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It is a quantum fractal algorithmic universe

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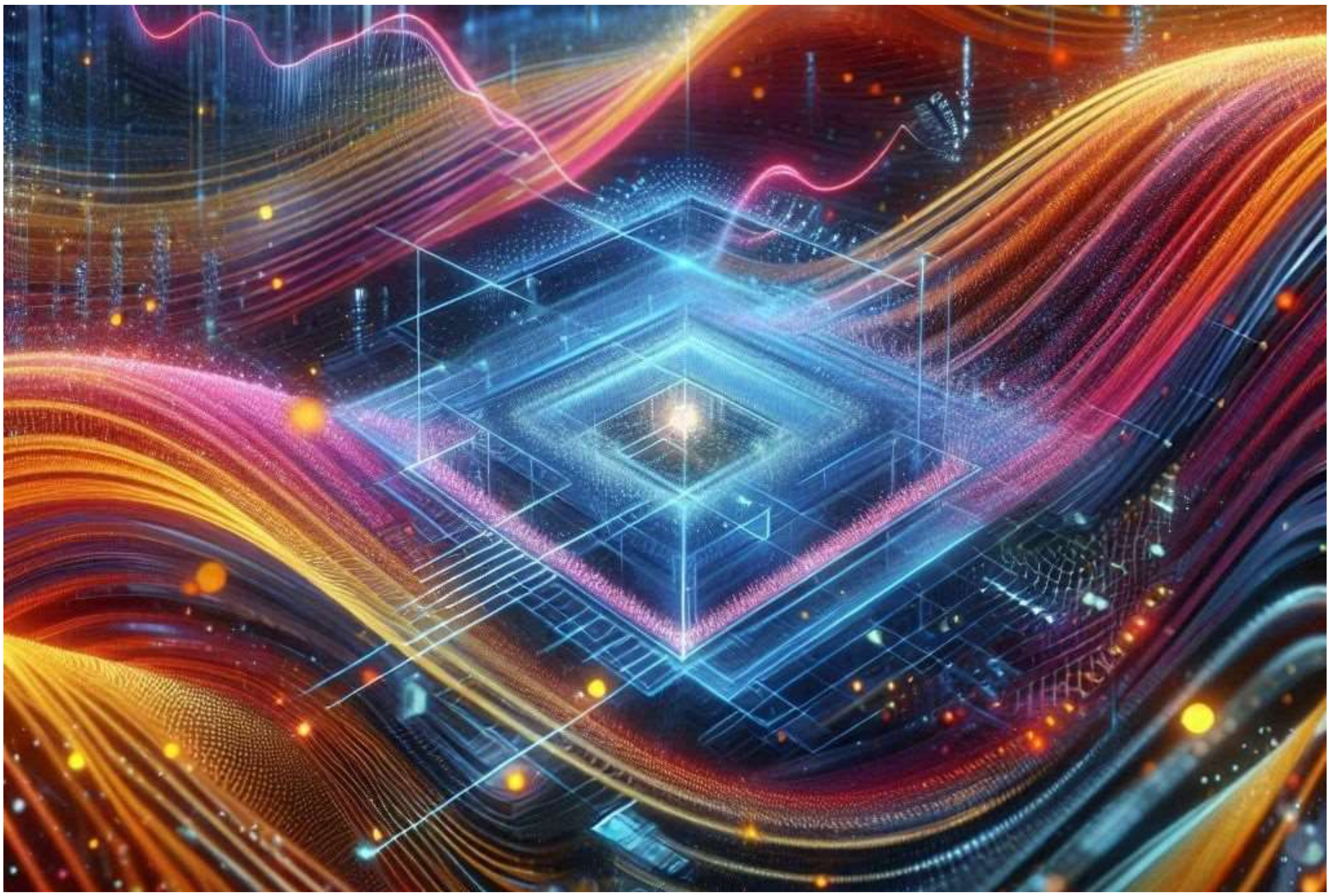
Atom Interferometers - A Way To Devise To Miniaturize Them

Atom interferometers are quantum sensors that use atoms' wave-like nature to measure gravity, acceleration, and rotation with exceptional precision. Atom interferometric quantum sensors are huge, but a U-M research group has devised a way to miniaturize them.



Quantum sensor – artistic impression. Image credit: Copilot Designer / Alius Noreika

Most current atom interferometers are large instruments, occupying buildings and requiring towers that can reach tens of meters in height. Now, University of Michigan physicists have developed a design for a quantum rotation sensor with a core size barely visible to the human eye.

According to lead author and U-M doctoral student Bineet Dash, the proof-of-concept design could help bring atom interferometer-based quantum sensors out of the laboratory and into the world.

