use a microwave antenna as a reference, which would allow them to rely on the behavior of atoms themselves to correct for any changes of the reference over time.

Study co-authors included Christopher Kiehl, a former graduate student at JILA; Tobias Thiele, a former postdoctoral researcher at JILA; and Thanmay Menon, a graduate student at JILA.

Atoms Guide the Way

Regal explained that atoms behave a bit like tiny magnets. If you zap one of the team's atoms with a microwave signal, its internal structure will wiggle—a sort of atomic dance that can tell physicists a lot.

"Ultimately, we can read out those wiggles, which tell us about the strength of the energy transitions the atoms are undergoing, which then tells us about the direction of the magnetic field," Regal said.

In the current study, the team was able to use that atomic dancing to pinpoint the orientation of a magnetic field to an accuracy of nearly one-hundredth of a degree. Some other kinds of sensors can also reach this level with careful calibration, but the researchers see atoms as having significant potential with further development.

Unlike mechanical devices with internal parts that can morph, "atoms are always the same," Regal said.

The team still has to improve the precision of its tiny compasses before bringing them out into the real world. But the researchers hope that, one day, airplane pilots could use atoms to fly around the globe, following local changes in Earth's magnetic field, much like migratory birds using their own biological magnetic sensors.

"It's now a question of: 'How far can we push these atomic systems?'" Knappe said.

Christopher Kiehl, Thanmay S. Menon, Svenja Knappe, Tobias Thiele, and Cindy A. Regal. "Accurate vector optically pumped magnetometer with microwave-driven Rabi frequency measurements." Optica. 12(1), 77–87, 2025.

Written by Dan Strain

Quantum Billiard Balls: Digging Deeper into Light-Assisted Atomic Collisions

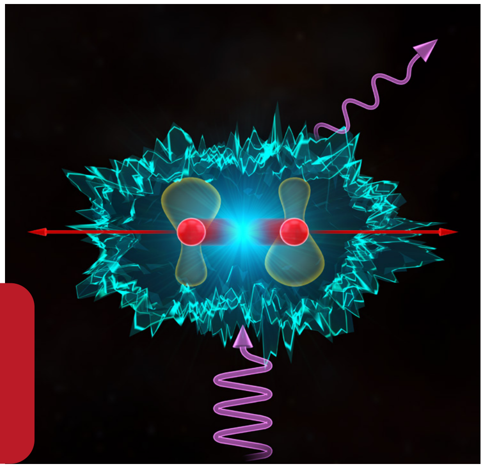
When atoms collide, their exact structure—for example, the number of electrons they have or even the quantum spin of their nuclei—has a lot to say about how they bounce off each other. This is especially true for atoms cooled to near-zero Kelvin, where quantum mechanical effects give rise to unexpected phenomena. Collisions of these cold atoms can sometimes be caused by incoming laser light, resulting in the colliding atom-pair forming a short-lived molecular state before disassociating and releasing an enormous amount of energy. These so-called light-assisted collisions, which can happen very quickly, impact a broad range of quantum science applications, yet many details of the underlying mechanisms are not well understood.

In a new study published in *Physical Review Letters,* JILA Fellow and University of Colorado Boulder physics professor Cindy Regal, along with former JILA Associate Fellow Jose D’Incao (currently an assistant professor of physics at the University of Massachusetts, Boston) and their teams developed new experimental and theoretical techniques for studying the rates at which light-assisted collisions occur in the presence of small atomic energy splittings. Their results rely upon optical tweezers—focused lasers capable of trapping individual atoms—that the team used to isolate and study the products of individual pairs of atoms.

A Collision Puzzle

As physicists work to improve control over atoms in optical tweezer experiments, JILA graduate student Steven Pampel, the paper’s first author, wanted to better understand how the rate at which light-assisted collisions occur changes under a range of circumstances. Light can create a wild array of outcomes, depending mostly on its frequency with respect to atomic transitions.

“Light-assisted collisions can generate large amounts of energy compared to what is often tolerated in the world of ultracold atomic gases,” Regal elaborates. “This energy is imparted to the colliding atoms, which can be considered bad as they are large enough to cause atoms to escape from typical traps. But these collisions can also be useful when that energy can be controlled.”



