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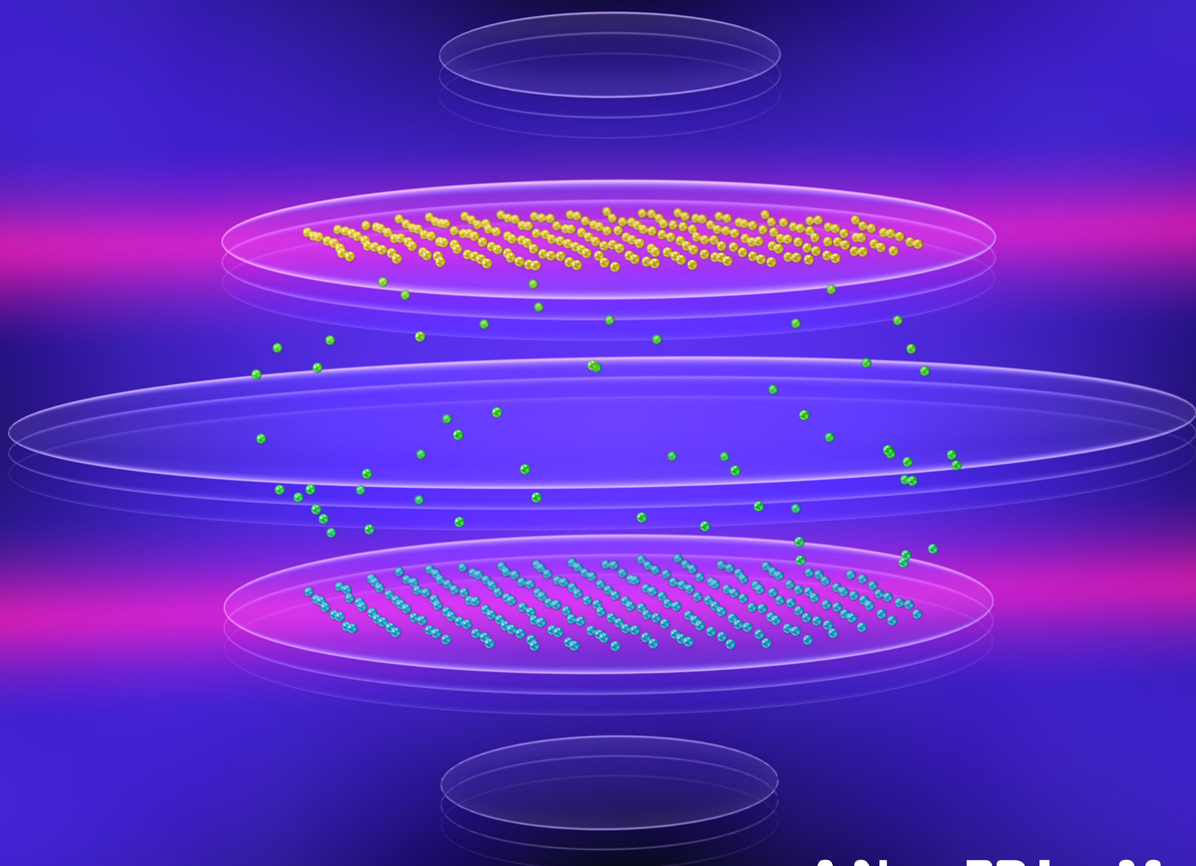

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JILA
CU Boulder and NIST

JILA and NIST Fellow and University of Colorado Boulder Physics professor Eric Cornell explains the science of the summer solstice to onlookers in the X-wing basement.
Credit: Christine Jackson/JILA

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Research Articles

Feature Articles

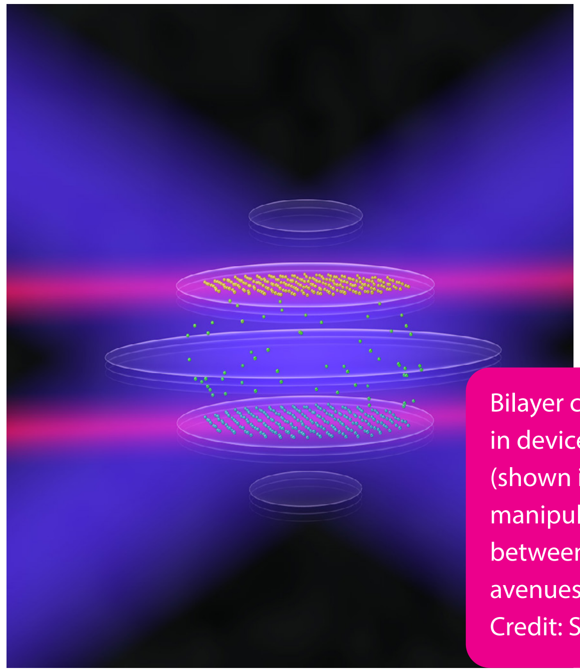
A 3D Ion Magnet: the New Experimental Frontier for Quantum Information Processing

Many quantum devices, from quantum sensors to quantum computers, use ions or charged atoms trapped with electric and magnetic fields as a hardware platform to process information.

However, current trapped-ion systems face important challenges. Most experiments are limited to one-dimensional chains or two-dimensional planes of ions, which constrain the scalability and functionality of quantum devices. Scientists have long dreamed of stacking these ions into three-dimensional structures, but this has been very difficult because it's hard to keep the ions stable and well-controlled when arranged in more complex ways.

To address these challenges, an international collaboration of physicists from India, Austria, and the USA—including JILA and NIST Fellow Ana Maria Rey and NIST scientists Allison Carter and John Bollinger—proposed that tweaking the electric fields that trap the ions can create stable, multilayered structures, opening up exciting new possibilities for future quantum technologies. The researchers published their findings in *Physical Review X*.

"The capability to trap large ensembles of ions in two or more spatially separated layers under fully controllable conditions opens exciting opportunities to explore new regimes and phenomena not easily accessible in purely 2D crystals, such as topological chiral modes, teleportation, and precision measurements of spatially varying fields all relevant for quantum information science," says Rey.



Bilayer crystals of trapped ions can be realized in devices called Penning traps, and lasers (shown in red and blue) can be used to manipulate the ions and engineer interactions between them. Such crystals may open new avenues for quantum technology applications. Credit: Steven Burrows/JILA

Among the various platforms being explored for quantum computing, trapped ions have emerged as a leading candidate due to their high degree of controllability and the ability to perform precise quantum operations. These ions can be manipulated with laser or microwave pulses, which change their quantum states, allowing them to be "coded" with specific information. These coded ions are often called quantum bits or "qubits."

During this process, ions also experience the Coulomb force (interactions with other ions) which physicists can use to entangle them, reducing the system's overall noise and enhancing its measurements.

"Previous work has shown that ion crystals can form 3D spheroidal structures, but what we were looking for was a way to realize a stacked array of 2D layers," Samarth Hawaldar, the paper's first author and a researcher at the Indian Institute of Science, explained. "We started to explore ways to realize such structures in a specific type of ion trap called a Penning trap, because these traps are good at storing large numbers of ions, typically many hundreds to thousands."

In a Penning trap, ions can be forced to self-ensemble into crystalline structures generated by the competition between repulsive Coulomb interactions and the confinement potential—the combined electric and magnetic force that keeps ions securely trapped in a specific region of space.

"Confinement is achieved via electromagnetic forces created by a stack of electrodes and by making the ions rotate in a powerful magnetic field," explains Carter.

For physicists, Penning traps are particularly useful because they can store a large number of ions, making them a good option for experimenting with more complex, three-dimensional structures. Penning traps have been used to arrange ions into a single, two-dimensional layer or more rounded, three-dimensional shapes. The rounded, three-dimensional shape happens because the confining electric field in these traps usually increases linearly with distance from the trap's center, like that of an ideal spring, naturally guiding the ions into these simpler, rounded formations.

However, the researchers, including Prakriti Shahi of the Indian Institute of Technology Bombay, tried modifying the trap's electric field to be more nuanced and dependent on the distance from the center of the trap. This subtle change allowed them to coax the ions into forming a new kind of structure—a bilayer crystal, where two flat layers of ions were stacked one above the other.

The team conducted extensive numerical simulations to validate their new approach, showing that this bilayer configuration could be stabilized under certain conditions and even suggesting the potential to extend the method to create crystals with more than two layers.

"We're excited to try forming bi-layer crystals in the lab with our current Penning trap set-up," says John Bollinger, an experimental physicist and co-author of the publication. "In the longer term, I think this idea will motivate a redesign of the detailed electrode structure of our traps."

A New Frontier for Ion Trapping

Shifting ion trapping from 2D to 3D has significant implications for the future of quantum devices such as sensors or quantum computers.

