LIGHT + MATTER

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JILA
CU Boulder and NIST

The participants of JILA's 2023 pumpkin carving contest (left to right): Missy Gillam, Joyce Kroll, Francesca Fama, Henrik Hirzler, Hui Li, Lane Terry, Maddie Klumb, John Wilson, and Lyryl Varekamp

Credit: Christine Jackson/JILA

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Research Highlights

Feature Articles

Diamonds in the Quantum Rough: A Sparkling Breakthrough

In quantum information science, many particles can act as “bits,” from individual atoms to photons. At JILA, researchers utilize these bits as “qubits,” storing and processing quantum 1s or 0s through a unique system.

While many JILA Fellows focus on qubits found in nature, such as atoms and ions, JILA Associate Fellow and University of Colorado Boulder Assistant Professor of Physics Shuo Sun is taking a different approach by using “artificial atoms,” or semiconducting nanocrystals with unique electronic properties. By exploiting the atomic dynamics inside fabricated diamond crystals, physicists like Sun can produce a new type of qubit, known as a “solid-state qubit," or an artificial atom.

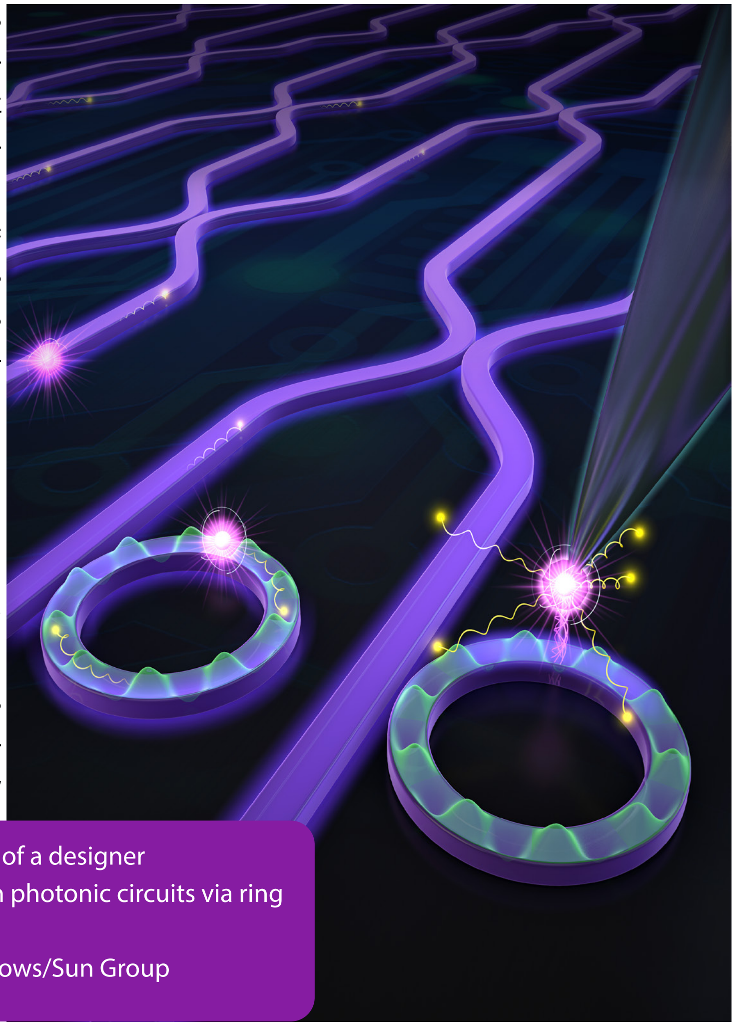
Because these artificial atoms do not move, one way to let them talk to each other is to place them inside a photonic circuit. The photons traveling inside the photonic circuit can connect different artificial atoms. Like hot air moving through an air duct to warm a cold room, photons move through the quantum circuit to induce interactions between the artificial atoms. “Having an interface between artificial atoms and photons allows you to achieve precise control of the interactions between two artificial atoms,” explained Sun.

Historically, there have been problems with integrating artificial atoms with photonic circuits. This is because creating the artificial atoms (where atoms are knocked out of a diamond crystal) is a very random process, leading to random placement of the artificial atoms, random numbers of artificial atoms at each location, and random colors each artificial atom emits.

Adding to the issue is the incompatibility between the material that hosts the artificial atoms and the material that hosts the photonic circuit. Despite years of research, scientists have yet to find a suitable material that can be a good host of both, making the integration more difficult.

In a new *Nano Letters* paper, Sun, his research team, and collaborators from Stanford University proposed a new method that would pave the way to solving these two challenges, enabling a more complicated integrated quantum photonic circuit.

This new technique suggests bigger implications for the future of quantum information science, including a way to scale up the circuits. “We now have a way to integrate multiple artificial atoms on one photonic chip,” explained first author and JILA graduate student Kin Fung Ngan.



Hybrid integration of a designer nanodiamond with photonic circuits via ring resonators.
Credit: Steven Burrows/Sun Group

Combining Diamonds with Other Materials

Historically, diamond has been a popular choice for hosting artificial atoms, as it’s incredibly pure with a large bandgap, allowing physicists more control over the excitation of the atom inside the crystal.

“Our qubits are embedded into the diamond,” explained Ngan. “The benefit here is that we don't need any additional apparatus to hold them in space.”

However, the downside of using a diamond as a qubit host is that it’s incredibly hard to carve, making it difficult to define photonic circuits on them. It is also difficult to get a large diamond piece, unlike other photonic materials such as silicon nitride, where eight-inch wafers are readily available.

To make a large quantum photonic circuit, the diamond-based artificial atoms must be placed inside a photonic circuit based on a different material, such as silicon nitride. Sun, Ngan, and JILA graduate student Yuan Zhan had to find ways to integrate the two different components residing in different materials. “If the integration was not achieved properly, you may have a weaker coupling between the atom and the photon or a loss of photons during transmission. These effects will generate errors when we use photons to mediate interactions between two artificial atoms,” elaborated Sun.

While previous studies tried to combine the two materials using external junctions, the researchers took a different approach by embedding a nanosized chunk of diamond containing the artificial atom directly inside the silicon nitride circuit. Using an ultraprecise placement method for arranging the nanodiamonds on the chip, the researchers added nanodiamonds containing an artificial atom to the chip, coated the entire chip with a silicon nitride layer, and then fabricated photonic circuits centered around each atom. This process ensures the maximum coupling between the artificial atom and the photonic circuit.

Testing the New Experimental Setup

After embedding the artificial atoms into the silicon nitride circuit, the researchers tested the coupling efficiency by exciting the artificial atoms and measuring the light collected by the photonic circuit. Their tests showed that the light shone brighter when the atom was placed inside an optical cavity, revealing the ability to efficiently couple light from the artificial atom to the photonic circuit.

Besides contributing to better compatibility, the ultraprecise placement technique allowed researchers to align several artificial atoms in a row on the same circuit, showing the flexibility of their process and its capability to host multiple qubits at once. Currently, Ngan, Zhan, and other JILA researchers are working on techniques to make these artificial atoms interact with each other with the help of photons and to entangle two artificial atoms with the help of photons.