Exploiting the hyperfine structure in repulsive light-assisted collisions (LAC) on a ^{87}Rubidium atom pair in an optical tweezer. Credit: Steven Burrows/Regal group

In fact, the Regal group and other groups worldwide have previously used this energy to study how to load atoms into optical tweezers. However, a more comprehensive theoretical understanding of the collision process leading to such energy release was hard to come by, especially when considering atomic hyperfine structure—small energy shifts resulting from the coupling between an atom's nuclear spin and angular momentum from the atom’s electrons.

The basic model for light-assisted collisions has been understood for decades. In fact, the go-to model was developed by JILA Fellow Allan Gallagher and collaborator Prof. David Pritchard of MIT. But until recently, our understanding of light-assisted collisions came from very large optical traps that contain millions of atoms where the same light that confines the atoms also drives collisions, limiting control over the frequency of the light and information someone could obtain

To determine how fast the collisions occur, the researchers in Regal’s laboratory began their experiment by preparing exactly two rubidium atoms in an optical tweezer. To accomplish this, the team harnessed a technique where single atoms are loaded into two separate optical tweezers and then the atoms are merged into a single optical trap. After merging, a carefully controlled pulse of laser light was applied to drive collisions between the two atoms.

This collisional laser light excites the atoms, creating a quantum superposition state where either atom could have absorbed a photon, but it is unclear which one. In this state, electronic forces act at much larger distances than they otherwise would and give the atoms such a large amount of kinetic energy that they escape the trap. In this game of “quantum billiard balls”, the photon is like the cue ball that smashes into two other balls (the atoms) simultaneously, sending them flying off the table.

The team then varied the frequency of the collisional light, i.e., the energy of the photon “cue”, and measured how quickly atom-pairs escaped the optical tweezer.

“We set the laser at a certain frequency, then varied the duration of the collisional light to see how many atoms remained in the trap,” Pampel adds. “From this, we could determine how quickly the atoms collided and gained enough energy to escape. By repeating this process at different frequencies, we could map out the influence of hyperfine structure in these collisions.”

This process allowed the researchers to measure the loss rates of the atoms quantitatively and in relation to the hyperfine effects, something that had never been done before.

New Imaging Methods and Quasi-Molecular Stress

During the experiments, the team developed a novel imaging technique to accurately determine if both atoms remained in the trap after a collision. This technique was crucial because standard imaging methods in optical tweezers would inadvertently kick both atoms out of the trap during the collision, making it impossible to tell whether the collisional light or the imaging light kicked out the atoms.

“We came up with a method that uses a special type of light-assisted collisions where only one atom gets kicked out most of the time,” Pampel explains. “This allowed us to identify the presence of two atoms by detecting a single atom. This mechanism is commonly used for loading single atoms in tweezers, but we showed it can be used in a more controlled setting for two-atom detection purposes as well.”

The researchers also developed a theoretical model to understandd their experimental results, particularly why setting the light frequency to be close to that of certain hyperfine states resulted in different rates than other hyperfine states.

“Mapping out the potential energy curves for two colliding atoms in the presence of light and the hyperfine interaction required more complex analysis than previous works that had only taken into account the atomic fine structure—the interaction between electron’s spin and angular momentum,” D’Incao says.

This model could also be extended beyond rubidium atoms, helping to predict how other atomic elements might behave in similar situations.

Steven K. Pampel, Matteo Marinelli, Mark O. Brown, José P. D’Incao, and Cindy A. Regal. "Quantifying Light-Assisted Collisions in Optical Tweezers across the Hyperfine Spectrum." Physical Review Letters, 134 (1), 013202, 2025.

Written by Kenna Hughes-Castleberry

Trying to Solve a Key Black Hole Mystery: Simulating Magnetic Flows Around Black Holes

Black holes have been fascinating subjects of study, not just because they are cosmic vacuum cleaners, but also as engines of immense power capable of extracting and redistributing energy on a staggering scale. These dark giants are often surrounded by swirling disks of gas and dust, known as accretion disks. When these disks are strongly magnetized, they can act like galactic power plants, extracting energy from the black hole's spin in a process known as the Blandford-Znajek (BZ) effect.