Scientists could use atom interferometers in quests ranging from the continual hunt for the tiny ripples in the fabric of our universe caused by gravitational waves to understanding minute, localized changes in Earth's gravity caused by melting ice sheets in Antarctica, Dash says. But because of their size, atom interferometers are typically bound to laboratory settings. Currently, the most sensitive atom interferometers use tall towers inside buildings to shoot beams of atoms across tens of meters to gather information.

The new design developed by Dash and the lab of U-M physicist Georg Raithel uses a special kind of laser beam that traps atoms in a pinwheel-shaped geometry, which can be scaled from a 30 micron radius, smaller than the diameter of a human hair, and up to about 10 times larger, about 300 microns. The researchers' design is published in the journal AVS Quantum Science.

“This interferometer is not an incremental improvement on existing designs that were developed elsewhere,” Dash said. “This is based on a fundamentally different approach proposed by our group in 2021.”

Currently, researchers often use interferometers that are based on laser-wave interference. In astrophysics, such optical interferometers are employed to detect gravitational waves, Dash said. In inertial navigation, optical interferometers are used to measure the rotation of airplanes, ships and satellites.

“People often say that there is already a sensor that works with light. Why do we need to develop a sensor that uses quantum mechanics?” Dash said. “A major motivation is that atom interferometers can be orders of magnitude more sensitive than optical interferometers under the same conditions.”

Light-interferometer-based rotation sensors use what's called the Sagnac effect. French physicist Georges Sagnac discovered that light could be used to measure rotation: If you send light around a rotating body, then send another stream of light counter to the rotation, the waves of light overlap. But these waves of light “interfere” with each other and begin to show a difference in the path that they travel. This difference can be used to measure the speed of rotation.

Atom-interferometric rotation sensors are based on the same concept. According to quantum mechanics, atoms are particles, but they also behave like waves. Because their wavelength is much smaller than that of light, according to Dash, they allow for more accurate and sensitive rotation measurement than light interferometers.

But in addition to their large size, the way a majority of existing atom interferometers operate also presents problems for their use outside of the lab. Atoms are shot up into a vacuum within a laboratory tower on separate paths using laser pulses, Dash said. One atomic path reaches higher than the other, and then they meet back at the bottom. The lag between when they meet gives information about the background acceleration.

When atoms are set loose into free space, they can disperse, and when they disperse, information is lost. At some point, atoms will disperse enough that all information is lost. And although the atom streams are launched together, many atoms don't meet back, which leads to more missed information.

In 2021, Raithel's lab, in which Dash is a student, used the idea of “optical lattices” to try to scale down the size of atom interferometers. Optical lattices are created when two laser beams moving in opposite directions cross paths giving rise to grids of light. Under appropriate conditions, atoms can be trapped at the minima of the light grid, like eggs sitting in an egg carton, Dash said. The optical lattices keep the atoms confined and allow experimenters to guide the atoms on predetermined paths that are certain to meet back again.

The 2021 study showed that atoms in different quantum states can be trapped in separate lattices by carefully tuning the laser parameters. Using laser pulses, the researchers can craft a quantum superposition of states trapped in two such optical lattices. Moving these two lattices in opposite directions creates a lag between the two streams of atoms, which can then be used to read background acceleration.

But the 2021 design only sent atoms back and forth along a straight line, which is not amenable for rotation sensing.

In the current study, Raithel's lab devised a way to use a special kind of laser beam that sends atoms in an angular pattern rather than a linear standing wave pattern.

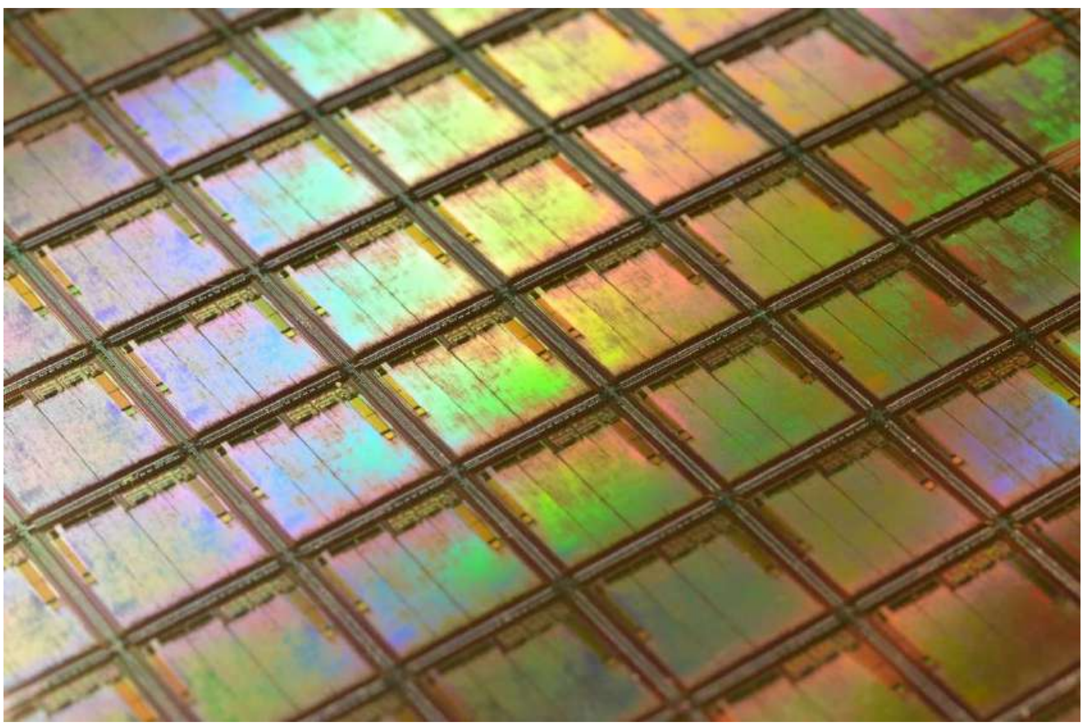
"It looks like a pinwheel, and by changing the laser frequencies slightly, the speed of the pinwheel can be changed," Dash said. "After a predetermined time of spinning, a lag develops between the pinwheels, and we can use this lag to figure out the background rotation."