A Duality in Design

While this current quantum photonic circuit leverages photons as mediators for interactions between the artificial atoms (or qubits), the photons themselves can also act as separate qubits within the system. “The circuit can indeed work for two purposes,” Sun elaborated. “By embedding artificial atoms inside a photonic quantum circuit, we can use the artificial atoms as sources and memories of single photons, potentially reducing the resource required to build a photonic quantum processor.” The combination of the material compatibility and the duality of the qubits in the system suggests that Sun’s circuit design could have big implications for the future of quantum information, offering an effective way to scale up the integrated quantum photonic systems.

Kinfung Ngan, Yuan Zhan, Constantin Dory, Jelena Vučković, and Shuo Sun. "A Quantum Photonic Circuits Integrated with Color Centers in Designer Nanodiamonds." Nano Letters, 23(20), 9360–9366, 2023.

Written by Kenna Hughes-Castleberry,

Questions about Quasars: How to Best Weigh a Celestial Body

In a new paper in *The Astrophysical Journal,* JILA Fellow and Assistant Professor of Astrophysical and Planetary Sciences Jason Dexter, graduate student Kirk Long, and other collaborators compared two main theoretical models for emission data for a specific quasar, 3C 273. Using these theoretical models, astrophysicists like Dexter can better understand how these quasars form and change over time.

Quasars, a type of active galactic nuclei (AGN), are believed to be powered by supermassive black holes at their centers. Among the brightest objects in the universe, quasars emit a brilliant array of light across the electromagnetic spectrum. This emission carries vital information about the nature of the black hole and surrounding regions, providing clues that astrophysicists can exploit to better understand the black hole's dynamics.

A Tale of Two Models

Light emission from a quasar gives astrophysicists many insights into the mechanics of the supermassive black hole. For Dexter and Long, the emission data from quasar 3C 273 came from GRAVITY, an instrument on Chile's Very Large Telescope Interferometer (VLTI). "Specifically, we used near-infrared light—too red for your eyes to see but still close enough to the visible spectrum that a normal [optical] telescope mirror reflects it—to look at quasar 3C 273 in this work, as the emission line we care about emits in this wavelength regime," explained Long.

Per previous findings, Long and Dexter expected the GRAVITY emission data to reveal one peak for quasar 3C 273. While this single peak is a hallmark of quasar emission spectra, the mechanism that produces it is still up for debate, as some people believe that this comes from the emission falling into the black hole and swirling within the galactic whirlpool.

"But how far does this geometry extend?" asked Long. "If you were to think about this area where these emission lines come from—which we call the broad-line region—if you imagine that as a spinning disk emitting isotropically, where every part of the disk is glowing at the same temperature, you would expect to see two emission peaks. "This is because one peak is red-shifted toward the viewer and one blue-shifted away from the viewer due to the Doppler effect.

However, as seen in the data from quasar 3C 273 (and many other quasars), there aren't two peaks but just one. This means that the emission from the quasar is not following the simplest model, and something more complicated is happening. Astrophysicists apply various models to their data to examine the mechanisms causing the one emission peak.

To better understand the data variations, Dexter and Long looked at the two main theoretical models proposed as possible underlying mechanisms: the cloud and disk-wind models. For Dexter, comparing these two models could offer more insight into the modeling process itself.

Dexter added: "In this particular case, we can also check consistency because we know how we look at this black hole from other data. The view that [a] particular model [may] not match the other data. So we can say that that's probably a disfavored solution. It's important for future work to keep in mind that the model you choose impacts the measurements you get. So, we aren't going to know how we're looking at these systems in general, which means it's important to try to figure out which of these models holds water in the biggest number of cases."

The cloud model proposes that the emission lines observed in quasar spectra arise from clouds of ionized gas near the central black hole. Long elaborated: "There are basically a bunch of clouds chaotically spinning around the black hole. Those clouds make the single peak because you've filled in more of a spherical type geometry instead of just a disk, like a star. So, you can get one peak because most of the emitting gas isn't moving towards or away from you. The clouds are on weird tilted orbits but still in stable orbits so you can weigh the black hole."

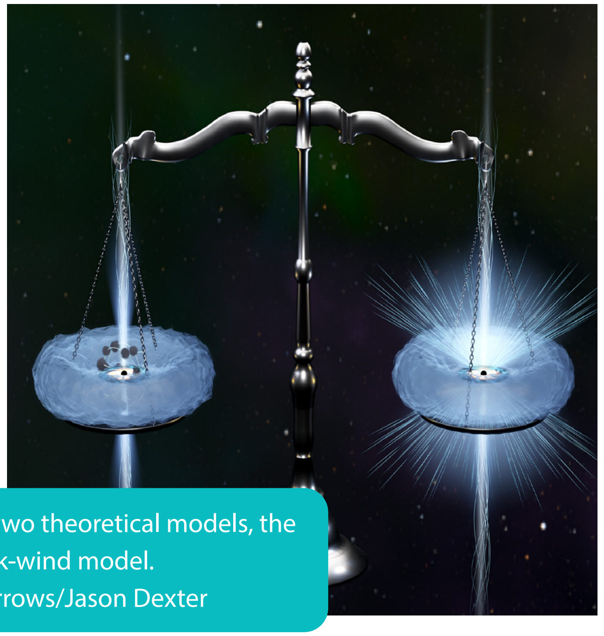
While the cloud model fits several quasar data sets, the mechanics don't seem to add up. "There's this mystery that you assume that the clouds should be falling in and swirling around in this disk," Dexter stated. "But, if this process produces atomic gas transitions, it should produce these two peaks where you see lines. But that's not what we see; it's always the single peak." To explain this difference, several astrophysicists theorize that the atomic gases have puffed up, causing a change in the emission spectra.

To address the disparity between the one- and two-peak emission lines, other astrophysicists proposed a different model called the disk-wind model. This model suggests that the observed quasar emissions come from the "footprints" of winds embedded in the disk. Long explained: "In this model, you can still have a thin disk all the way out to the broad-line region, but now your extra assumption is that you will add shears to the disk. In our study, we added a couple of different shears because we see observational evidence for outflows and inflows, where gases are being blown away or blown in from this region."

Comparing Models and Data

Using the University of Colorado Boulder's supercomputing system, Dexter and Long applied the disk-wind model to the quasar 3C 273 data set to see how well it fit. From their computations, Dexter and Long found that the disk-wind model would indeed change the calculated amount for black hole mass by a factor of 5.

But the disk-wind model had more uncertainties than the cloud model, which Dexter previously analyzed. "I think, while we disfavored the disk-wind model based on our results, the only reason we can disfavor it for quasar 3C 273 is not that it actually fits the data that much worse—it actually fits the data about as well as the cloud model—it's that it requires you to be looking at the disk in a different way than the way you would be looking at the-



A comparison of two theoretical models, the cloud and the disk-wind model.
Credit: Steven Burrows/Jason Dexter

clouds," Long explained.