"Bilayer crystals open up several new capabilities for quantum information processing that are not straightforward with 1D chains or 2D planes," Dr. Athreya Shankar, a postdoctoral researcher at the Indian Institute of Science, said. "For instance, the generation of quantum entanglement between large sub-systems separated by a distance, such as the two layers in this system, is a sought-after capability across all quantum hardware."

The team is eager to test these findings experimentally in their Penning traps. If successful, this could lead to new quantum hardware architectures that make more efficient use of 3D space, thus increasing the scalability and robustness of quantum technologies.

Besides hardware opportunities, the bilayers open new quantum simulations and sensing possibilities.

"For example, the normal modes of the ions in a bilayer can couple both vertical and radial degrees of freedom, favoring the clock[wise] over anti-clockwise circulation or vice versa," Rey elaborates. "This could be used to imitate rich behaviors experienced by electrons in strong magnetic fields but under fully controllable settings. Moreover, having more ions can enhance signal-to-noise in measurement and thus enable more precise estimation of quantities such as time, electric fields, or accelerations, which can be very important for discovering new physics."

Samarth Hawaldar, Prakriti Shahi, Allison L. Carter, Ana Maria Rey, John J. Bollinger, and Athreya Shankar. "Bilayer Crystals of Trapped Ions for Quantum Information Processing." Physical Review X. 14(3), 031030, 2024.

Written by Kenna Hughes-Castleberry

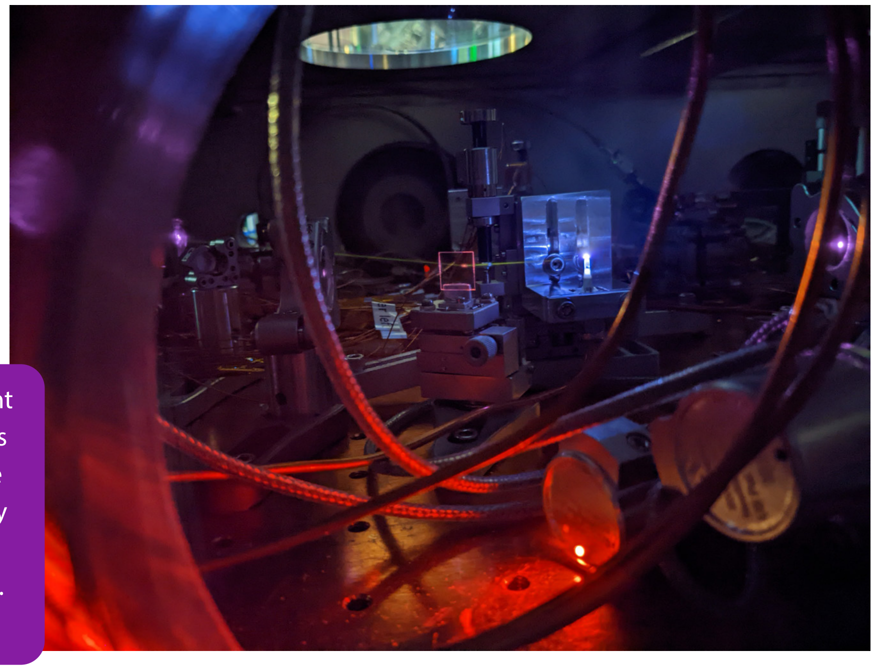
Major Leap for Nuclear Clock Paves Way for Ultraprecise Timekeeping

The world keeps time with the ticks of atomic clocks, but a new type of clock under development—a nuclear clock—could revolutionize how we measure time and probe fundamental physics.

An international research team led by scientists at JILA, a joint institute of the National Institute of Standards and Technology (NIST) and the University of Colorado Boulder, has demonstrated key elements of a nuclear clock. A nuclear clock is a novel type of timekeeping device that uses signals from the core, or nucleus, of an atom. The team used a specially designed ultraviolet laser to precisely measure the frequency of an energy jump in thorium nuclei embedded in a solid crystal. They also employed an optical frequency comb, which acts like an extremely accurate light ruler, to count the number of ultraviolet wave cycles that create this energy jump. While this laboratory demonstration is not a fully developed nuclear clock, it contains all the core technology for one.

Nuclear clocks could be much more accurate than current atomic clocks, which provide official international time and play major roles in technologies such as GPS, internet synchronization, and financial transactions. For the general public, this development could ultimately mean even more precise navigation systems (with or without GPS), faster internet speeds, more reliable network connections, and more secure digital communications.

Beyond everyday technology, nuclear clocks could improve tests of fundamental theories for how the universe works, potentially leading to new discoveries in physics. They could help detect dark matter or verify if the constants of nature are truly constant, allowing for verification of theories in particle physics without the need for large-scale particle accelerator facilities.



A powerful laser shines into a jet of gas, creating a bright plasma and generating ultraviolet light. The light leaves a visible white line as it interacts with leftover gas in the vacuum chamber. This process helps scientists precisely measure the energy needed to excite the thorium-229 nucleus, which will be the core of a future nuclear clock. Credit: Chuankun Zhang/JILA

Laser Precision in Timekeeping

Atomic clocks measure time by tuning laser light to frequencies that cause electrons to jump between energy levels. Nuclear clocks would utilize energy jumps within an atom's tiny central region, known as the nucleus, where particles called protons and neutrons cram together. These energy jumps are much like flipping a light switch. Shining laser light with the exact amount of energy needed for this jump can flip this nuclear "switch."

A nuclear clock would have major advantages for clock precision. Compared with the electrons in atomic clocks, the nucleus is much less affected by outside disturbances such as stray electromagnetic fields. The laser light needed to cause energy jumps in nuclei is much higher in frequency than that required for atomic clocks. This higher frequency—meaning more wave cycles per second—is directly related to a greater number of "ticks" per second and therefore leads to more precise timekeeping.

But it is very hard to create a nuclear clock. To make energy jumps, most atomic nuclei need to be hit by coherent x-rays (a high-frequency form of light) with energies much greater than those that can be produced with current technology. So scientists have focused on thorium-229, an atom whose nucleus has a smaller energy jump than any other known atom, requiring ultraviolet light (which is lower in energy than x-rays).

In 1976, scientists discovered this thorium energy jump, known as a "nuclear transition" in physics language. In 2003, scientists proposed using this transition to create a clock, and they only directly observed it in 2016. Earlier this year, two different research teams used ultraviolet lasers they created in the lab to flip the nuclear "switch" and measure the wavelength of light needed for it.

In the new work, the JILA researchers and their colleagues create all the essential parts of a clock: the thorium-229 nuclear transition to provide the clock's "ticks," a laser to create precise energy jumps between the individual quantum states of the nucleus, and a frequency comb for direct measurements of these "ticks." This effort has achieved a level of precision that is one million times higher than the previous wavelength-based measurement. In addition, they compared this ultraviolet frequency directly to the optical frequency used in one of the world's most accurate atomic clocks, which uses strontium atoms, establishing the first direct frequency link between a nuclear transition and an atomic clock. This direct frequency link and increase in precision are a crucial step in developing the nuclear clock and integrating it with existing timekeeping systems.

The research has already yielded unprecedented results, including the ability to observe details in the thorium nucleus's shape that no one had ever observed before—it's like seeing individual blades of grass from an airplane.

The team presents its results in the Sept. 4 issue of the journal *Nature* as a cover story.

Toward a Nuclear Future

While this isn't yet a functioning nuclear clock, it's a crucial step towards creating such a clock that could be both portable and highly stable. The use of thorium embedded in a solid crystal, combined with the nucleus's reduced sensitivity to external disturbances, paves the way for potentially compact and robust timekeeping devices.

"Imagine a wristwatch that wouldn't lose a second even if you left it running for billions of years," said NIST and JILA physicist Jun Ye. "While we're not quite there yet, this research brings us closer to that level of precision."

Chuankun Zhang, Tian Ooi, Jacob S. Higgins, Jack F. Doyle, Lars von der Wense, Kjeld Beeks, Adrian Leitner, Georgy Kazakov, Peng Li, Peter G. Thirolf, Thorsten Schumm and, Jun Ye. "Frequency ratio of the ^{229m}Th nuclear isomeric transition and the ^{87}Sr atomic clock." Nature. 633(8028), 63–70, 2024.