Dash said that while the paper describes a proof-of-concept design, the Raithel lab is currently working on a prototype experiment that utilizes a source of Bose condensed cold atoms.

"Current atom interferometers are great for fundamental physics, but they are heavy, power intensive, take up a lot of space, and essentially because of their geometric footprint, they are not practically useful," Dash said. "Our study is about prototype development. But it is a very general technique that can be adapted for practical applications in, for instance, inertial navigation and gravity mapping, as well as for research in fundamental physics."

Researchers Discover New Materials, Techniques With Promising Potential For Microelectronics And Quantum Technologies

As phones and computers shrink in size, our need for data storage and transfer is growing. Semiconductors have powered electronic devices for decades, but as the push to miniaturize continues, there's a limit to how small semiconductors can be made.



Microchips during the manufacturing process – illustrative photo. Image credit: Laura Ockel via Unsplash, free license

The next generation of handheld devices requires a novel solution. Spintronics, or spin electronics, is a revolutionary new field in condensed-matter physics that can increase the memory and logic processing capability of nano-electronic devices while reducing power consumption and production costs. This is accomplished by using inexpensive materials and the magnetic properties of an electron’s spin to perform memory and logic functions instead of using the flow of electron charge used in typical electronics. New work by Florida State University scientists is propelling spintronics research forward.

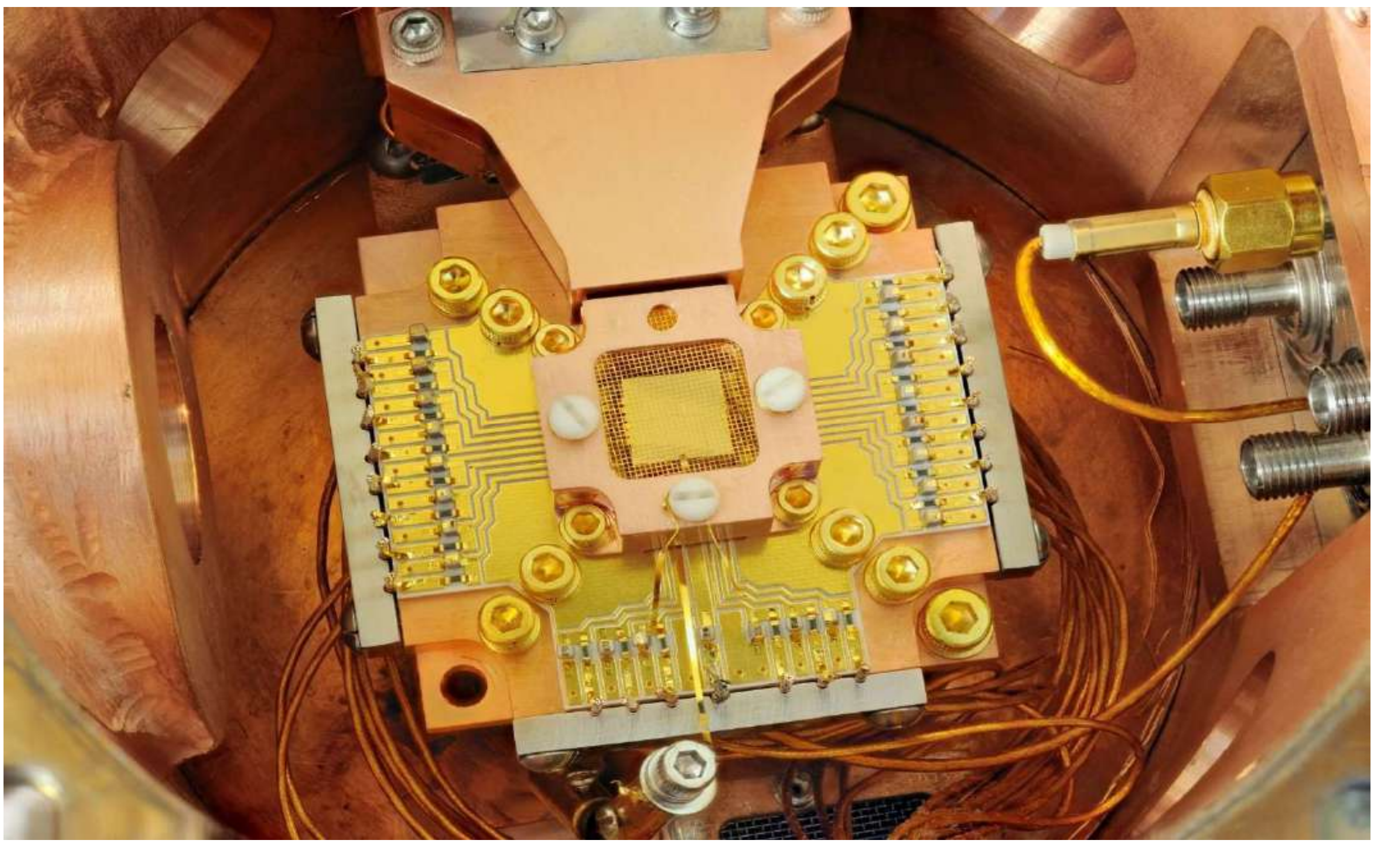
Professors Biwu Ma in the Department of Chemistry and Biochemistry and Peng Xiong in the Department of Physics work with low-dimensional organic metal halide hybrids, a new class of hybrid materials that can power optoelectronic devices like solar cells, light-emitting diodes, or LEDs and photodetectors. Together, they have identified new magnetic and electronic properties in these materials, pointing to impressive potential in spintronics. Xiong, in his solo work, has engineered the first instance of a magnet-free electron spin generation in a semiconductor, facilitating the low-cost development of high-powered electronic devices.