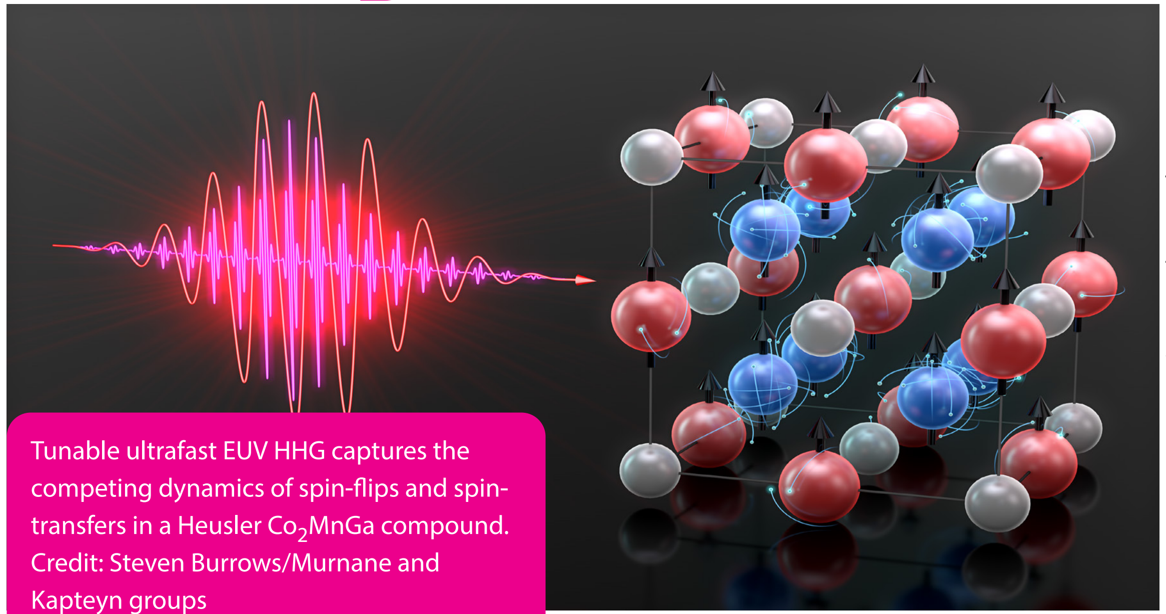
By fitting the disk-wind model to the data, Long and Dexter had to reorient their view of 3C 273 and look at it sideways. "That tells us that maybe this version of our proposed model is wrong," added Long. "But there may be other things we could add to the disk-wind model that could better align it to the jet, so we don't rule it out completely."

From their results, Dexter and Long can better understand how these uncertainties may affect the larger process of "weighing" supermassive black holes, which can be utilized by other astrophysicists to better understand the dynamics of quasars.

Kirk Long, Jason Dexter, Yixian Cao, Ric Davies, Frank Eisenhauer, Dieter Lutz, Daryl Santos, Jinyi Shangguan, Taro Shimizu, and Eckhard Sturm, "Confronting a Thin Disk-wind Launching Mechanism of Broad-line Emission in Active Galactic Nuclei with GRAVITY Observations of Quasar 3C 273." The Astrophysical Journal. 953(2), 184, 2023.

Written by Kenna Hughes-Castleberry,

Unlocking the Secrets of Spin with High-Harmonic Probes



Tunable ultrafast EUV HHG captures the competing dynamics of spin-flips and spin-transfers in a Heusler Co_2MnGa compound. Credit: Steven Burrows/Murnane and Kapteyn groups

Deep within every piece of magnetic material, electrons dance to the invisible tune of quantum mechanics. Their spins, akin to tiny atomic tops, dictate the magnetic behavior of the material they inhabit. This microscopic ballet is the cornerstone of magnetic phenomena, and it's these spins that a team of JILA researchers—headed by JILA Fellows and University of Colorado Boulder physics professors Margaret Murnane and Henry Kapteyn—has learned to control with remarkable precision, potentially redefining the future of electronics and data storage.

As reported in a new *Science Advances* paper, the JILA team, and collaborators from universities in Sweden, Greece, and Germany, probed the spin dynamics within a special material known as a Heusler compound: a mixture of metals that behaves like a single magnetic material. For this study, the researchers utilized a compound of cobalt, manganese, and gallium, which behaved as a conductor for electrons whose spins were aligned upwards and as an insulator for electrons whose spins were aligned downwards.

Using a form of light called extreme ultraviolet high-harmonic generation (EUV HHG) as a probe, the researchers could track the re-orientations of the spins inside the compound after exciting it with a femtosecond laser, which caused the sample to change its magnetic properties. The key to accurately interpreting the spin re-orientations was the ability to tune the color of the EUV HHG probe light.

"In the past, people haven't done this color tuning of HHG," explained co-first author and JILA graduate student Sinéad Ryan. "Usually, scientists only measured the signal at a few different colors, maybe one or two per magnetic element at most." In a historic first, the JILA team tuned their EUV light probe across the magnetic resonances of each element within the compound to track the spin changes with a precision down to femtoseconds (a quadrillionth of a second).

"On top of that, we also changed the laser excitation fluence, so we were changing how much power we used to manipulate the spins," Ryan elaborated, highlighting that that step was also an experimental first for this type of research. By changing the power, the researchers could influence the spin changes within the compound.

Using their novel approach, the researchers collaborated with theorist and co-first author Mohamed Elhanoty of Uppsala University, who visited JILA, to compare theoretical models of spin changes to their experimental data. Their results showed strong correspondence between data and theory. "We felt that we'd set a new standard with the agreement between the theory and the experiment," added Ryan.

To dive into the spin dynamics of their Heusler compound, the researchers brought an innovative tool to the table: extreme ultraviolet high-harmonic probes. To produce the probes, the researchers focused 800-nanometer laser light into a tube filled with neon gas, where the laser's electric field pulled the electrons away from their atoms and then pushed them back. When the electrons snapped back, they acted like rubber bands released after being stretched, creating purple bursts of light at a higher frequency (and energy) than the laser that kicked them out. Ryan tuned these bursts to resonate with the energies of the cobalt and the manganese within the sample, measuring element-specific spin dynamics and magnetic behaviors within the material that the team could further manipulate.

A Competition of Spin Effects

In their experiment, the researchers found that by tuning the power of the excitation laser and the color (or the photon energy) of their EUV probe, they could determine which spin effects were dominant at different times within their compound. They compared their measurements to a complex computational model called time-dependent density functional theory (TD-DFT). This model predicts how a cloud of electrons in a material will evolve from moment to moment when exposed to various inputs.

Using the TD-DFT framework, Elhanoty found agreement between the model and the experimental data due to competing spin effects within the Heusler compound: spin flips up or down and spin transfers. The spin flips happen within one element in the sample as the spins shift their orientation from up to down and vice versa. In contrast, spin transfers happen within multiple elements (in this case, cobalt and manganese) as they transfer spins between each other, causing each material to become more or less magnetic as time progresses. "What he [Elhanoty] found in the theory was that the spin flips were quite dominant on early timescales, and then the spin transfers became more dominant," explained Ryan. "Then, as time progressed, more de-magnetization effects take over, and the sample de-magnetizes."