Written by Katie Palubicki, NIST Public Affairs Specialist

The cover of Nature showcasing the research from Ye and his team. Credit: Nature

Mapping Noise to Improve Quantum Measurements

One of the biggest challenges in quantum technology and quantum sensing is "noise"—seemingly random environmental disturbances that can disrupt the delicate quantum states of qubits, the fundamental units of quantum information. Looking deeper at this issue, JILA Associate Fellow and University of Colorado Boulder Physics Assistant Professor Shuo Sun recently collaborated with Andrés Montoya-Castillo, assistant professor of Chemistry (also at CU Boulder), and his team to develop a new method for better understanding and controlling this noise, potentially paving the way for significant advancements in quantum computing, sensing, and control. Their new method, which uses a mathematical technique called a Fourier transform, was published recently in the journal *npj Quantum Information.*

While some noise sources, like music, can be enjoyable, others, such as the sounds of traffic or a bustling city, can be distracting and even lead to health issues over time. At a microscopic level, noise can also pose significant challenges. Even the smallest fluctuations in room temperature or floor vibration, or the qubit system's inherent instability, can disrupt a qubit's coherence, causing it to lose its quantum state in a process known as decoherence.

"Lots of quantum technologies that people are very excited about, like quantum computers and quantum sensors, face a practical limitation, which is implementation on a larger scale with higher sensitivity," explains CU Boulder Physics graduate student and co-first author of the paper, Nanako Shitara, who works in Montoya-Castillo's group. "This is because these quantum systems, or qubits, are very sensitive to fluctuations in the surrounding fields, and they often interact with each other."

Not only does the noise affect the measurements of fragile systems like an ultra-precise quantum sensor, but it can also make the system less manageable.

Understanding the sources of this noise, and finding ways to mitigate them, is crucial for developing reliable quantum devices, such as quantum computers or sensors.

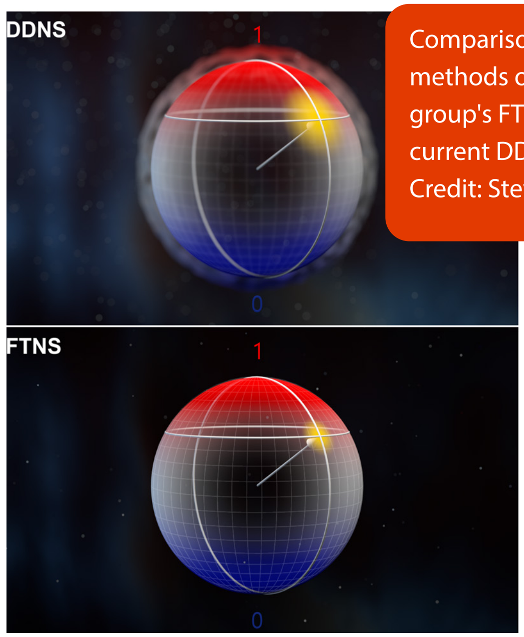
"Understanding the noise environment of a qubit is not only important for noise mitigation, but also serves as a valuable probe for materials," Sun explains. "In the latter case, the qubit acts as a sensor, providing insights into the behavior of the surrounding material environment."

To study and control this noise, scientists have traditionally used a method called dynamical decoupling noise spectroscopy (DDNS). This method involves applying precise pulses to the qubits and observing how they respond.

"Dynamical decoupling was originally, and still is, used for making the coherence times longer in qubits," adds Shitara. "It turns out, that if you apply very short light pulses onto a qubit that is interacting with its environment, in some periodic manner...[it] helps the qubit's coherence survive longer through some sort of effective decoupling."

More recently, dynamical decoupling was repurposed as a noise spectroscopy method (hence DDNS) to measure and characterize the noise among the qubits. Though effective, DDNS is complex and requires applying a large number of almost instantaneous laser pulses. It also requires several assumptions about the underlying noise processes, making it cumbersome and less practical for widespread use.

Shitara elaborated that the DDNS method has minimum and maximum frequency limits for noise spectrum reconstruction due to physical constraints, potentially causing scientists to miss interesting phenomena. "You can see that the lowest frequency at which they reconstruct the spectrum can be actually quite high, depending on the implementation," she adds.



Comparison of two noise spectroscopy methods of qubit environments. The Sun group's FTNS significantly outperforms current DDNS methods.
Credit: Steven Burrows/Sun Group

Looking at the challenges of DDNS, Shitara, Sun, Montoya-Castillo, and CU Boulder postdoctoral researcher Arian Vezvaee proposed a new method that required fewer laser pulses and utilized a mathematical technique known as the Fourier transform.

The new method, Fourier transform noise spectroscopy (FTNS), offers a straightforward, yet powerful, way to analyze the noise affecting qubits by focusing on the qubits' coherence dynamics. Coherence measures how well a qubit maintains its quantum state, which is critical for its performance in quantum computations. These measurements are typically done through simple experiments like free induction decay (FID) or spin echo (SE), which start the qubit in a specific initial state and let its coherence decay freely over time, with zero or one intermediate pulses applied during the decay, respectively.

Once these time-based measurements are collected, the data is treated using the Fourier transform. This process is like breaking down a digital painting into its basic color spectrum, pixel by pixel, to understand the units of color that it's made of. The units transform from pixels to color values through this process.

In this paper, the researchers used the Fourier transform to convert the time-domain data into frequency-domain data, effectively breaking down the complex signal into its constituent frequencies. By doing so, FTNS revealed the noise spectrum, showing which noise frequencies were present and how strong they were. The researchers found that the FTNS method also handled various types of noise, including complex noise patterns that were challenging for other methods like DDNS to decipher.

While a more streamlined method, FTNS has some limitations, like minimum and maximum frequency constraints and the need for high-resolution time and coherence measurements. However, the researchers demonstrated that these limitations are far less constraining than those of dynamical decoupling noise spectroscopy.

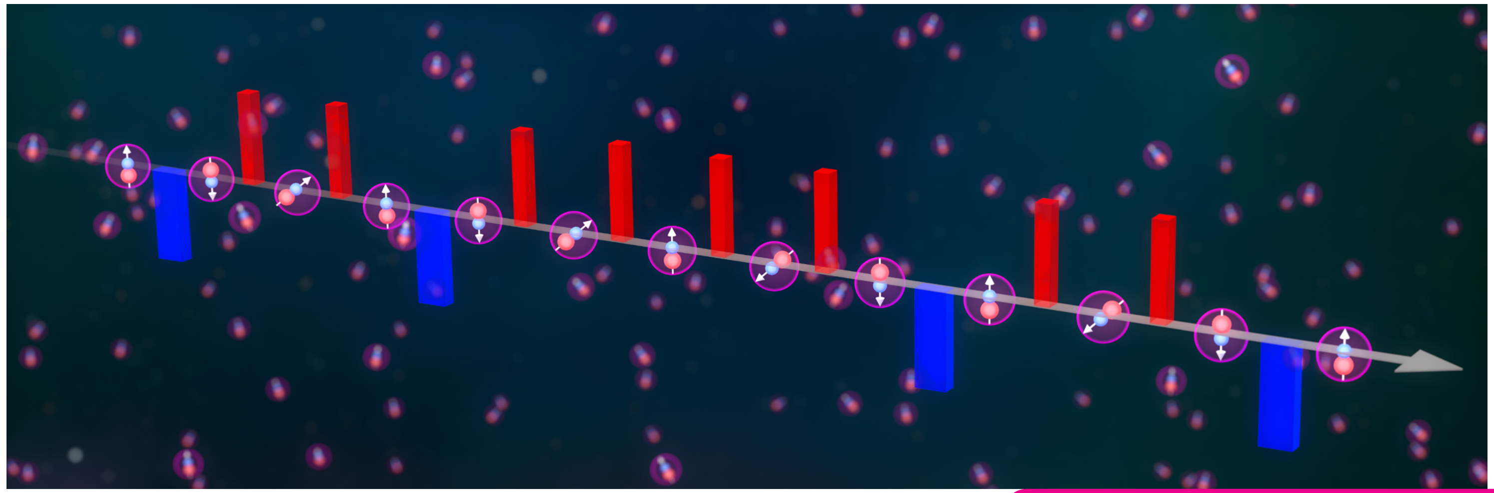
Sun and his team at JILA are now experimentally testing the FTNS method in nitrogen-vacancy centers, often found within synthetic diamonds that are used as qubits. Simultaneously, Joe Zadrozny, Associate Professor of Chemistry at Ohio State University, and his team are working to implement FTNS in molecular qubits and magnets.

"We are super excited about our method's ability to reveal the frequency-resolved conversation between a qubit or sensor and its environment—and even more about the new opportunities it offers," elaborates Montoya-Castillo. "From the sensing perspective, we are working to establish how FTNS can show hard-to-see physical processes near a sensor, whether this is a color center in a crystal, like nitrogen vacancies in diamond, trapped ions, or molecular magnets. This is an exciting frontier as quantum sensors may enable imaging of complex biological processes, like protein folding, with unprecedented detail and temporal resolution."