While scientists have theorized that the BZ effect is the primary mechanism in the energy extraction process, many unknowns remain, like what determines how much energy is funneled into powerful jets—powerful streams of particles and energy ejected along the black hole's poles—or dissipated as heat.

To answer these questions, JILA postdoctoral researcher Prasun Dhang, and JILA Fellows and University of Colorado Boulder Astrophysical and Planetary Sciences professors Mitch Begelman and Jason Dexter, turned to advanced computer simulations. By modeling black holes surrounded by thin, highly magnetized accretion disks, they sought to uncover the underlying physics that drives these enigmatic systems. Their findings, published in *The Astrophysical Journal,* offer crucial insights into the complex physics around black holes and could redefine how we understand their role in shaping galaxies.

"It's long been known that infalling gas can extract spin energy from a black hole," elaborates Dexter. "Usually, we assume this is important for powering jets. By making more precise measurements, Prasun has shown there's a lot more energy extracted than previously known. This energy could be radiated away as light, or it could cause gas to flow outwards. Either way, extracted spin energy could be an important energy source for lighting up the regions near the black hole event horizon."

Comparing Black Hole to Black Hole

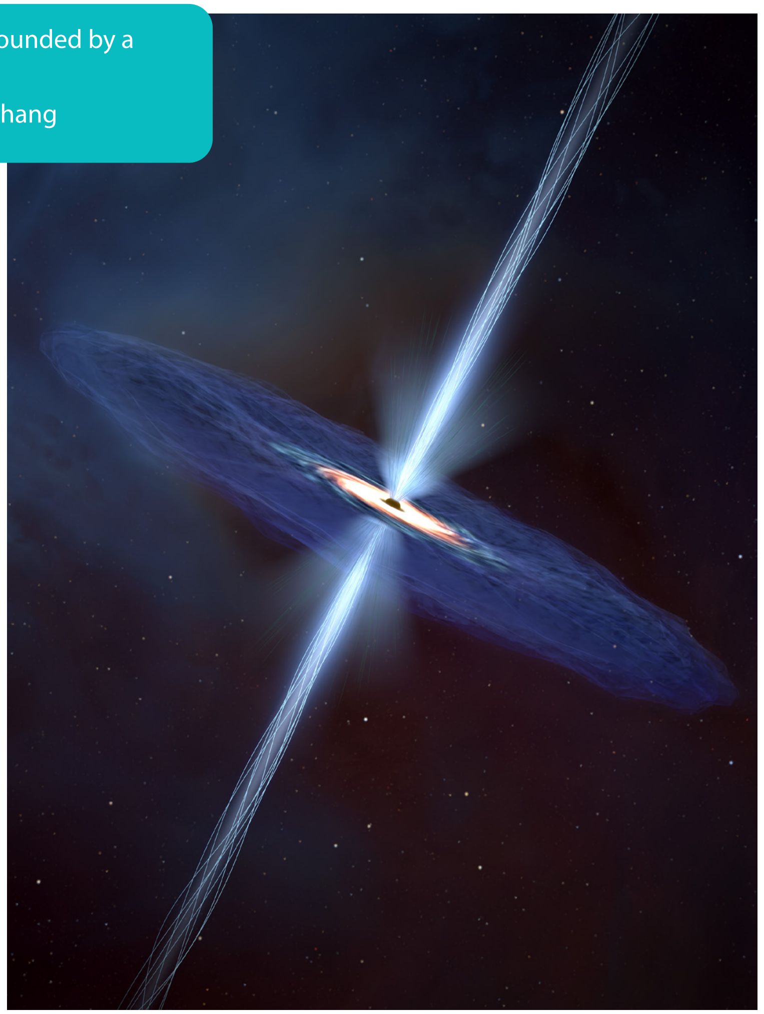
For decades, scientists have studied black holes and their interactions with surrounding gas and magnetic fields to understand how they power some of the universe's most energetic phenomena. Early research focused primarily on low-luminosity black hole sources with quasi-spherical accretion flow as these systems are comparatively easier to simulate and align with many observed jets.

However, high-luminosity black holes with geometrically thinner, denser magnetized disks present a unique challenge. These systems are theoretically unstable due to imbalances in heating and cooling.