Designing More Efficient Materials

Understanding which effects were dominant at which energy levels and times allowed the researchers to understand better how spins could be manipulated to give materials more powerful magnetic and electronic properties.

"There's this concept of spintronics, which takes the electronics that we currently have, and instead of using only the electron's charge, we also use the electron's spin," elaborated Ryan. "So, spintronics also have a magnetic component. Using spin instead of electronic charge could create devices with less resistance and less thermal heating, making devices faster and more efficient."

From their work with Elhanoty and their other collaborators, the JILA team gained a deeper insight into spin dynamics within Heusler compounds. Ryan said: "It was really rewarding to see such a good agreement with the theory and experiment when it came from this really close and productive collaboration as well." The JILA researchers hope to continue this collaboration in studying other compounds to understand better how light can be used to manipulate spin patterns.

Sinéad A. Ryan, Peter C. Johnsen, Mohamed F, Elhanoty, Anya Grafov, Na Li, Anna Delin Anastasios Markou, Edouard Lesne, Claudia Felser, Olle Eriksson, Henry C. Kapteyn, Oscar Grånäs, and Margaret M. Murnane. " Optically controlling the competition between spin flips and intersite spin transfer in a Heusler half-metal on sub–100-fs time scales." Science Advances 9(45), eadi14282023, 2023.

Written by Kenna Hughes-Castleberry

Making Use of Quantum Entanglement

Quantum sensors help physicists understand the world better by measuring time passage, gravity fluctuations, and other effects at the tiniest scales. For example, one quantum sensor, the LIGO gravitational wave detector, uses quantum entanglement (or the interdependence of quantum states between particles) within a laser beam to detect distance changes in gravitational waves up to one thousand times smaller than the width of a proton!

LIGO isn't the only quantum sensor harnessing the power of quantum entanglement. This is because entangled particles are generally more sensitive to specific parameters, giving more accurate measurements.

While researchers can generate entanglement between particles, the entanglement may only be useful sometimes for sensing something of interest. To measure the “usefulness” of quantum entanglement for quantum sensing, physicists calculate a mathematical value, known as the Quantum Fisher Information (QFI), for their system. However, physicists have found that the more quantum states in the system, the harder it becomes to determine which QFI to calculate for each state.

To overcome this challenge, JILA Fellow Murray Holland and his research team proposed an algorithm that uses the Quantum Fisher Information Matrix (QFIM), a set of mathematical values that can determine the usefulness of entangled states in a complicated system.

Their results, published in *Physical Review Letters* as an Editor’s Suggestion, could offer significant benefits in developing the next generation of quantum sensors by acting as a type of “shortcut” to find the best measurements without needing a complicated model.

“Being able to lay out a roadmap that allows you to understand the usefulness of entanglement in higher-level systems is a fundamental solution in quantum information science,” said Holland.

Looking at Multiple Dimensions

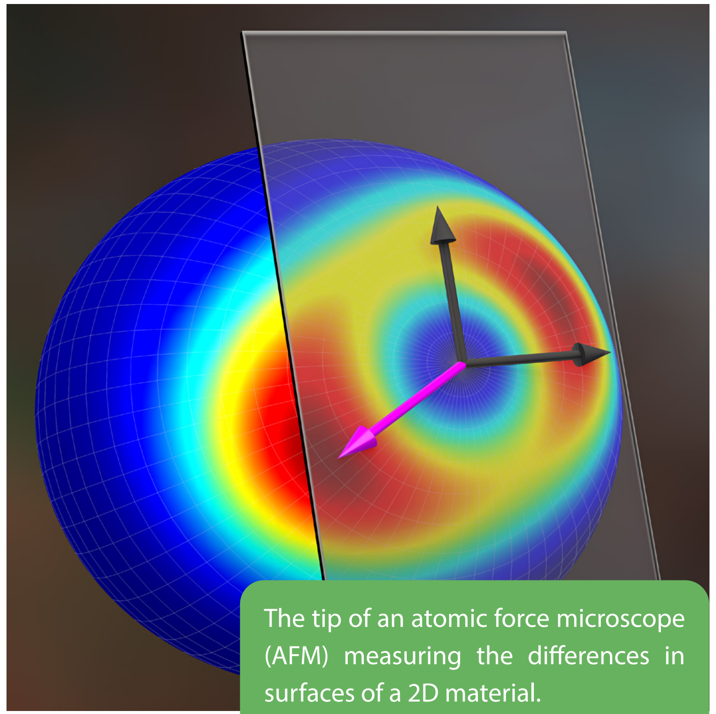
Most theoretical physicists researching quantum information science (which includes quantum sensing) focus on a system known as a quantum bit, or "qubit," graphically represented by a Bloch sphere or a 3D visual representation of all possible states of a qubit. A qubit is considered an SU(2) system where SU(*n*) is a simple way to mathematically describe how things in the quantum world can change and interact by exploiting the system’s symmetry. A qubit is considered an SU(2) system as it has a symmetry between two quantum levels, but as the number of levels go up, so does the SU(*n*).

Because these SU(*n*) systems can describe quantum entanglement, things get complicated quickly when *n* increases, as the system can exhibit multiple dimensions or ways that properties like entanglement can change in a multi-state system.

“You can think of the SU(*n*) system as putting a bunch of dots on a piece of paper and drawing a red, blue, and green line between these dots,” explained Jarrod Reilly, one of the paper’s first co-author and a graduate student in Holland’s group. The dots represent the different quantum states, while the lines highlight how the states “interact” with each other.

Instead of studying the SU(2) system with two distinct states (also known as degrees of freedom), Holland and his team looked at the SU(4) system, which describes four independent states. When studying the SU(4) setup, the researchers realized they were dealing with a mind-boggling 15 dimensions for how entanglement and other properties could change in the system!

Quickly, the team understood that a simple brute force calculation for the best use of the SU(4) system’s entanglement would be nearly impossible. “We had these states in this four-level system that were super complicated; we had no way of visualizing it,” elaborated John Wilson, a graduate student in the Holland group and the paper’s other first co-author.



The tip of an atomic force microscope (AFM) measuring the differences in surfaces of a 2D material.
Image Credit: Steven Burrows/Raschke Groups

To make it easier to calculate the QFI for these 15 dimensions, the researchers created an algorithm utilizing the QFIM, resulting in the best possible QFI value for the system. “We've come up with a method using the Quantum Fisher Information Matrix which says, here is the set of quantities for a given complicated state; these are the quantities that the state carries the most [useful] information about,” added Wilson.

Mathematical Shortcuts to Usefulness

Thanks to this algorithm, scientists have a type of “shortcut” that can give them the values of usefulness for more complicated systems without having to entangle them experimentally.

“If you have an experiment with complicated physics, you don't need a full model to pull out how entanglement in the sensor could be used.” elaborated Holland. “To test if it's a good sensor, you only need to know the underlying symmetries of what you want to sense.”

The other benefit of this new algorithm is that it can work on almost any complicated quantum setup, making it useful for physicists in advancing current levels of quantum sensing technology.