Arian Vezvaee, Nanako Shitara, Shuo Sun, and Andrés Montoya-Castillo. " Fourier transform noise spectroscopy." npj Quantum Information, 10(1), 52, 2024.

Written by Kenna Hughes-Castleberry,

Polar Molecules Dance to the Tunes of Microwaves



Pulse sequences for generating two-axis twisting rotate the spins of KRb molecules, transforming the spin exchange interactions.
Credit: Steven Burrows/Ye Group

The interactions between quantum spins underlie some of the universe's most interesting phenomena, such as superconductors and magnets. However, physicists have difficulty engineering controllable systems in the lab that replicate these interactions.

Now, in a recently published *Nature* paper, JILA and NIST Fellow and University of Colorado Boulder Physics Professor Jun Ye and his team, along with collaborators in Mikhail Lukin's group at Harvard University, used periodic microwave pulses in a process known as Floquet engineering, to tune interactions between ultracold potassium-rubidium molecules in a system appropriate for studying fundamental magnetic systems. Moreover, the researchers observed two-axis twisting dynamics within their system, which can generate entangled states for enhanced quantum sensing in the future.

In this experiment, the researchers manipulated ultracold potassium-rubidium molecules, which are polar. As polar molecules are a promising platform for quantum simulations, the tunable molecular interactions using Floquet engineering could open new doors for understanding other quantum many-body systems.

"There is a lot of interest in using these quantum systems, especially [with] polar molecules—there can be sensitivity to many new physics effects because the molecules have a rich energy structure that depends on many different physical constants," explains JILA graduate student, and the study's first author, Calder Miller. "So, if we can engineer their interactions, in principle, we can create entangled states that give better sensitivity to new physics."

Implementing Floquet Engineering

Floquet engineering has emerged as a useful technique for driving interactions within physical systems. This method acts like a "quantum strobe light," which can create different visual effects, like making objects appear to move in slow motion or even stand still, by adjusting the speed and intensity of the flashes.

Similarly, by using periodic microwave pulses to drive the system, scientists can create different quantum effects by controlling how particles interact.

"In our old setup, we were limited in the number of pulses we could drive," says Annette Carroll, a JILA graduate student on Ye's research team and a fellow author of this study. "So, we worked with the electronics shop to develop an FPGA-based arbitrary waveform generator, which allows us to apply thousands of pulses now. This means that not only can we engineer a pulse sequence that removes single particle noise, but we can also modify the interactions in the system."

Before implementing the Floquet engineering, the researchers first encoded quantum information in the molecules' two lowest rotational states (though molecules have many more states). Using an initial microwave pulse, the molecules were put into a quantum superposition of these two "spin" states.

After encoding the information, the researchers used the Floquet engineering technique to see if they could tune specific types of quantum interactions, known as XXZ and XYZ spin models. These models describe how the particles' inherent quantum spins interact with each other, which is fundamental to understanding magnetic materials and other many-body phenomena.

While physicists use a mathematically constructed Bloch sphere to show how spins evolve in these models, it can be easier to visualize the molecules as changing their dance pattern based on how they interact with their neighbors, or dance partners. These molecular dancers may switch from pulling or pushing on their partners, which, on a quantum level, can be equated to changes in spin orientation.

In the study, the "quantum strobe light," or Floquet engineering, nudged these changes in interactions between molecules, which the researchers verified had produced similar spin dynamics to those generated by fine-tuning of the interactions using an applied electric field. In addition, the researchers precisely controlled the pulse sequence to realize less symmetric interactions that cannot be generated using electric fields.

Doing the (Two-Axis) Twist

The researchers also observed that their technique produced two-axis twisting dynamics.

Two-axis twisting involves pushing and pulling the quantum spins along two different axes, which can lead to highly entangled states. This process is valuable for advancing sensing and precision measurements, as it allows for the efficient creation of spin-squeezed states. These states reduce the quantum uncertainty in one component of a spin system while increasing it in another orthogonal component, leading to enhanced sensitivity in spectroscopy experiments.

"It was pretty exciting when we saw the initial signatures of two-axis twisting," Miller says. We weren't sure that we were going to be able to make it work, but we tried it, and a day and a half later, it was pretty clear that we had a signal."

The concept of two-axis twisting was proposed in the early 1990s, but its realization in two JILA laboratories had to wait until 2024. In addition to this work by Ye and his team, JILA and NIST Fellow and University of Colorado Boulder Physics professor James Thompson and his team used a completely different approach to working on atoms—cavity quantum electrodynamics, or cavity QED—also demonstrating two-axis twisting this year.

While the researchers did not attempt to detect entanglement in their system, they plan to do so in the future.

"The most logical next step is to improve our detection so we can actually verify the generation of entangled states," Miller adds.

Calder Miller, Annette N. Carroll, Junyu Lin, Henrik Hirzler, Haoyang Gao, Hengyun Zhou, Mikhail D. Lukin, Jun Ye "Two-axis twisting using Floquet-engineered XYZ spin models with polar molecules" Nature, 2024.

Written by Kenna Hughes-Castleberry,

World's Most Accurate & Precise Atomic Clock Pushes New Frontiers in Physics

In humankind's ever-ticking pursuit of perfection, scientists have developed an atomic clock that is more precise and accurate than any clock previously created. The new clock was built by researchers at JILA, a joint institution of the National Institute of Standards and Technology (NIST) and the University of Colorado Boulder.

Enabling pinpoint navigation in the vast expanse of space as well as searches for new particles, this clock is the latest to transcend mere timekeeping. With their increased precision, these next-generation timekeepers could reveal hidden underground mineral deposits and test fundamental theories such as general relativity with unprecedented rigor. For atomic-clock architects, it's not just about building a better clock; it's about unraveling the secrets of the universe and paving the way for technologies that will shape our world for generations to come.

The worldwide scientific community is considering redefining the second, the international unit of time, based on these next-generation optical atomic clocks. Existing-generation atomic clocks shine microwaves on atoms to measure the second. This new wave of clocks illuminates atoms with visible light waves, which have a much higher frequency, to count out the second much more precisely. Compared with current microwave clocks, optical clocks are expected to deliver much higher accuracy for international timekeeping—potentially losing only one second every 30 billion years.

But before these atomic clocks can perform with such high accuracy, they need to have very high precision; in other words, they must be able to measure extremely tiny fractions of a second. Achieving both high precision and high accuracy could have vast implications.

Trapped in Time

The new JILA clock uses a web of light known as an "optical lattice" to trap and measure tens of thousands of individual atoms simultaneously. Having such a large ensemble provides a huge advantage in precision. The more atoms measured, the more data the clock has for yielding a precise measurement of the second.

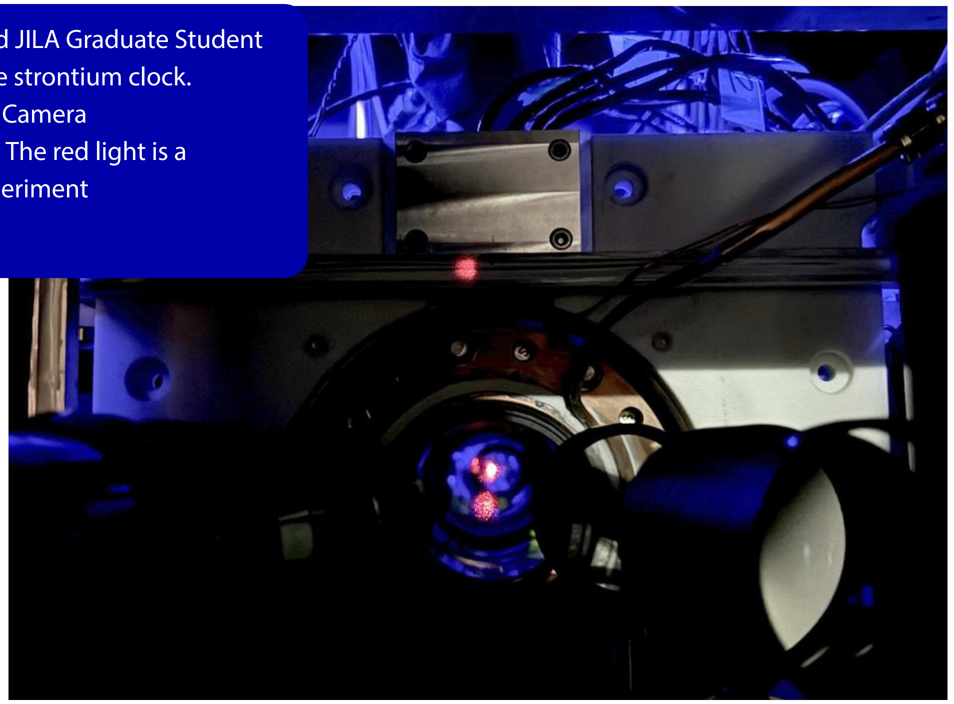
To achieve new record-breaking performance, the JILA researchers used a shallower, gentler "web" of laser light to trap the atoms, compared with previous optical lattice clocks. This significantly reduced two major sources of error—effects from the laser light that traps the atoms, and atoms bumping into one another when they are packed too tightly.