Yet, previous studies, including those by Mitch Begelman, suggested that strong magnetic fields might stabilize these thin disks, but the details of their role in energy extraction and jet formation remained unclear in such conditions.

"We wanted to understand how energy extraction works in these highly magnetized environments," Dhang explains.

The team used advanced computer simulations to explore this phenomenon, specifically, a special type of model called the 3D general relativistic magnetohydrodynamic (GRMHD) model. The GRMHD model works as a computational framework that simulates the behavior of magnetized plasma in the curved spacetime around black holes, combining the physics of magnetic fields, fluid dynamics, and Einstein's theory of general relativity to capture the complex interactions in these extreme environments. Using the framework, the researchers observed how magnetic fields interacted with black holes spinning at different speeds.



Artist render of a black hole surrounded by a highly magnetized thin disk.
Credit: Steven Burrows/Prasun Dhang

"The goal was to see how magnetic flux threading [permeating] the black hole impacts energy extraction and whether it leads to the formation of jets," Dhang says.

The simulations modeled thin, magnetized accretion disks and examined how much energy the black hole transferred to its surroundings. By studying the efficiency of this energy extraction, the team identified various black hole spins and magnetic configurations with jets.

Manifestation of BZ Power

From their simulations, the team found that depending on the black hole's spin, between 10% and 70% of the energy extracted through the BZ process was channeled into jets.

"The higher the spin, the more energy the black hole can release," Dhang notes.

However, not all energy went into jets; some was absorbed back into the disk or dissipated as heat.

While the simulations couldn't determine where the excess energy went, Dhang plans to study this further to better understand how jets form, as jets are often found in active galactic nuclei systems such as quasars.

Mysteries Continue

From their models, the researchers found that the strong magnetic fields increased the disk's radiative efficiency, making it brighter. This extra luminosity may explain why some black holes appear far more luminous than theoretical models predict.

"The unused energy close to the black hole could heat the disk and contribute to a corona," Dhang notes.

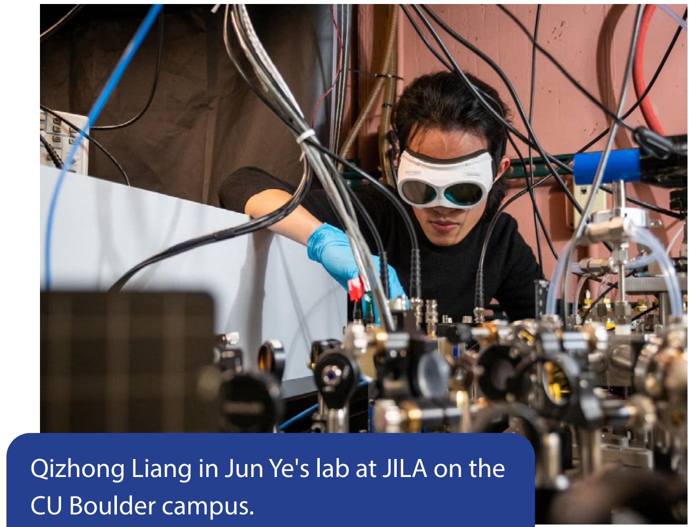
The corona, a region of hot gas surrounding the black hole that emits intense x-rays, is crucial for shaping the light we observe from these systems, but its exact formation process remains unclear.

The researchers hope to use further simulations to understand the dynamics of making a black hole corona.

Prasun Dhang, Jason Dexter, and Mitchell C. Begelman. " Energy Extraction from a Black Hole by a Strongly Magnetized Thin Accretion Disk" The Astrophysical Journal, 980(2), 203, 2025.

Written by Kenna Hughes-Castleberry

New Sensor Can Take Any Gas and Tell You What’s in It



Qizhong Liang in Jun Ye's lab at JILA on the CU Boulder campus.
Credit: Patrick Campbell/CU Boulder

Expert sommeliers can take a whiff of a glass of wine and tell you a lot about what’s in your pinot noir or cabernet sauvignon.

A team of physicists at CU Boulder and the National Institute of Standards and Technology (NIST) have achieved a similar feat of sensing, only for a much wider range of substances.