Reilly elaborated that the algorithm works as an optimization problem. As an illustration, Reilly explained that if you were hypothetically trying to find the steepest part of a hill—which Reilly highlighted could have 15 dimensions—to roll a ball down, you could use the algorithm to calculate this solution without checking each direction.

“The algorithm leverages an underlying connection between quantum information (via entanglement) and geometrical concepts from Einstein's theory of relativity, two pinnacle fields of physics that rarely interact in research,” Reilly added.

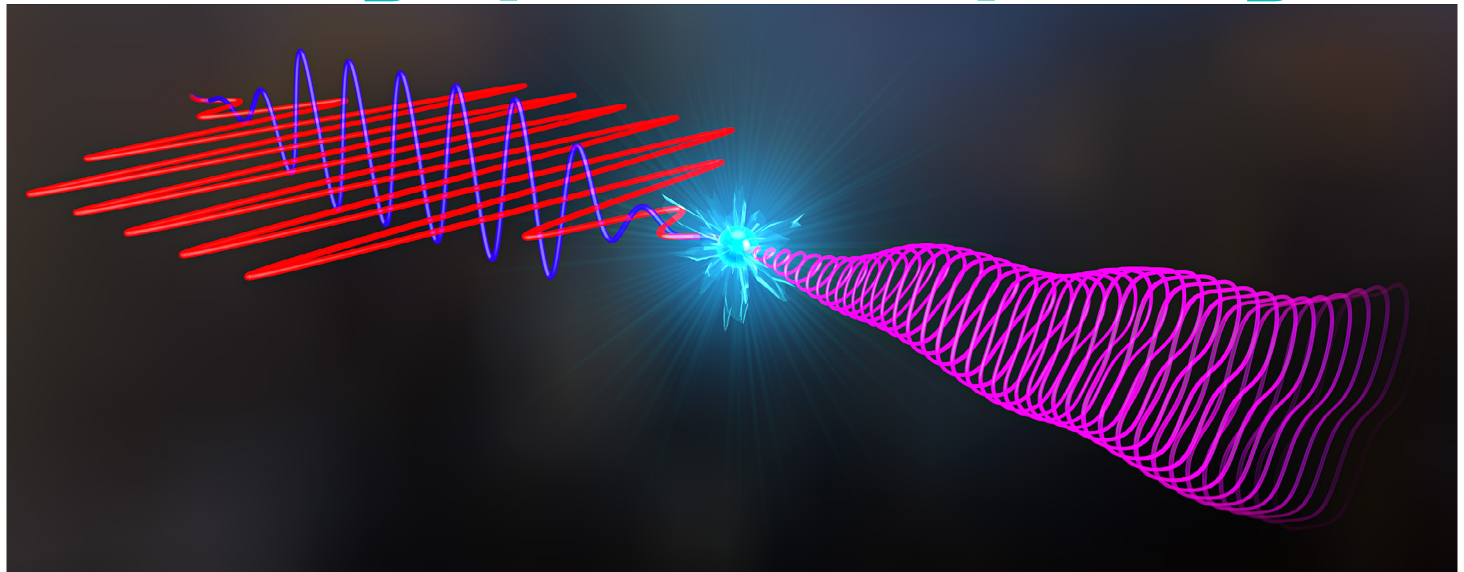
While previous research has looked at measuring the QFI of quantum entanglement from a state-first perspective (where the sensor was created first, and then the entanglement was generated), this paper is one of the first to take the opposite approach.

“We can generate these classes of states, so we ask ourselves: What could we build with it?” Holland added. “It’s a new approach to understanding this whole sensing domain and a compelling method for quantum metrology.”

Jarrod T. Reilly, John Drew Wilson, Simon B. Jäger, Christopher Wilson, and Murray J. Holland "Optimal Generators for Quantum Sensing." Physical Review Letters, 131(15) 131, 150802, 2023.

Written by Kenna Hughes-Castleberry

Creating the "Goldilocks Zone": Making Special-Shaped Light



Two different polarized lasers of different power combine in the process of High Harmonic Generation
Credit: Steven Burrows/Becker Group

In a new study published in *Scientific Reports*, JILA Fellow and University of Colorado Boulder physics professor Andreas Becker and his team theorized a new method to produce extreme ultraviolet (EUV) and x-ray light with elliptical polarization, a special shape in which the direction of light waves' oscillation is changing. This method could provide experimentalists with a simple technique to generate such light, which is beneficial for physicists to further understand the interactions between electrons in materials on the quantum level, paving the way for designing better electronic devices such as circuit boards, solar panels, and more.

Many physicists use a process called High-harmonic generation (HHG) as a source to generate ultrashort EUV and x-ray laser light and use this light to study the ultrafast dynamics of charged particles in different materials. By shooting high-powered laser pulses into a gas of atoms, the researchers can force the atoms to absorb the photons from the laser pulses. This causes the electrons in the atoms to jump to a higher energy level, then fall back to the ground level and emit energy as the atoms radiate in integral multiples of the laser frequency.

JILA graduate student and first author Bejan Ghomashi explained that "these [energies] will be the harmonics. So, if an 800-nanometer light is absorbed, it's also emitted, along with 400 nanometers, 200 nanometers, etc."

This process can be conveniently performed within a tabletop laser setup, as pioneered in the laboratories of JILA Fellows Margaret Murnane and Henry Kapteyn. It gives scientists a relatively cost-effective option to learn more about ultrafast electron dynamics.

"More people have access to an idea and can explore it," Becker added.

Creating Polarization States of Light

Light polarization is a way to describe the direction in which light waves are oscillating. More specifically, polarization describes in which direction the oscillation of the electric field of the light in a laser beam varies over time. For example, the light's electric field may wiggle along a line, making it linearly polarized. In other cases, the direction of the wiggling electric field may rotate, making the light circularly polarized. Creating light in which the electric field varies along an elliptical shape is a middle-ground between pure linearly and circularly polarized light.

Historically, however, it has been challenging to produce elliptically polarized HHG light, but in this new study, Becker and his team explored how to use two linearly cross-polarized lasers at differing frequencies and directions to produce this desired shape. Unlike other, more complex, methods proposed to generate elliptically polarized HHG, an experimental set-up with two cross-polarized laser pulses interacting with an atomic gas is relatively simple.

Sources of elliptically polarized X-ray and EUV light can be useful in helping to study chiral and magnetic materials, as their electrons are sensitive to the direction of applied laser fields. Chiral materials, or materials with a special symmetry, are commonly found in foods and medicines. An example is aspartame sweetener: the left-handed version is sweet, while the right-handed version is not.

Resolving An Odd Puzzle

While previous theories had postulated that it is impossible to create elliptically polarized light using the configuration of two cross-polarized pulses, in 2015, an experimental study produced that exact result. Ghomashi elaborated: "At the time, theoretical physics had no explanation for the ellipticity generated in this experiment and argued it, in fact, should not exist. This was a puzzle to be resolved."

Intrigued by this discrepancy, Ghomashi, recently graduated JILA Ph.D. student Spencer Walker, and Becker developed a method to analyze the experimental set-up in computer simulations. The results of those simulations produced the same results as found in the 2015 experiment for certain sets of parameters of the two cross-polarized laser pulses.