The researchers describe their advances in *Physical Review Letters*.

Clocking Relativity on the Smallest Scales

"This clock is so precise that it can detect tiny effects predicted by theories such as general relativity, even at the microscopic scale," said NIST and JILA physicist Jun Ye. "It's pushing the boundaries of what's possible with timekeeping."

General relativity is Einstein's theory that describes how gravity is caused by the warping of space and time. One of the key predictions of general relativity is that time itself is affected by gravity—the stronger the gravitational field, the slower time passes.



(Left): JILA Postdoc Kyungtae Kim and JILA Graduate Student Alexander Aeppli stand in front of the strontium clock.
Credit: Matthew Jonas/Boulder Daily Camera
(Right): A look at the strontium clock. The red light is a reflection of the laser used in the experiment
Credit: Katie Palubicki/NIST

This new clock design can allow detection of relativistic effects on timekeeping at the submillimeter scale, about the thickness of a single human hair. Raising or lowering the clock by that minuscule distance is enough for researchers to discern a tiny change in the flow of time caused by gravity's effects.

This ability to observe the effects of general relativity at the microscopic scale can significantly bridge the gap between the microscopic quantum realm and the large-scale phenomena described by general relativity.

Navigating Space and Quantum Advances

More precise atomic clocks also enable more accurate navigation and exploration in space. As humans venture farther into the solar system, clocks will need to keep precise time over vast distances. Even tiny errors in timekeeping can lead to navigation errors that grow exponentially the farther you travel.

"If we want to land a spacecraft on Mars with pinpoint accuracy, we're going to need clocks that are orders of magnitude more precise than what we have today in GPS," said Ye. "This new clock is a major step towards making that possible."

The same methods used to trap and control the atoms could also produce breakthroughs in quantum computing. Quantum computers need to be able to precisely manipulate the internal properties of individual atoms or molecules to perform computations. The progress in controlling and measuring microscopic quantum systems has significantly advanced this endeavor.

By venturing into the microscopic realm where the theories of quantum mechanics and general relativity intersect, researchers are cracking open a door to new levels of understanding about the fundamental nature of reality itself. From the infinitesimal scales where the flow of time becomes distorted by gravity, to the vast cosmic frontiers where dark matter and dark energy hold sway, this clock's exquisite precision promises to illuminate some of the universe's deepest mysteries.

"We're exploring the frontiers of measurement science," Ye said. "When you can measure things with this level of precision, you start to see phenomena that we've only been able to theorize about until now."

Alexander Aeppli, Kyungtae Kim, William Warfield, Marianna S. Safronova, and Jun Ye. "Clock with 8×10^{-19} Systematic Uncertainty." Physical Review Letters, 133(2), 023401, 2024

Written by Katie Palubicki, NIST Public Affairs Specialist

Meet the JILA Postdoc and Graduate Student Leading the Way in a NASA-Funded Quantum Sensing Project

In the quiet halls of the Duane Physics building at the University of Colorado Boulder, two JILA researchers, postdoctoral research associate Catie LeDesma and graduate student Kendall Mehling, combine machine learning with atom interferometry to create the next generation of quantum sensors. Because these quantum sensors can be applied to various fields, from satellite navigation to measuring Earth's composition, any advancement has major implications for numerous industries.

As reported in a recent article preprint, the researchers successfully demonstrated how to build a quantum sensor using atoms moving through crystals made entirely of laser light. They applied accelerated forces to atoms along multiple directions and, using this sensor, measured the results, which closely matched values predicted by quantum theory. LeDesma and Mehling also showed that their device could accurately detect accelerations from just one run of their experiment, a feat that is very difficult to accomplish with traditional cold-atom interferometry.

The experimental setup involved a sophisticated arrangement of lasers and other optical devices to manipulate and measure atoms at ultracold temperatures. Their approach was initially met with skepticism by many in the scientific community due to the novelty of the design and absolute reliance upon nonintuitive machine learning algorithms.

"Many thought that this type of measurement wouldn't work," explains JILA Fellow and University of Colorado Boulder Physics professor Murray Holland, the project's principal investigator at CU Boulder. "But the data is convincing."

While the scientific community may still be coming to terms with the potential of LeDesma's, Mehling's, and Holland's project to merge AMO (Atomic, Molecular, and Optical) physics with machine learning, the unique approach has already secured a $15 million grant from NASA as part of the Quantum Pathways Institute (QPI). The Quantum Pathways Institute is centered at the Center for Space Research (CSR) in Austin, Texas, and is led by Srinivas Bettadpur and colleagues.

Other collaborators in the Quantum Pathways Institute in Boulder include JILA Fellow and CU Boulder professor of physics Dana Anderson, professor of aerospace engineering Penina Axelrad, associate professor of electrical engineering Marco Nicotra, and group lead for the Sources and Detectors Group at NIST (National Institute of Standards and Technology) Michelle Stephens.

This institute is NASA's first step in exploring the potential advantages of quantum metrology over classical sensors deployed in space. As stated on the QPI website, the quantum sensors will be placed "aboard satellites in orbit around Earth to collect mass change data—a type of measurement that can tell scientists about how ice, oceans, and bodies of water are moving and changing." Such technology would lead to more accurate pictures of the effects of climate change and global warming on Earth.

Taking the Quantum Reins

Because their complicated nature can often span longer than the time to obtain a PhD, many research projects within the physics community are inherited by a graduate student from a graduating doctoral student. In LeDesma's case, there was no prior graduate student to hand over a working experiment to her when she started on the project as a new graduate student in the fall of 2019.

"My introduction to the world of quantum gases was with a magneto-optical trap, or MOT," she says. "However, to do any of the precision metrology we wanted, I needed to learn how to make a Bose-Einstein-Condensate, and there were no students in the lab who could pass on that prior knowledge."