The group has developed a new laser-based device that can take any sample of gas and identify a huge variety of the molecules within it. It is sensitive enough to detect those molecules at minute concentrations all the way down to parts per trillion. Its design is also simple enough that researchers could employ the method quickly and at a low cost in a range of settings, from diagnosing illnesses in human patients to tracking greenhouse gas emissions from factories.

The study was led by scientists at JILA, a joint research institute between CU Boulder and NIST. The team published its findings on Feb. 19 in the journal *Nature*.

“Even today I still find it unbelievable that the most capable sensing tool can in fact be built with such simplicity, using only mature technical ingredients but tied together with a clever computation algorithm,” said Qizhong Liang, lead author of the research and a doctoral student at JILA.

To show what the tool is capable of, Liang and his colleagues drilled down on an important question in medicine: What’s in the air you breathe out?

The researchers analyzed breath samples from real human subjects and showed that they could, for example, identify the types of bacteria living in peoples’ mouths. The technique could one day help doctors diagnose lung cancer, diabetes, chronic obstructive pulmonary disease (COPD) and much more.

Physicist Jun Ye, senior author of the study, said the new work builds on nearly three decades of research into quantum physics at CU Boulder and NIST—especially around a type of specialized device known as a frequency comb laser.

“The frequency comb laser was originally invented for optical atomic clocks, but very early on, we identified its powerful application for molecular sensing,” said Ye, a fellow of JILA and NIST and professor adjoint of physics at CU Boulder. “Still, it took us 20 years to mature this technique, finally allowing universal applicability for molecular sensing.”

A Shaking Cavity

To understand how the team’s technology works, it helps to understand that all gases, from pure carbon dioxide to your stinky breath after you eat garlic, carry a fingerprint of sorts.

If you probe those gases with a laser that spans multiple “optical frequencies,” or colors, the molecules in the gas samples will absorb that light at different frequencies. It’s almost like a burglar leaving behind a thumbprint at a crime scene. In a previous study, for example, Liang and his colleagues used this laser absorption detection principle to screen human breath samples for signs of SARS-CoV-2 infections.

Frequency combs are well suited to that technique because, unlike traditional lasers, they emit pulses of light in thousands to millions of colors at the same time. (JILA’s Jan Hall pioneered these lasers, winning the Nobel Prize in Physics for his work in 2005).

But to detect molecules at low concentrations, those lasers must also pass through the gas sample over distances of miles or more so that the molecules can absorb enough light.

To be practical, scientists must realize that distance within containers for gases that are measured on the scale of a foot.

“We enclose the gas sample with a pair of high-reflectivity mirrors, forming an ‘optical cavity,’” Liang said. “The comb light can now bounce between those mirrors several thousand times to effectively increase its absorption path length with the molecules.”

Or that’s the goal. In practice, optical cavities are tricky to work with and eject laser beams if they aren’t properly matched to the resonant modes of the cavity. As a result, scientists previously could only use a narrow range of comb light, and detect a narrow range of molecules, in a single test.

In previous research, Ye, Liang and their colleagues used specialized lasers to detect signs of COVID-19 infections in human breath. (Credit: NIST)

In the new study, Liang and his colleagues overcame this longstanding challenge. They presented a new technique they named Modulated Ringdown Comb Interferometry, or MRCI (pronounced “mercy”). Rather than keep its optical cavity steady, the team periodically changed its size. This jiggling, in turn, allowed the cavity to accept a much wider spectrum of light. The team then deciphered the complicated laser intensity patterns emerging from the cavity with computational algorithms to determine the samples’ chemical contents.

“We can now use mirrors with even larger reflectivity and send in comb light with even broader spectral coverage,” Liang said. “But this is just the beginning. Even better sensing performance can be established using MRCI.”

A Sensor for Breath

The team is now turning its new gas sniffer on human breath.

“Exhaled breath is one of the most challenging gas samples to be measured, but characterizing its molecular compositions is highly important for its powerful potential for medical diagnostics,” said Apoorva Bisht, co-author of the research and a doctoral student in Ye’s lab.