"You must find what we call the 'sweet spot'—it is not just one parameter—but you have to tune several parameters simultaneously," added Ghomashi.

Besides fiddling with the pulse length of the lasers, the researchers also fine-tuned the intensity (or the peak electric fields) of the two laser beams, where one beam was more intense than the other. The result of manipulating these two parameters created a "Goldilocks zone" for producing the rare, elliptically-shaped HHG light.

Walker elaborated that "by reducing the pulse duration, we control the amount of radiation in both [the *x* and *y*] directions simultaneously. And if you have emission in both directions at the right energy, you have ellipticity."

Because of this method's simplicity, the researchers hope that it will be possible for other physicists to reproduce their results in an experimental setup in order to validate their theoretical interpretation.

"It resolves an odd puzzle in the science community," Becker stated, "which is always important for scientists and researchers."

As JILA Fellows Margaret Murnane and Henry Kapteyn develop some of the world's most precise table-top laser setups, testing the team's concept at JILA would also be possible. "The mechanism, so how to change the knobs and why adjusting the parameters achieves the outcome, is very straightforward," Walker said. "It's just a matter of the details."

Bejan Ghomashi, Spencer Walker, and Andreas Becker. "Enabling elliptically polarized high harmonic generation with short cross polarized laser pulses" Scientific Reports, 13(1), 12843, 2023.

Written by Kenna Hughes-Castleberry

A Drum Sounding Both Hot and Cold

When measuring minor changes for quantities like forces, magnetic fields, masses of small particles, or even gravitational waves, physicists use micro-mechanical resonators, which act like tuning forks, resonating at specific frequencies. Traditionally, it was assumed that the temperature across these devices is uniform.

However, new research from JILA Fellow and University of Colorado Boulder physics professor Cindy Regal and her team, Dr. Ravid Shaniv and graduate student Chris Reetz, has found that in specific scenarios, such as advanced studies looking at the interactions between light and mechanical objects, the temperature might differ in various resonator parts, which leads to unexpected behaviors. Their observations, published in *Physical Review Research*, can potentially revolutionize the design of micro-mechanical resonators for quantum technology and precision sensing.

"In quantum science experiments, understanding this temperature difference's ramifications will allow you to generate your mechanical quantum state with better fidelity and keep it unperturbed for longer, both essential starting points for quantum applications," elaborated JILA postdoctoral research associate and first author Ravid Shaniv.

The Modes of Minute Measurers

Due to their flexible design, micro-mechanical resonators are a standard tool in many different fields of physics. These devices are often made of silicon or similar materials and can take various shapes: beams, cantilevers, membranes, or disks. Their small size allows them to oscillate at high frequencies, often in the megahertz (MHz) to gigahertz (GHz) range.

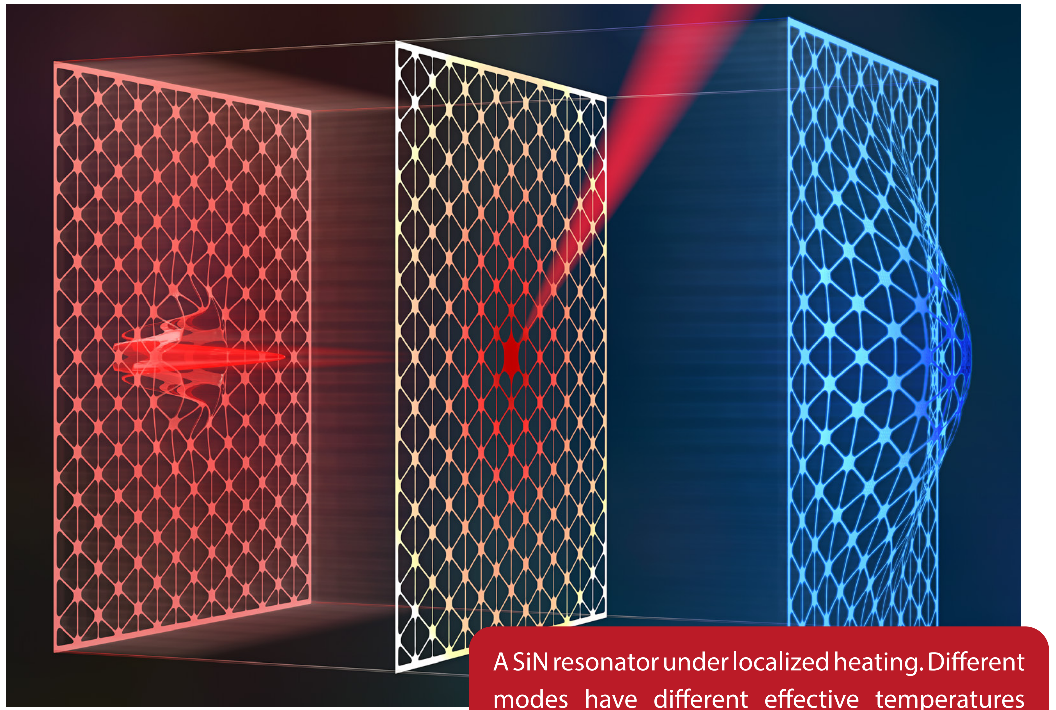
The versatility of a micro-mechanical resonator's design also allows physicists to fine-tune their oscillations. Just as a guitar string can vibrate in multiple ways (with the whole string moving back and forth or just parts wiggling while the rest remains still), micro-mechanical resonators can oscillate in different patterns or "modes." The most familiar mode is the fundamental mode, where the entire structure moves in unison. But there are also higher-order modes, where other resonator parts move in more complex patterns.

To measure a resonator's motion, physicists use laser beams. The resonator acts like a moving mirror, and the laser light that bounces off carries information about its position. When compared to light that bounces off a separate fixed mirror, an interference pattern is developed, revealing the resonator's motion to ultra-high precision.

Over the years of observing these modes optically and discussing them with other physicists, Shaniv and Regal realized something interesting. "People have observed that some of these modes exhibit more thermal motion than others," Shaniv stated. "Typically, people want to eliminate this motion as much as possible because it could overshadow any small effect they want to sense."

Physicists have posited that this excess of thermal motion could be due to the resonator absorbing laser light in the form of heat. Different resonator modes can have different movement patterns, leading to varying areas of stress or strain, which can, in turn, lead to distinct magnitudes of thermal motion.

In many observations, the more complex the mode of the resonator, the more it's thermal energy deviates from previous theories, which suggests the temperature for every mode was identical. Shaniv continued: "We wanted to track down the reason for that and how you can achieve the optimum design for these modes."



A SiN resonator under localized heating. Different modes have different effective temperatures depending on the spatial overlap between the local temperature and the dissipation density of the mode.
Credit: Steven Burrows/ Regal Group

Creating Temperature Profiles

To dive deeper into this temperature conundrum, Shaniv and Regal created specific temperature profiles for each mode. To do this, the researchers utilized a "phononic crystal" comprised of silicon nitride. The crystal acted as a playground where the researchers could engineer the resonator modes and generate varying temperature profiles, allowing them to observe the induced thermal motion of each resonator mode.