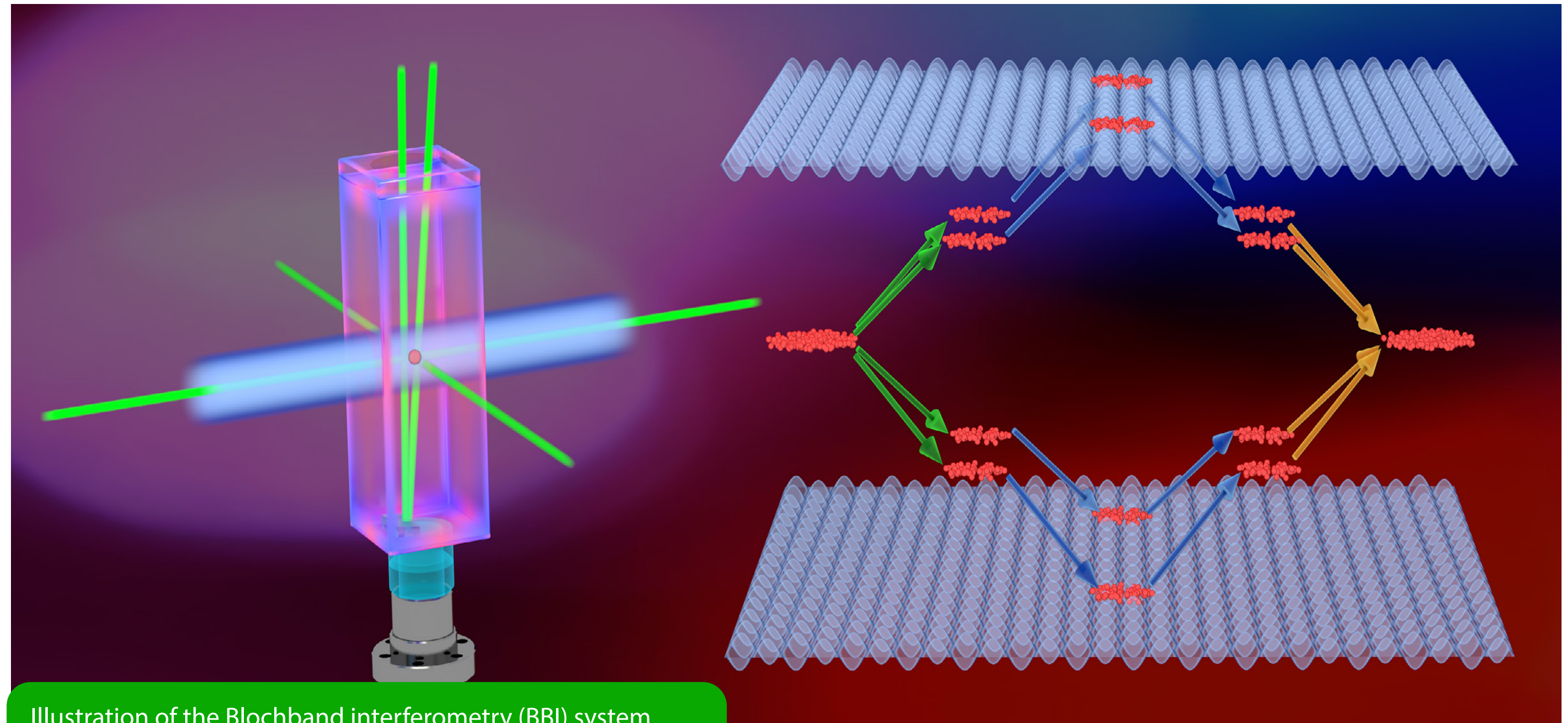


Illustration of the Blochband interferometry (BBI) system (right), using an optical lattice. The sequence shows the BEC splitting into four 2D momenta (green arrows), reflection after propagation (blue arrows), and the reverse beam splitter providing recombination (orange arrows) to form a 2D interference pattern.
Credit: Steven Burrows/Holland Group

Considered the fifth state of matter, Bose-Einstein-Condensates (BECs) are composed of dense, ultracold clouds of gaseous atoms in the quantum regime. They have a long history at JILA, as JILA and NIST Fellow Eric Cornell and former JILA Fellow Carl Wieman were awarded the 2001 Nobel Prize in Physics for experimentally creating the first BEC.

When LeDesma arrived at JILA, just before the COVID-19 pandemic, she began to work on the BEC quantum metrology project that had formed the core doctoral work of a former graduate student Carrie Weidner, under the supervision of Professor Dana Anderson. Both Anderson and Weidner had spent years previously developing a special type of quantum metrology known as shaken-lattice interferometry, which uses controlled vibrations of a grid-like structure to measure and study the behavior of particles precisely.

The BEC quantum metrology experiment was (and still is) housed in the Duane Physics building C-wing, an area susceptible to vibration, noise, and temperature variation, all unfavorable conditions for a sensitive precision experiment.

"For about a year and a half, I had to teach myself a lot of basic experimental skills. In that time, I completely rebuilt the 780-nm laser system necessary for cooling and trapping rubidium atoms and making BEC on an atom chip using RF evaporation. This experience proved instrumental for our future work which involved moving to a newer method of achieving BEC," LeDesma explains.

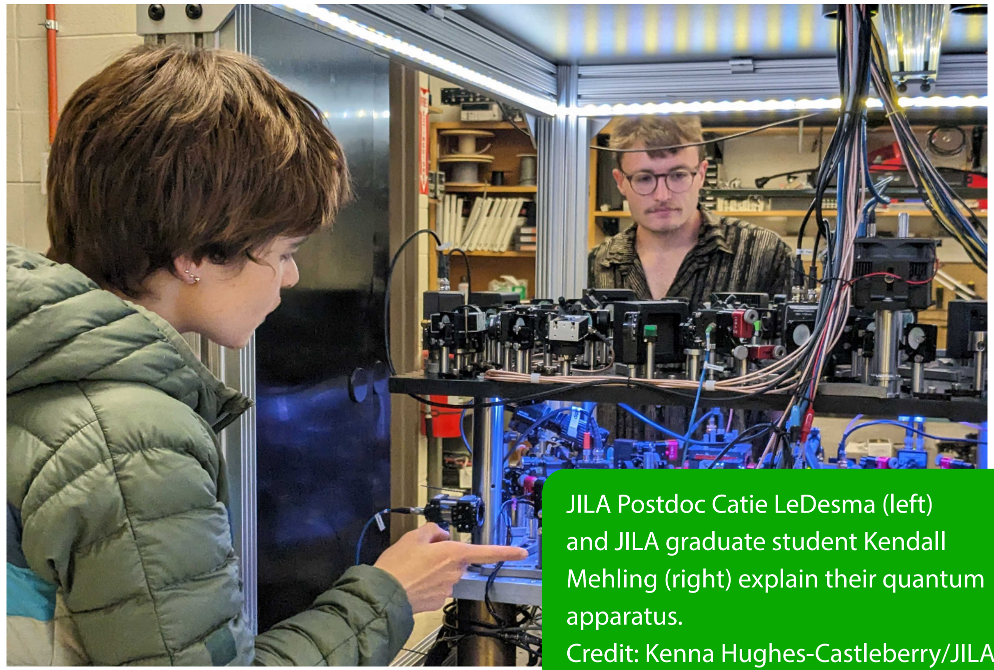
In 2021, Mehling arrived as a new graduate student in the laboratory. Together, LeDesma and Mehling made great strides in their BEC quantum sensor apparatus, including significant changes from the 2017 project. This included completely rethinking both how the experiment creates BECs and the method of performing interferometry itself, which involved a full experimental redesign and construction.

Together, they applied a contemporary method to evaporatively cool atoms with an all-optical sequence, successfully observing their first BEC with this method in the fall of 2022.

All-optical evaporation is performed within tightly focused, high-intensity laser beams. When two of these laser beams intersect, their crossing forms an optical trap where large numbers of hot atoms can be stored and collide with each other. Forced evaporative cooling is then performed by reducing the power of the laser beams. This process boils off the hot atoms similarly to the release of steam from a hot cup of coffee as it cools.

Using an all-optical method, the researchers do not need to use any magnetic fields during the cooling process, enhancing the BEC's potential size and stability. Additionally, this design allows the BEC to be more easily transferred into an optical lattice—a structure formed by interfering laser beams that create a standing potential of light. This lattice acts like a "light crystal" that can hold and manipulate atoms in a very controlled manner, enabling their use in interferometry experiments.

Engineering Your Own Quantum Sensor



JILA Postdoc Catie LeDesma (left) and JILA graduate student Kendall Mehling (right) explain their quantum apparatus.
Credit: Kenna Hughes-Castleberry/JILA

Interferometers have a long, rich history as precision metrology instruments. Optical interferometers operate by splitting, mirroring, and recombining coherent light beams, resulting in discernable phase shifts in the light's interference pattern because of minute differences along the two paths. Measurement of these phase shifts can reveal information about the environment and enable the sensing of inertial signals such as accelerations, rotations, and gravity gradients. These measurements form the basis of commercial gyroscopes such as ring laser gyroscopes and fiber optic gyroscopes.

More recently, AMO physicists have invested considerable research into atom interferometry, where the role of light and matter are effectively switched—that is, light pulses are used to split, mirror, and recombine the matter waves of neutral atoms to measure slight changes in their environment.

LeDesma, Mehling, and Holland further modified this approach, performing interferometry while the atoms interact with an optical lattice during the entirety of their sensing sequence. Dynamic control of the lattice phase (i.e., the location of light and dark regions) according to machine-learned protocols allowed the researchers to realize the necessary interferometry components.

At the sensor's core is a custom double-MOT system built by Infleqtion, a quantum technology company. Within this ultrahigh-vacuum chamber, a combination of magnetic fields and precisely tuned laser light damp the motion of rubidium atoms with decelerations of up to 1000 m/s2, or 100 times the force of Earth's gravity.

This cooling is achieved through Doppler cooling, a process in which lasers tuned to a color that is a slightly lower frequency than the color that the atoms typically absorb. This causes atoms to slow down when they move against the direction of the laser light. This laser force is strong as it reduces the temperature of the atoms by a factor of 10,000 in a few milliseconds.

In addition to the cooling effect of the laser light, magnetic field gradients are applied to exert a position-dependent force on the atoms. Combined, this process, known as a magneto-optical trap, or MOT, is a critical first step in many AMO experiments for quantum science.

In this common setup, the apparatus produces ultracold atoms in two distinct regions. In a lower glass chamber, dispensed atoms are initially cooled along two dimensions, and a laser push beam is used to propel the atoms vertically up through a tiny tube. They then appear and are recaptured in an upper chamber which has the pristine vacuum quality necessary to perform experiments where confining atoms for seconds is desirable.

"We produce a MOT in the bottom cell, and then we push atoms up to the 3D science chamber, where we load a three-dimensional MOT that would look maybe the size of a thumbnail," Mehling elaborates.

The 3D MOT typically accumulates one billion cold rubidium atoms over a five-to-ten-second load time. Additional cooling is achieved by changing the chamber's magnetic field strength and further detuning the laser light from atomic resonance.