“While this new class of materials has proven useful in creating optical materials for optoelectronic devices, like LEDs, this is the first time we’re observing some unique magnetic properties,” said Ma, a renowned expert in materials chemistry. “Depending on the choices of appropriate organic and metal halide components, which theoretically could be unlimited, we are able to assemble them into crystalline structures with different dimensionalities. Different compositions and structures make them exhibit diverse properties, which can have a variety of applications, ranging from optoelectronics to spintronics, and even a combination of both.”

Ma’s lab synthesizes materials in varying configurations before sending them to Xiong’s lab for electronic and magnetic characterizations — graduate students in both labs lead the experiments. Xiong’s lab then gives feedback about the properties of the synthesized materials. In the article “Antiferromagnetic Ordering in A One-Dimensional Organic Copper Chloride Hybrid Insulator,” published in Angewandte Chemie this summer, Ma and Xiong unveiled newly discovered properties, highlighting the potential of these materials as a highly tunable quantum platform for spintronics.

An Idea Rooted In ‘Twistronics’ Yields An Electrifying, ‘Dizzying’ Outcome

In 2018, a discovery in materials science sent shock waves throughout the community. A team showed that stacking two layers of graphene—a honeycomb-like layer of carbon extracted from graphite—at a precise “magic angle” turned it into a superconductor, says Ritesh Agarwal of the University of Pennsylvania. This sparked the field of “twistronics,” revealing that twisting layered materials could unlock extraordinary material properties.



Researchers led by Ritesh Agarwal of the School of Engineering and Applied Science and Gene Mele of the School of Arts & Sciences uncovered how twisting multiple layers of a material can generate a mysterious sideways deflection of moving electrons—analogous to the Coriolis effect seen in ocean currents—unlocking new possibilities for controlling light and electrons in quantum materials. Image credit: NIST

Building on this concept, Agarwal, Penn theoretical physicist Eugene Mele, and collaborators have taken twistronics into new territory. In a study published in *Nature*, they investigated spirally stacked tungsten disulfide (WS_2) crystals and discovered that, by twisting these layers, light could be used to manipulate electrons. The result is analogous to the Coriolis force, which curves the paths of objects in a rotating frame, like how wind and ocean currents behave on Earth.

“What we discovered is that by simply twisting the material, we could control how electrons move,” says Agarwal, Srinivasa Ramanujan Distinguished Scholar in the School of Engineering and Applied Science. This phenomenon was particularly evident when the team shined circularly polarized light on WS_2 spirals, causing electrons to deflect in different directions based on the material’s internal twist.