To create the temperature profile, the team heated a point on the crystal to very high temperatures while keeping the resonator edge at room temperature. After a profile was developed and thermal motion was measured, the researchers found some rather interesting results. Depending on the mode geometry, some modes showed increased thermal motion, while, even though parts of the resonator were extremely hot, others showed only mild heating, and some exhibited no heating at all. "By turning the knob all the way in the experiment, you could see this striking difference," elaborated Regal.

Shaniv continued: "Looking at these really large temperature differences between modes, we were able to construct the temperature profile of a resonator directly from measured thermal motion and even find some material parameters that are typically not straightforward to evaluate, for example, the emissivity, which is how much radiation our device emits."

By seeing which modes correlated to different thermal motions, the team could begin to predict how the resonators' performance may change depending on their mode. As Regal explained: "A natural next step is to ask whether these concepts can be put to use not only in understanding how to keep resonators cold for quantum studies but also in thermal sensing."

Designing Better Resonators

With the insights gained, the scientific and engineering communities could make significant strides in designing and applying these minuscule yet crucial devices. "We actually gave in our paper a real figure of merit, with which groups can work in this direction," Shaniv elaborated. "For example, we now have a specific parameter to throw as a constraint into the computer and try to generate the best possible resonator."

Ravid Shaniv, Chris Reetz, and Cindy A. Regal, "Direct measurement of a spatially varying thermal bath using Brownian motion." Physical Review Research, 5(4), 043121, 2023.

Written by Kenna Hughes-Castleberry

Remembering JILA Fellow W. Carl Lineberger

Dr. William Carl Lineberger, 83, loving husband, died on October 17, 2023, in Boulder, Colorado. Born in 1939, in Hamlet, North Carolina, Carl was the only child of Evelyn Pilot Cooper and Caleb Henry Lineberger. He is survived by his wife, Kitty Edwards, and his beloved dog, Jude.

Carl received his B.S., M.S., and Ph.D. at the Georgia Institute of Technology and served in the Army Ordnance Corps during the Vietnam War. He was a teacher, mentor, and research scientist in the Department of Chemistry, University of Colorado, for 52 years. He was appointed by President Obama to the National Science Board in 2010 and served in that capacity until 2022. The American Chemical Society and the American Physical Society, both of which he was a member, granted him their top awards. In 1983, he was elected to the National Academy of Sciences; in 2015, he received their NAS Award in the Chemical Sciences, given for both scientific achievement and benefit to humanity.

Carl Lineberger's incredibly productive approach to scientific research derived from his unusual combination of expertise in chemistry and physics, together with his mastery of engineering. These complementary skills allowed him to attack new classes of chemical problems with his signature blend of elegance and precision. His unique perspective also enabled him to see connections in nature that could be overlooked by his contemporaries. Carl's colleagues knew to listen especially carefully when he shared a seeming childlike view regarding some aspect of science, as it was then in fact that they might gain the deepest insights into nature's inner workings.

Carl Lineberger's enduring impact on the scientific community is broader than the important paradigms he contributed from his laboratory. He was described by a colleague as having been instrumental in creating the "magic" of JILA, a joint institute between the National Institute of Science and Technology and the University of Colorado devoted to research into the frontier interface between chemistry and physics. He molded a style of collaborative research starting in the 1970s that continues today.

Carl was not only brilliant, but kind. It was known that, however close he was to a proposal or other deadline, if a troubled student, staff member, or colleague knocked on his door, he would drop everything to listen and try to help.

His sense of humor was present to the end. In his final days he was asked if he had any regrets. He smiled and quipped, "Maybe I should have spent more time hang gliding."

Carl will be remembered not just for the heights of his science, but for the depth of his humanity.

Written by Kitty Edwards.

Life After JILA: Bin Wang

While academia has traditionally been the primary path for physicists, the industrial sector offers unique opportunities and advantages. This was certainly the case for Dr. Bin Wang, who was recently a JILA postdoctoral researcher, now a Senior Software Engineer at ASML. "At ASML, we are trying to use photolithographic machines to print very small features on a semiconducting wafer," Wang said. "It works like a projector where a template is projected onto a screen. But our 'projector' is not perfect and there is some distortion between what is on the template and what we get on the screen (silicon wafers in our case)."

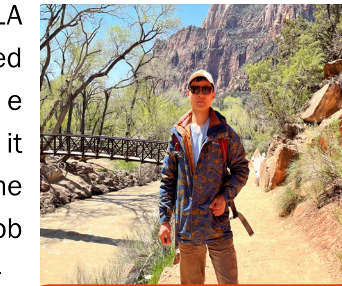
To overcome this issue, Wang and his team work on designing software systems that can modify patterns on the template to compensate for the distortion. "The software incorporates physics, chemistry, maths, and computer science altogether to get the best correct on the template," he added.

Before starting at ASML in April of 2023, Wang worked with JILA Fellows and University of Colorado Boulder professors Margaret Murnane and Henry Kapteyn. Wang joined the Murane/Kapteyn research group in 2016 as a graduate student (though he eventually became a JILA postdoc), focusing on specialized ultraviolet light sources and applications. According to Wang: "The past couple of grad student generations had spent a lot of time and effort developing our coherent EUV light source. So people started thinking about how we could take advantage of this light source and actually use it."

Expanding on this idea, Wang and other JILA researchers investigated if this light could be used for microscopic imaging. "What I ended up choosing was close to what I'm doing right now," Wang elaborated. "We were trying to use this short wavelength UV light to build microscopes to image surface details in the nanoscale. We hoped that this could be used in the semiconductor industry to take images of the circuit chips and look for defects."

As a JILA postdoc, Wang experienced firsthand the supportive nature of the JILA community. He explained: "People were very knowledgeable and willing to share and to teach. So, I learned a lot from Margaret, Henry, and all of the grad students in the group. It was also fun, as we had many snacks and coffee breaks. Our group also took a lot of group trips, which made the grad school life a lot more enjoyable."

Thanks to his research group and wider JILA community, Wang felt that JILA had helped prepare him when it came time to find a job in industry. Wang elaborated that this support and preparation came in multiple levels, the first being the knowledgeable people around him who could share their wisdom about physics, lasers, and more. "They are world-class experts," added Wang. "So being around them makes it easier to develop my knowledge and skills in terms of math derivation, thinking about physics problems, tuning the laser systems in the lab, programming, and writing papers and getting published."