The cold and dense atoms that result are then captured by intense 15-watt laser beams to perform all-optical evaporation to degeneracy. The brightness of the beams, and therefore the trap depth, is slowly lowered to cool the atoms below the critical temperature necessary to form a BEC. For a typical experimental run, LeDesma and Mehling produce 100,000 BEC atoms at an effective temperature of below 10 nK, 300,000 times colder than the initial MOT atoms.

Following these numerous cooling steps, the BEC is then loaded into their multidimensional optical lattice. While many experiments use retroreflecting mirrors to create their optical lattices because it is easier, LeDesma and Mehling instead use counterpropagating laser beams. This design offers greater versatility and flexibility in controlling the location of the lattice nodes and antinodes but is harder and requires meticulous alignment.

"It's like taking two strands of hair and overlapping them, and they have to align perfectly to create your lattice," Mehling adds. "It becomes more complicated because our lasers aren't visible light; they're in the IR (infrared) spectrum, so we can't see them with the naked eye and have to use IR cards to detect where they are and then align them manually."

Adding AI to Quantum

The complexity of controlling pure quantum states like a BEC in an optical lattice involves numerous variables, each of which can drastically affect the outcome. The researchers employ sophisticated machine design techniques such as reinforcement learning (RL) and quantum optimal control (QOC) to develop and optimize the control sequences that manipulate the atomic wave functions within the lattice to perform interferometry.

Holland and his former graduate student Liang-Ying Chih developed much of the initial theory that the current experimental procedures

Catie LeDesma crawls on top of the table-top apparatus as part of the laboratory rebuild.
Credit: Murray Holland/JILA

for interferometry rely on. They applied reinforcement learning, a form of machine learning and artificial intelligence, to the quantum design problem and showed that atom interferometry could be done in this manner.

Additionally, LeDesma and Mehling worked alongside associate professor of electrical engineering Marco Nicotra and his former graduate student Jieqiu Shao to implement quantum optimal control algorithms to generate an alternative class of interferometry solutions. High-fidelity solutions obtained through both approaches demonstrated a successful interface between atom interferometry and computer programming.

The researchers experimentally apply these machine-generated solutions by changing the relative phase of individual lattice beams as needed.

The lattices' counterpropagating design enables the relative phase to be adjusted by inputs from a control computer. This means that controls can be changed on the fly, and the sensor's behavior can be changed at will by software programming rather than by modifying the experimental hardware. This programmability of their sensor allows the device to operate as either an accelerometer in one dimension or a multi-dimensional gyroscope via the flick of a virtual switch. However, initial experiments wielding this additional flexibility proved nontrivial.

"There was quite a learning curve to go through to understand how to apply the machine-learned protocols and to get the BEC atoms to do precisely what we wanted" explains Holland. "But we are now so good at it that if we find a great solution on the computer, we know with high confidence that we will be able to apply it to the experiment."

The final component of their sensing sequence involves the detection and imaging of the atoms. A resonant probe aligned with each lattice axis enables absorption imaging of the atoms following lattice phase modulation. Absorption images of the atoms provide detailed information about the momentum and position of the atoms, allowing the researchers to reconstruct the atomic wavefunctions and measure the atoms' response to inertial signals.

In practice, the matter-wave interference pattern from which a signal is extracted is seen by allowing atoms to fall under gravity and separate into discrete momentum components. The relative occupation of atoms in these multi-order momentum states changes with an applied inertial signal. Imaging the atoms after they have undergone interferometry and time of flight enables the researchers to reconstruct the applied signals.

In their most recent experiments, the sequencing of the machine-learned protocols allowed the experimental team to perform a special type of measurement known as two-dimensional Michelson interferometry, which is used in other apparatuses that do not involve machine learning.

LeDesma and Mehling revealed the resulting 49 momentum diffraction peaks in the atoms' 2D interference pattern, which had not previously been seen by other experiments. Measurements of the many-order diffraction pattern provided the critical information needed to determine the magnitude and direction of external accelerations. This information was crucial for calibrating the sensor's sensitivity, optimizing performance, and calculating the application's experimental stability.

To better understand the systems dynamics and predict their sensor's response and performance, LeDesma and Mehling worked closely with JILA Fellow Murray Holland.

"This project works because we've been working heavily with the theorists, who can help translate all the protocols," Mehling adds. "Murray was here sitting in the lab with us, trying to get the control protocols to work from the beginning of the project. He comes down to the lab and gets his hands dirty, and I don't think we could oversell Murray's importance and how good of an advisor he is."

While Holland's research has been in quantum theory, his 30-year history of studying BEC dynamics allowed him to help guide the implementation of these novel interferometry sequences and realize the importance of their research.

"It's impressive what Catie and Kendall have been able to achieve in such a short time," Holland commented. "They quickly recognized what problems had to be solved and found solutions. The result is work that is opening a whole new avenue of research which will develop into a substantial field, with JILA at the forefront."

NASA Buys In

In March 2023, the BEC quantum metrology experiment got a significant boost in funding with the help of the NASA Quantum Pathways Institute grant, a $15 million grant over five years to several universities working on applying remote quantum sensing to study the Earth's climate.

As CU Boulder has been designated as the testbed site for this grant, LeDesma and Mehling are leading the charge, along with Holland, the lead PI for the Colorado portion of the grant, and with the other CU Boulder research collaborators.

Rebuilding a Laboratory in Seven Days

Away from JILA's dampening floors and piped-in purified water and air, the C-wing of the Duane Physics Building suffers from vibrations and thermal fluctuations from the glass windows and countless students walking, biking, and skateboarding past the lab on the concrete sidewalks and paths outside.

In the fall of 2023, LeDesma and Mehling, fed up with the older building's issues, decided to remodel the experiment, taking apart the entire apparatus and rebuilding it from the ground up.

Left: The Quantum Pathways Institute's site visit to JILA.
Credit: Kenna Hughes-Castleberry/JILA
Edited by Srinivas Bettadpur

Right: A photo of the quantum machine learning apparatus.
Credit: Murray Holland/JILA

"The temperature stability in this lab is horrendous," LeDesma elaborates, "The temperature swings up to five degrees daily, which can greatly affect laser beam pointing stability. In our original system, this caused drifts in the alignment of the light used for all-optical evaporation as well as our lattice beams used for interferometry. We were having to realign beams at least four to five times daily to combat this."

To compensate for these issues, LeDesma and Mehling worked with JILA's instrument shop to create a custom climate-controlled enclosure to supply cooled, filtered air to their experimental system. However, to install this new enclosure, the experiment had to be deconstructed. The full demolition day was August 15, 2023.

"Installation of the new enclosure required us to not only remove a majority of the optics off the table but also included removing all the electronics and other elements used to control the experiment. We had to uninstall all the rack units that originally held all of these components above the optics table." LeDesma says. "After we installed the new enclosure, we started putting optics back on the table. It took us six days to obtain our first BEC following the rebuild."

The rebuild took seven days, not because of external pressure but because of LeDesma and Mehling's efficiency in working with their system, which they had reconfigured dozens of times.

Their experimental rebuild has proven instrumental in the researchers' abilities to conduct interferometry experiments. With the enhanced stability, the team can go months at a time without anything more than slight alterations to the experiment, consistency LeDesma and Mehling hope to leverage as they continue to explore the potential of their sensor.

Skeptics Emerge

While combining AI's machine learning processes with the sensitivity of quantum mechanics could produce the next generation of quantum sensors, not all are convinced by the results of these experiments.

The standard point of view is that if a scientist wants to measure things precisely, they will want their atoms in the dark and not interacting with anything, a notion popularized by the 1989 Nobel Prize winner Norman Ramsey in his method of separated oscillatory fields.

But here in the lab, the atoms always see the light crystal that they move in, and so the environment must be perfectly controlled. As upgrades to the experimental system are installed and the team continues to report improved performance metrics, Mehling believes more experimenters will be willing to adopt some of their strategy and design philosophies.

In March of 2024, Holland presented the accelerometry results from the one-dimensional and two-dimensional experiments for the first time at a CU Boulder Physics Department Colloquium. For both LeDesma and Mehling, the feeling was one of validation.

"We finally had some significant results to show that this thing actually worked," Mehling says. "After the talk, people came up and asked questions. Later, more people visited the lab, wanting to understand what we were doing. We have been very isolated in Duane, and it's nice to feel that way no longer."

Moving Toward Greater Sensitivity

Now, with an improved setup, a NASA grant, and possible future collaborations with other JILA researchers, LeDesma and Mehling are interested in pushing the boundaries of their apparatus as much as possible.