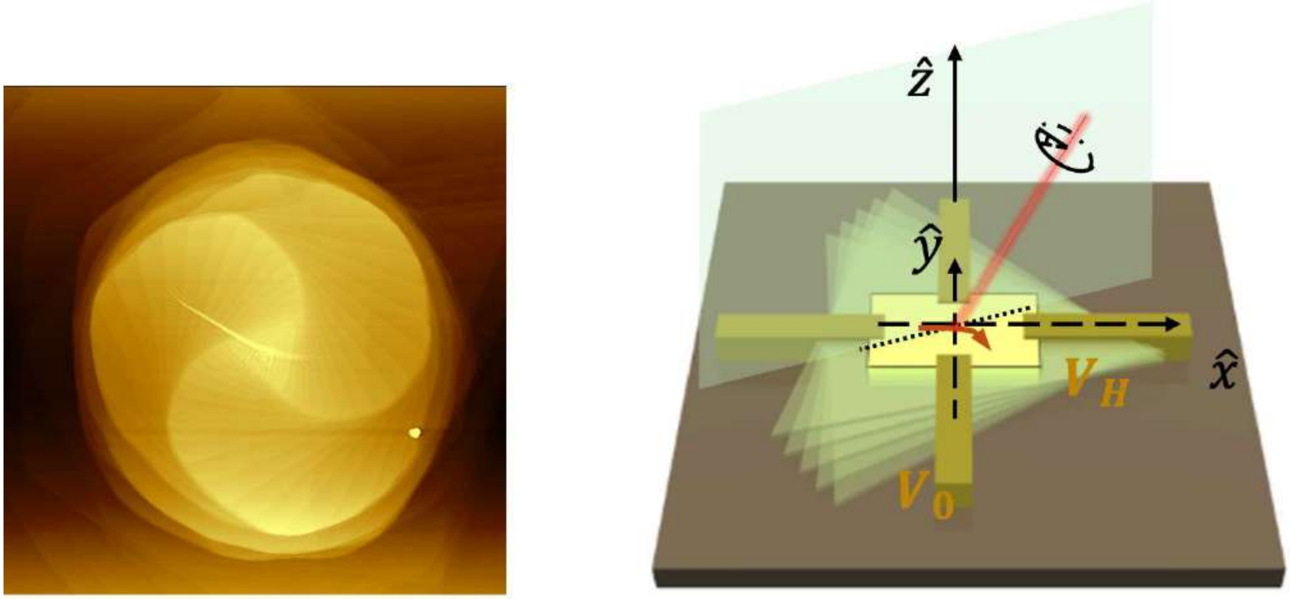
The origins of the team’s latest findings trace back to the early days of the COVID-19 pandemic lockdowns when the lab was shut down and first author Zhurun (Judy) Ji was wrapping up her Ph.D.

Unable to conduct physical experiments in the space, she shifted her focus to more theoretical work and collaborated with Mele, the Christopher H. Browne Distinguished Professor of Physics in the School of Arts & Sciences. Together, they developed a theoretical model for electron behavior in twisted environments, based on the speculation that a continuously twisted lattice would create a strange, complex landscape where electrons could exhibit new quantum behaviors.

“The structure of these materials is reminiscent of DNA or a spiral staircase. This means that the usual rules of periodicity in a crystal—where atoms sit in neat, repeating patterns—no longer apply,” Ji says.

As 2021 arrived and pandemic restrictions lifted, Agarwal learned during a scientific conference that former colleague Song Jin of the University of Wisconsin-Madison was growing crystals with a continuous spiral twist. Recognizing that Jin’s spirally twisted WS_2 crystals were the perfect material to test Ji and Mele’s theories, Agarwal arranged for Jin to send over a batch. The experimental results were intriguing.

Mele says the effect mirrored the Coriolis force, an observation that is usually associated with the mysterious sideways deflections seen in rotating systems. Mathematically, this force closely resembles a magnetic deflection, explaining why the electrons behaved as though a magnetic field were present even when there was none. This insight was crucial, as it tied together the twisting of the crystal and the interaction with circularly polarized light.



(Left) An atomic force microscope image showing a sample of twisted layers of WS_2 (a material made of tungsten and sulfur). The scale bar represents 4 micrometers (4 millionths of a meter). (Right) A diagram showing how the Hall effect (a sideways voltage) was measured in the twisted material. The red arrow represents the path of electrons, while
V_0 and V_H are the voltages applied and measured in the experiment. Image credit: left, Yuzhao Zhao; right Judy Ji

Agarwal and Mele compare the electron response to the classic Hall effect wherein current flowing through a conductor is deflected sideways by a magnetic field. But, while the Hall effect is driven by a magnetic field, here “the twisting structure and the Coriolis-like force were guiding the electrons,” Mele says. “The discovery wasn’t just about finding this force; it was about understanding when and why it appears and, more importantly, when it shouldn’t.”