Bisht, Liang and Ye are now collaborating with researchers at CU Anschutz Medical Campus and Children’s Hospital Colorado to use MRCI to analyze a range of breath samples. They are examining whether MRCI can distinguish samples taken from children with pneumonia from those taken from children with asthma. The group is also analyzing the breath of lung cancer patients before and after tumor removal surgery and is exploring whether the technology can diagnose people in early stages of chronic obstructive pulmonary disease (COPD).

“It will be tremendously important to validate our approach on real world human subjects,” Ye said. “Through close collaboration with our medical colleagues at CU Anschutz, we are committed to developing the full potential of this technique for medical diagnosis.”

Qizhong Liang, Apoorva Bisht, Andrew Scheck, Peter G. Schunemann & Jun Ye. "Modulated ringdown comb interferometry for sensing of highly complex gases." Nature, 638, 941–948 . 2025.

Written by Dan Strain

JILA News

News

Introducing the Next "Humans of JILA" podcast: CU Phonon Club. Many researchers at JILA and CU Boulder study phonons—tiny quantum packets of sound that play a crucial role in condensed matter physics and quantum materials. To unite this growing research community, JILA scientists established the CU Phonon Club, a collaborative space for sharing insights through regular seminars. In this episode of *Humans of JILA,* we hear from Joshua Knobloch (Assistant Professor, Utah State University), Brendan McBennett (Postdoctoral Researcher, NIST), and Emma Nelson (JILA Graduate Student) as they discuss the science behind phonons, the impact of the CU Phonon Club, and how it fosters collaboration in Colorado's quantum research ecosystem.

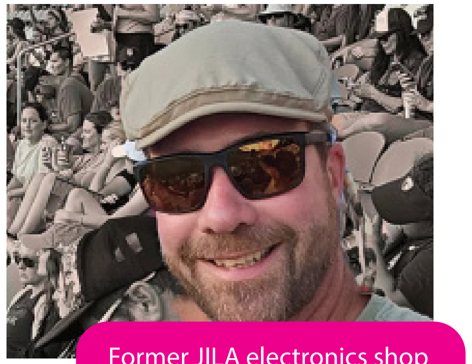
Remembering Former JILA Electronics Shop Member Carl Sauer. Carl Sauer, a distinguished electrical engineer, passed away on February 2, 2025. He is survived by his wife and two sons, Carl and Evan. Sauer's passion for electrical engineering led him to a remarkable career marked by innovation and dedication.

Sauer earned his Bachelor of Science in Electrical Engineering with honors from Michigan State University in 2002. He then completed a graduate certificate in engineering management from University of Colorado Boulder in 2020 and was pursuing a master's degree in engineering management at CU Boulder at the time of his passing.

Sau began his professional journey at JILA, where he contributed significantly to the electronics shop. His work at JILA was instrumental in supporting various research initiatives, reflecting his commitment to advancing scientific understanding.

In 2019, Sauer joined Honeywell Quantum Solutions as an Advanced Electrical Engineer, where he played a pivotal role in developing cutting-edge quantum computing technologies. Following the merger that formed Quantinuum, Sauer continued his work as a Senior Advanced Electrical Engineer, contributing to groundbreaking projects that have left a lasting impact on the industry.

Beyond his professional achievements, Sauer was known for his collaborative spirit and mentorship. His colleagues remember him as a dedicated professional who approached challenges with enthusiasm and creativity.



Former JILA electronics shop member Carl Sauer
Credit: Sauer family

*CU Boulder Physics and JILA Students Lead the 2025 CU*iP Conference,* Inspiring Future Physicists. In January, 180 undergraduate students gathered in the Duane Physics building at the University of Colorado Boulder for the Conference for Undergraduate Women and Gender Minorities in Physics (CU*iP).This annual three-day event, sponsored by the American Physical Society, aimed to support and inspire undergraduate women and gender minorities to continue their degrees and explore the various places their education can take them.

The local organizing committee (LOC), composed primarily of graduate and undergraduate students from CU Boulder—with guidance from two University of Colorado Boulder Physics professors, including Bethany Wilcox—volunteered to help organize the event over the past year. The LOC worked hard to ensure that programming reflected the needs of attendees—especially given the diverse backgrounds of students arriving from different institutions. As many of the organizers had attended CU*iP conferences as undergraduates, they hoped to pass on the crucial lessons they learned to the inspiring scientists.