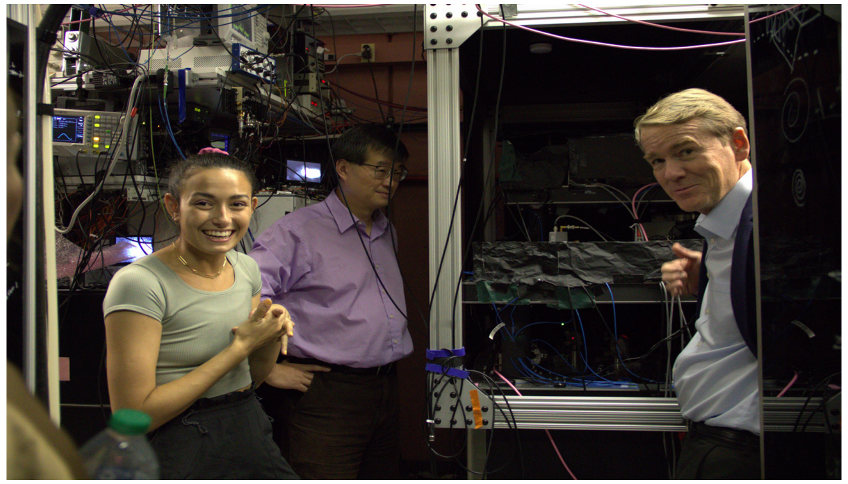


JILA Alumnus Bin Wang
Credit: Bin Wang

The second level of support was the inviting nature of the bigger JILA community. "I got to know a lot of people during my time at JILA," said Wang. "Before I came to grad school, I was very shy and not very good at talking to people. Because JILA has so many opportunities to be social with people and join in the community, that helped me a lot in terms of developing English as a second language as well as communication skills."

Written by Kenna Hughes-Castleberry,

U.S. Senator Michael Bennet Visits JILA



On October 20th, 2023, Colorado Senator Michael Bennet visited JILA, a joint institute between the National Institute of Standards and Technology (NIST) and the University of Colorado Boulder. During his visit, Bennet engaged with several of the institute's scientists and students, discussing their groundbreaking research and its implications. JILA Fellows Konrad Lehnert, Cindy Regal, Jun Ye, and Ana Maria Rey all spoke about their research during Bennett's walking tour of JILA. Bennet visited Ye's laboratory, discussing with several of his students the importance of atomic clocks and their impacts on technology such as GPS.

Bennet's engagement with JILA reinforces the significance of Colorado as a hub for scientific innovation and quantum research, and it sheds light on the potential collaborations that could emerge between political leadership and the scientific community.

On the same day that Senator Bennet visited, Colorado Governor Jared Polis made an important announcement about the Colorado quantum ecosystem. The recent announcement from Governor Polis and the Colorado Office of Economic Development and International Trade (OEDIT) further emphasizes Colorado's determination to be at the forefront of technology and innovation as they unveiled the quantum Technology and Innovation Hub (Tech Hub) designation under the U.S. CHIPs and Science Act, for Colorado.

This designation is a strategic move aimed at positioning Colorado for a significant funding opportunity, as the U.S. Economic Development Administration (EDA) is set to allocate $500 million in 2023 to aid the selected Tech Hubs.

A recent news article from Colorado Public Radio states, “The amount of the initial grant has not yet been announced, but it is just the first phase of Commerce's Economic Development Administration Regional Tech Hub designation process...Those grants are expected to be awarded in 2024.”

CU Boulder President Todd Saliman recently acknowledged this significant news in a newsletter. “CU's federal partnerships – with the National Institute of Standards and Technology through JILA, the National Science Foundation, and the U.S. Department of Energy – are core to our strength in this space, which is by no means theoretical: CU Boulder's College of Engineering and Applied Science recently launched the Quantum Engineering Initiative to accelerate the translation and commercialization of quantum into real-world applications.”

Above left: Senator Bennet (right) discusses atomic clocks with graduate student Maya Miklos (left) and JILA and NIST Fellow Jun Ye (middle).

Above: Senator Bennet (right) listens to JILA instrument maker Hans Green (middle) while JILA Chair and Fellow Konrad Lehnert (right) listens on.
Credit: Kenna Hughes-Castleberry

News and Awards

News

JILA Fellow and University of Colorado Boulder Professor of Chemistry Robert Parson Retires from Teaching. Parson's career spanned over 30 years and focused on theoretical chemistry and Physics Education Research (PER).

JILA Fellow Shuo Sun Becomes a Science Advisor for Colorado Quantum Startup. Sun recently became the science advisor for Boulder-based quantum technology company Icarus Quantum, which is focused on developing on-demand single- and entangled-photon generators for the future quantum internet network.

JILA Fellows Ana Maria Rey and Adam Kaufman Featured in an "IEEE Spectrum" Article. In a pair of *Nature* papers, Rey and Kaufman both demonstrated the phenomena of spin-squeezing to reduce noise in their quantum systems.

JILA Fellow Daniel Dessau's work featured in "The Washington Post." Dessau's research was recently highlighted in an article from *The Washington Post* focusing on the recent room-temperature superconductor and its controversial science. As Dessau focuses on heating materials to 1,700 degrees Fahrenheit and seeing their by-products, his work could help pave the way for discovering possible other exotic materials.

Awards

JILA Graduate Students Qizhong Liang and Drew Morrill Win Awards in the Colorado Photonics Industry Association Poster Contest. Morrill's poster, titled "High-harmonic generation from a 3 μm wavelength OPCPA," discussed a method to generate soft X-rays using laser arrays. Liang's poster focused on using frequency combs for molecular detection. His poster was titled "Detect COVID-19 with a frequency comb laser breathalyzer."

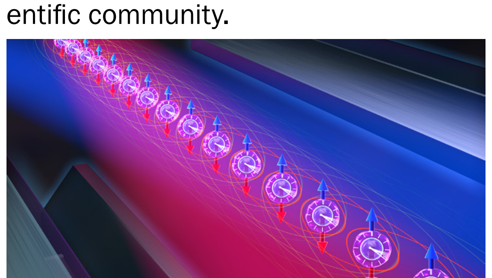
JILA Graduate Student Jeremy Thurston is Awarded a Prize for Emil Wolf Outstanding Student Paper Competition. This year, JILA graduate student Jeremy Thurston of the Murnane and Kapteyn research group showcased his work in both a paper and presentation titled "Bright Tunable Ultrafast Deep- and Vacuum-Ultraviolet Harmonic Combs," which was awarded a prize by the judges for excellence in communication.

JILA Graduate Student Daniel Carlson is awarded a Best Paper Award at Optica International Conference on Advanced Solid State Lasers. This year, JILA graduate student Daniel Carlson was among the list of winners, with his presentation "Carbon K-Edge Soft X-Rays Driven by a 3 μm, 1 kHz OPCPA Laser System" winning over the judges.

JILA and NIST Fellow Ana Maria Rey Receives a 2023 Presidential Rank Award for Distinguished Senior Professional. Rey has been recognized within the Department of Commerce for her work in precision measurement and quantum physics.

JILA Postdoctoral Researcher Vít Svoboda is Awarded a 2023 JUNIOR STAR project grant by the Czech Science Foundation. Svoboda's JUNIOR STAR project titled “Probing Chiral Dynamics on Femtosecond Timescales,” will dive into using time-resolved photoelectron spectroscopy to study the physics of chiral molecules during chemical transformations.

JILA and NIST Fellow Jun Ye Awarded a 2023 Highly Cited Researcher Designation. This notable recognition is bestowed upon researchers whose work ranks in the top 1% of citations for their field, highlighting their significant influence in the scientific community.



Higher accuracy atomic clocks could result from linking or “entangling” atoms in a new way through a method known as “spin squeezing.” Credit: Steven Burrows/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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