One of the major challenges, Mele adds, was that, once they recognized this Coriolis deflection could occur in a twisted crystal, it seemed that the idea was working too well. The effect appeared so naturally in the theory that it appeared hard to switch off even in scenarios where it shouldn’t exist. It took nearly a year to establish the exact conditions under which this phenomenon could be observed or suppressed.

Agarwal likens the behavior of electrons in these materials to “going down a slide at a water park. If an electron went down a straight slide, like conventional material lattices, everything would be smooth. But, if you send it down a spiraling slide, it’s a completely different experience. The electron feels forces pushing it in different directions and come out the other end altered, kind of like being a little ‘dizzy.’”

This “dizziness” is particularly exciting to the team because it introduces a new degree of control over electron movement, achieved purely through the geometric twist of the material. What’s more, the work also revealed a strong optical nonlinearity, meaning that the material’s response to light was amplified significantly.

“In typical materials, optical nonlinearity is weak,” Agarwal says, “but in our twisted system, it’s remarkably strong, suggesting potential applications in photonic devices and sensors.”

Another aspect of the study was the moiré patterns, which are the result of a slight angular misalignment between layers that plays a significant role in the effect. In this system, the moiré length scale—created by the twist—is on par with the wavelength of light, making it possible for light to interact strongly with the material’s structure.

“This interaction between light and the moiré pattern adds a layer of complexity that enhances the effects we’re observing,” Agarwal says, “and this coupling is what allows the light to control electron behavior so effectively.”

When light interacted with the twisted structure, the team observed complex wavefunctions and behaviors not seen in regular two-dimensional materials. This result ties into the concept of “higher-order quantum geometric quantities,” like Berry curvature multipoles, which provide insight into the material’s quantum states and behaviors. These findings suggest that the twisting fundamentally alters the electronic structure, creating new pathways for controlling electron flow in ways that traditional materials cannot.

And finally, the study found that by slightly adjusting the thickness and handedness of the WS_2 spirals, they could fine-tune the strength of the optical Hall effect. This tunability suggests that these twisted structures could be a powerful tool for designing new quantum materials with highly adjustable properties.

“We’ve always been limited in how we can manipulate electron behavior in materials. What we’ve shown here is that by controlling the twist, we can introduce completely new properties,” Agarwal says. “We’re really just scratching the surface of what’s possible. With the spiral structure offering a fresh way for photons and electrons to interact, we’re stepping into something completely new. What more can this system reveal?”

Harnessing AI For A Greener Grid: The Pioneering Work Of Bolun Xu

As the world races to wean itself off fossil fuels and move towards renewable energy, integrating variable energy sources like solar and wind into the grid is a complex puzzle. Large-scale batteries are essential for storing up wind and solar for later use, but the success of these batteries in reducing costs and emissions is determined by more than the technology: Electricity markets decide when, how, and even if energy sources are widely adopted and used.

Solar power plant in Germany – associative photo. Image credit: Andreas Gücklhorn via Unsplash, free license

Although current market designs might support the initial use of energy storage, they can struggle to balance economic and environmental goals as storage systems expand. How can we ensure that the solutions we adopt are both effective and financially viable, now and in the future?

At Columbia University, Bolun Xu, a member of the Data Science Institute and Assistant Professor in the Department of Earth and Environmental Engineering, is working to address these issues, developing computational tools to lead the way toward a grid that is both climate-ready and cost-effective.

His work has garnered major funding and recognition, including a National Science Foundation (NSF) CAREER award, a powerful vote of confidence in a young investigator's research.

But when discussing his success, Xu says one award that helped propel his research stands out: a Data Science Institute Seed Funds grant in 2022. These grants support promising faculty research collaborations that bring data science and AI to new domain areas.

"The Data Science Institute Seed Funds award was my first grant at Columbia, and all the others followed," said Xu, who joined the Columbia University faculty in 2020. "That project has branched off into at least five related projects."

A Catalyst for Innovation: Data Science Institute (DSI) Seed Fund

The DSI Seed Funds were established in 2018, and since then they have supported 38 projects exploring a range of topics across fields and disciplines, from assessing the psychological impact of no-knock search warrants on communities to developing new AI-based tools to improve detection of disease. In the past two years, Seed Funds have supported projects in 18 departments across 9 schools.

Xu's grant supported a collaboration with Upmanu Lall, a visiting professor and the Director of the Columbia Water Center at the Climate School, to advance research on the value of energy storage in mitigating climate impacts on the electric grid — an area that's become central to plans to decarbonize electricity. Although the tool has not been deployed, it performed very well in simulations.

Their work involved a deep dive into the economics of energy storage. Using data from New York, Xu and his colleagues devised an AI algorithm for energy price arbitrage, where electricity is bought at low prices and discharged when prices are high, which lowers the cost of electricity overall. The tool, which performed very well in simulations, has not been deployed.

Scaling Up: From Theory to Real World Application

Since the initial DSI funding, Xu's research has expanded, contributing to ambitious, large-scale projects that apply his theories to real-world challenges. A forthcoming project will investigate integrating hydro storage, which is an energy storage system that uses gravity and water to store and generate electricity, into the power grid in New Mexico.