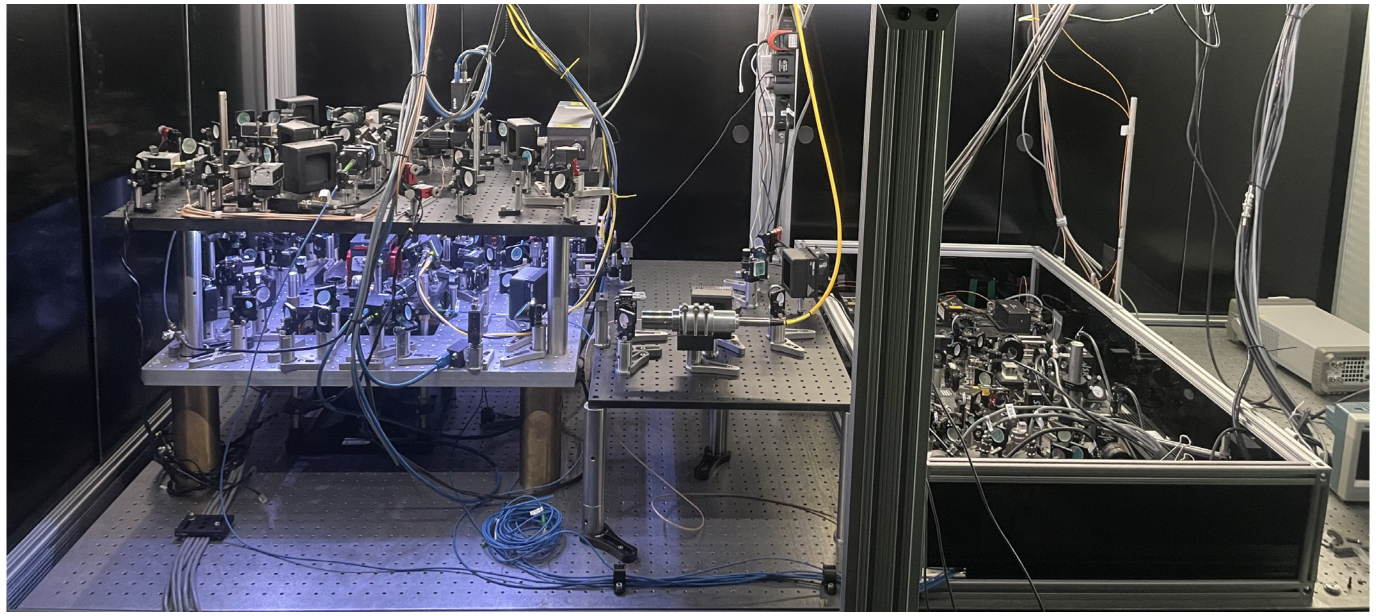
"We want to turn this into a precision measurement experiment," Mehling adds. "Currently, it's not as sensitive as we need. We have an end-user for our experiment, goals, and a timetable to keep progress moving sustainably."

With its versatile design, the researchers have proposed that the apparatus can potentially measure various phenomena, from Earth's gravity and tidal distribution to the detection of dark matter.

"The realization of the fact that matter can behave as waves and interfere constructively and destructively lies right at the core of the development of quantum mechanics more than one hundred years ago," explains Holland. "And so, atom optics systems are very fundamental, and to show that we can control them exquisitely with modern machine learning and optimization methods introduces a disruptive solution to a very old technology. We think this experiment is now placed to have a bright future—full of potential—and we don't know at this point how far we will be able to take it."

Catie LeDesma, Kendall Mehling, Murray Holland. "Vector Atom Accelerometry in an Optical Lattice." arXiv: 2407.04874 [quant-ph], 2024.

Written by Kenna Hughes-Castleberry



The group photo taken at the Quantum Light Conference hosted by JILA in July 2024.
Credit: Kenna Hughes-Castleberry/JILA

JILA Hosts the Inaugural Workshop on Quantum Light Generation, Detection, and Applications. The conference was dedicated to recent advancements in the field of quantum light, particularly in nonlinear optics, integrated photonics, and materials synthesis. These fields of physics have significantly contributed to our ability to generate various quantum states of light. The workshop also highlighted the innovative applications of these advancements in imaging, sensing, and spectroscopy.

Colorado Representative Yadira Caraveo visits JILA and the University of Colorado Boulder for Quantum Discussions. As a House Committee on Science, Space, and Technology member, Caraveo's visit came just a day after the Mountain West was granted a $127 million boost for quantum technology and workforce development. During her tour, including a visit to Jun Ye's renowned lab, Caraveo expressed her commitment to ensuring robust funding for agencies vital to quantum research.

JAGS (JILA Association of Graduate Students) Hosts First Graduate Student Seminar Series. JAGS proudly hosted its inaugural Graduate Student Seminar, marking the beginning of a promising seminar series to foster academic exchange, collaboration, and community within JILA. The event showcased the cutting-edge research conducted by three JILA graduate students, drawing an audience of over 70 graduate students, postdoctoral researchers, and staff members. "We are excited to bring this opportunity for students to present their work and to connect with other researchers across JILA," added JILA graduate student and one of JAGS leading members Anya Grafov. "We hope that this new seminar series will not only give students valuable presentation experience, but will also bring the JILA community closer together."

JILA Celebrates Summer Solstice 2024. JILA marked the summer solstice with a unique celebration in the X-wing basement, which became a sunlit patio for a few brief minutes, allowing JILA Fellow Eric Cornell to do a quick experiment on the architecture. "It turns out that JILA was constructed to be a modern-day Stonehenge," explains Cornell, a NIST Fellow and University of Colorado Boulder physics professor. "In previous years, JILA's astronomers have had trouble interpreting the portents because of multiple-reflected overlapping light beams arriving in the basement." To overcome this issue, Cornell's research team, led by undergraduate researcher Rohan Kompella, created a series of precision apertures made of cardboard to separate the light beams, making it easier to see the sun's refraction pattern.

JILA grad students John D. Wilson (left) and Anya Grafov (right) field questions at the JILA JAGS Seminar.
Credit: Kenna Hughes-Castleberry/JILA

JILA and University of Colorado Boulder is Awarded $20 million to Build a new "Quantum Machine Shop." The U.S. National Science Foundation awarded JILA and the University of Colorado Boulder a $20 million grant to create the National Quantum Nanofab (NQN), a cutting-edge facility poised to revolutionize quantum technology.

JILA Postdoctoral Researcher Jake Higgins is Awarded Spot at 2024 MIT Chemistry Future Faculty Symposium. The Future Faculty Symposium is a two-day event designed to provide postdoctoral scholars with extensive opportunities to engage with the MIT community.

CU Boulder Physics Undergraduate Luke Coffman is Awarded a 2024 Astronaut Scholarship. Double-majoring in physics and math with a minor in quantum engineering, Coffman's research looks at quantum information theory, focusing particularly on quantum entanglement.

JILA Fellow Adam Kaufman is Awarded Prestigious Gordon and Betty Moore Foundation Grant. Kaufman, a JILA Fellow, NIST Physicist, and CU Boulder physics professor, has been awarded a $1.25 million grant from the Gordon and Betty Moore Foundation for its third annual cohort of Experimental Physics Investigators. This prestigious five-year grant will support Kaufman's innovative research on many-electron systems, mainly using ultracold atoms in optical lattices to simulate the Hubbard model—a fundamental framework for understanding complex phenomena like superconductivity and magnetism.

JILA Fellow Adam Kaufman has been awarded a 2024 Grant by the Gordon and Betty Moore Foundation
Credit: Kenna Hughes-Castleberry/JILA

JILA Graduate Student Anya Grafov is Awarded Best Poster From the IEEE Magnetics Society Summer School 2024. Studying with JILA Fellows and University of Colorado Boulder Physics professors Margaret Murnane and Henry Kapteyn, Grafov's poster titled "Probing Ultrafast Spin Dynamics with Extreme Ultraviolet High Harmonics" was one of only nine to receive this prestigious recognition.

JILA Graduate Student Yunzhe "Oliver" Shao Wins Best Paper Award at the IEEE Conference on Computational Imaging Using Synthetic Apertures. Shao's winning research focused on developing an extreme ultraviolet (EUV) reflectometer. This innovative instrument is designed to characterize various nanostructured samples' chemical compositions and spatial properties.

JILA Graduate Student Emma Nelson Wins Third Place at the 2024 CU Boulder Innovation in Materials Symposium. Held at CU Boulder, this symposium is a significant platform for the materials research community, bringing together faculty, students, and industry professionals from CU Boulder and beyond.

JILA Graduate Student Tatsuya Akiba is Awarded 2024 Richard Nelson Thomas Award. This honor is bestowed annually to an outstanding APS graduate student at JILA and recognizes excellence in research and academic achievements.

JILA graduate student Tatsuya Akiba (left) receives the Richard Nelson Thomas Award from JILA Fellow and APS professor Ann-Marie Madigan (right).
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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