JILA Awards

Awards

JILA Fellow and University of Colorado Boulder APS Distinguished Professor Mitch Begelman is Inducted as 2025 AAS Fellow. Professor Begelman was honored for his pioneering analytical and computational studies of high-energy astrophysical phenomena, including developing the "quasi-star theory" explaining the formation of supermassive black holes. His dedication to public engagement has further enriched the public's understanding of black holes through two acclaimed books.

"I am deeply honored to be recognized by the AAS and to share this distinction with my esteemed colleagues," said Begelman. "This recognition reflects the collaborative spirit of research at CU Boulder and JILA, where groundbreaking ideas flourish."

JILA Graduate Student Clay Klein is Awarded 2025 Nick Cobb Memorial Scholarship, presented by SPIE, the International Society for Optics and Photonics, and Siemens EDA. The scholarship, valued at $10,000, recognizes Klein's outstanding contributions to the field of optics and photonics.

"I am honored to be awarded the Nick Cobb Memorial Scholarship," Klein stated. "This scholarship provides me with the exciting opportunity to share my research in this field and connect with others in the industry at the SPIE conference in February."

Klein conducts research in the laboratories of JILA Fellows and University of Colorado Boulder physics professors Margaret Murnane and Henry Kapteyn. His work focuses on cutting-edge advancements in nanoscale extreme ultraviolet imaging science.

JILA Fellow and NIST Physicist and CU Boulder Physics Professor Adam Kaufman has been awarded the prestigious Presidential Early Career Award for Scientists and Engineers (PECASE). President Joe Biden announced that this accolade represents the highest honor conferred by the U.S. government to early-career scientists and engineers who exhibit extraordinary potential and leadership in their respective fields. Kaufman's groundbreaking contributions to quantum science have cemented his place among nearly 400 recipients recognized for their innovative research and commitment to advancing scientific frontiers.

"I feel very honored to receive the PECASE in recognition of my group's work over the past several years," Kaufman says. "I am also very appreciative of the unique environment at JILA, from administrative to shop support, that enables so much of our research."

JILA Graduate Students Anya Grafov and Iona Binnie Receive Top Honors at MMM Intermag 2025 Conference. Grafov earned first place in the Young Professionals Lightning Talks for her presentation, "Measuring Magnetic Dynamics with Extreme Ultraviolet Light," while Binnie won the Best Poster Award in her session for her poster, "Probing Skyrmions via High Harmonic Driven Ultrafast Magnetic Scattering and Coherent 3D X-ray Vector Ptychography."

"Presenting my poster was a demanding but very rewarding experience," added Binnie. "I really enjoyed the opportunity to share my research with the magnetics community, which is a different audience than I am used to. Their questions sparked new insights into my own research challenges."

JILA graduate student Clay Klein has been awarded the 2025 Nick Cobb Memorial Scholarship by SPIE.
Credit Kenna Hughes-Castleberry/JILA

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

University of Colorado **Boulder**

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

About JILA

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

JILA's faculty includes two Nobel laureates, Eric Cornell and John Hall, as well as two John D. and Catherine T. MacArthur Fellows, Margaret Murnane and Ana Maria Rey. JILA's CU members hold faculty appointments in the Departments of Physics; Astrophysical & Planetary Science; Chemistry; Biochemistry; and Molecular, Cellular, and Developmental Biology, as well as in the School of Engineering.

The wide-ranging interests of our scientists have made JILA one of the nation's leading research institutes in the physical sciences. They explore some of today's most challenging and fundamental scientific questions about quantum physics, the design of precision optical and x-ray lasers, the fundamental principles underlying the interaction of light and matter, and processes that have governed the evolution of the Universe for nearly 14 billion years. Research topics range from the small, frigid world governed by the laws of quantum mechanics through the physics of biological and chemical systems to the processes that shape the stars and galaxies. JILA science encompasses eight broad categories: Astrophysics, Atomic & Molecular Physics, Biophysics, Chemical Physics, Laser Physics, Nanoscience, Precision Measurement, and Quantum Information Science & Technology.

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