"This is exactly the topic we studied with the DSI Seed Funds, but applied to a real pumped hydro storage project," said Xu.

In addition to his work on pumped hydro storage, Xu is conducting research in collaboration with California's power system operator, developing models to optimize the deployment of dispatch storage resources on the state's grid, and working with Johns Hopkins University to assess the emissions impact of home battery systems used to store energy for personal use. Other projects explore integrating power systems and climate models, studying consumer behaviors in power systems, optimizing carbon capture and utilization processes, and advancing market design and operational optimization in energy storage.

All of these projects draw on the initial research launched through the DSI Seed Funds, and even rely on the high performance computing resources Xu was able to acquire through that grant.

"Bolun is an outstanding, super-focused young researcher who provides an excellent demonstration of how seed funds can help build not just a winning proposal but also define a career," says Lall.

The Next Data Challenge: Bridging the Gap Between Climate Models and Energy Research

While much of Xu's current research builds on what he was able to accomplish with seed funds, and he and his team have established themselves as leaders in combining energy storage models with machine learning techniques, one of the more vexing aspects of Xu's initial Seed Funds proposal – incorporating climate modeling data so his models can take climate change into account–has proven more difficult.

Because climate change, and the resulting changes in weather patterns, can affect both renewable energy supply (in the form of sunshine and wind) and demand (often in the form of heating and cooling during extreme weather events), it is important that his models take changing weather into account.

But as Xu discovered, this is not as straightforward a task as one might expect.

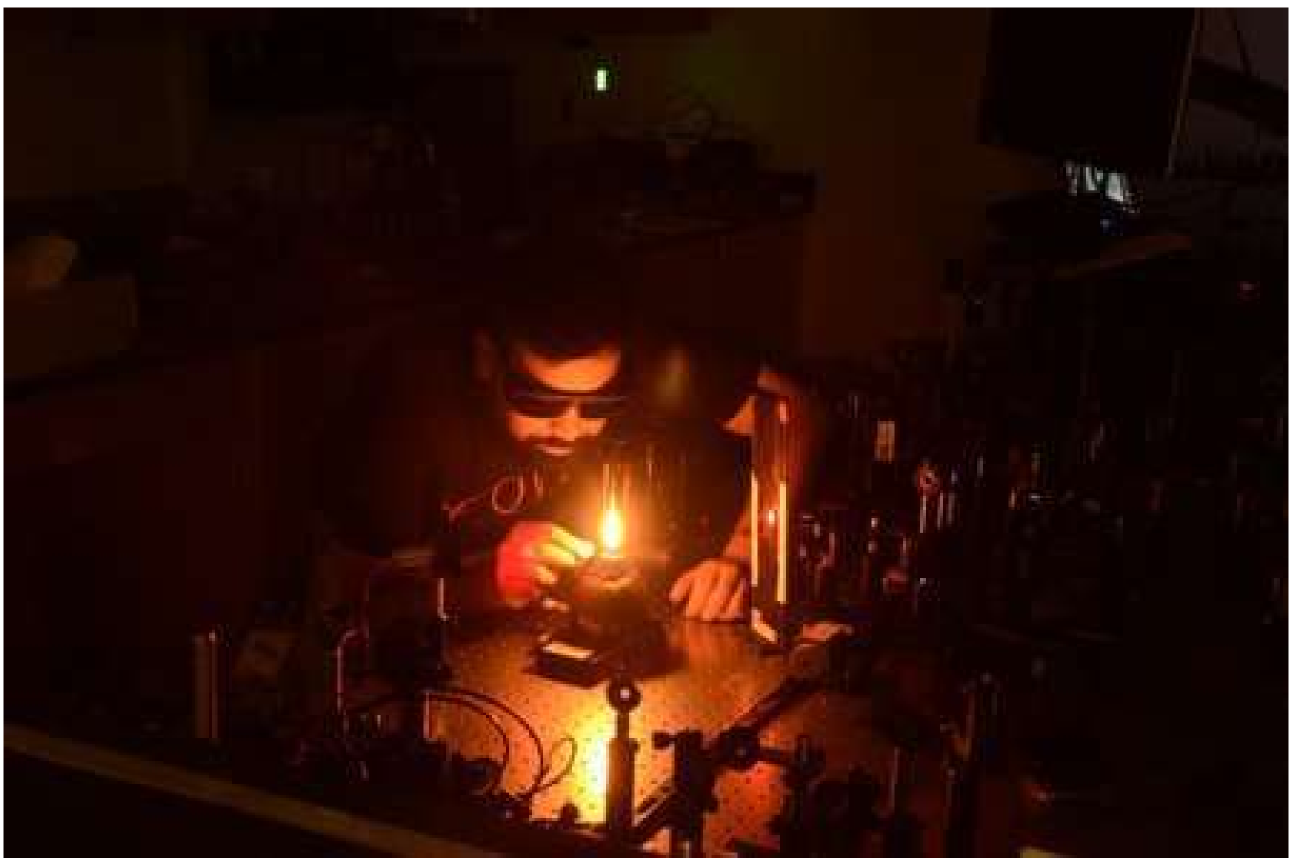
This is an important challenge to solve because as climate change makes weather more volatile, this impacts both energy supply (in the form of sunshine and wind) and demand (often in the form of heating and cooling during extreme weather).

While the data for power systems modeling requires high space and time resolution, the data from climate models tends to be in more coarse scales, limiting its applicability in high-resolution power system models. Without the ability to integrate this data, Xu has worked to combine power system studies with specific climate-related data points, a challenging workaround until he can develop a systematic solution.

“Bridging that gap in granularity is one of our primary goals,” said Xu. “We need to be able to answer critical questions: What happens if the Earth is one degree warmer in 20 years? Two degrees? Three? Each scenario impacts energy storage decisions in profound ways. We’ve made significant strides, but we are far from done. The future of energy storage—and the stability of our grid—depends on finding solutions to these complex problems.”

New Ultrafast Imaging Technique Provides Insight Into Combustion Processes

Details of combustion—the chemical reactions that take place when, for example, a flame is lit—are fleeting and, therefore, difficult to study. But scientists would like to better understand the complex processes that occur in those billionths of seconds, not only to make engines more efficient but also to shed light on how candle flames, cars, and airplanes produce gases and particles that are harmful to humans and the environment.



Yogeshwar Nath Mishra, a co-lead author of a paper describing a new ultrafast imaging technique capable of capturing the fleeting details of combustion at 250 billion frames per second. Image credit: Caltech

Now a team of scientists from Caltech's campus and JPL (which Caltech manages for NASA), and the University of Erlangen–Nuremberg, in Germany, have developed an ultrafast imaging technique, called femtosecond laser sheet-compressed ultrafast photography (fsLS-CUP), that can compile videos of those incredibly transient details.

Capturing 250 billion frames per second, the new technique is 20,000 times faster than conventional high-speed imaging cameras, and about 100 times faster than state-of-the-art imaging systems. It has already revealed some of the underlying dynamics involved in the formation of soot particles during combustion.

A paper highlighting the new technique appeared online in the journal *Light: Science & Applications*.

How Does Soot Form?

Soot is a major contributor to global warming, thought to be number two behind carbon dioxide in terms of its impact on climate. Yet how exactly soot particles form is still an open question. While scientists have previously suggested that the particles might be built from polycyclic aromatic hydrocarbons (PAHs), a class of chemicals that are formed during the incomplete burning of coal, oil, gasoline and even charbroiled meat, the precise mechanism by which this happens has not been fully determined, leaving room for debate.

"With the movies we have been able to capture with our new technique, we now have a very clear indication that soot particles do indeed grow from PAHs," says Yogeshwar Nath Mishra, a co-lead author of the new paper and a Swedish Research Council-funded researcher in the Caltech Optical Imaging Laboratory. "We can see that the PAHs attach together and form nascent soot particles that further grow in the flame to form very large particles."

Introducing fsLS-CUP

The new technique involves shining a femtosecond laser—one that emits a single pulse of light for just a quadrillionth of a second—on a sample flame and pairing that with a modified version of a method called compressed ultrafast photography, which was developed in the lab of Lihong Wang, the Bren Professor of Medical Engineering and Electrical Engineering at Caltech, who is also an author of the new paper.

"We are thrilled to see a high-impact application of the world's fastest camera that captures events in a single shot without repetition," says Wang, who is also the Andrew and Peggy Cherng Medical Engineering Leadership Chair and executive officer for medical engineering at Caltech. "This technology opens new doors across both biological and physical sciences, with applications ranging from microscopy to telescopy, and holds the potential for significant societal impact in understanding the underlying biology and physics."

Without disturbing the flow of the sample flame, the single femtosecond laser in fsLS-CUP accomplishes a couple of things. First, its wavelength is selected such that it excites the PAHs present, allowing their fluorescence to be detected. And second, it causes the soot nanoparticles present to rapidly heat up. As they relax back to normal temperatures, the particles emit a signal of incandescence. The fluorescence and incandescence can then be used to study the lifespan of the PAHs and soot particles created through combustion.

Still, both the fluorescence of PAHs and the laser-induced incandescence of soot particles have extremely short lifespans, lasting only nanoseconds to thousands of nanoseconds. To measure such fleeting signals in real time, the new technique uses something called a light sheet to define a two-dimensional plane within the flame and then employs a special imaging system offset by 90 degrees to capture what takes place within that plane. This imaging system includes spatial encoding by a digital micro-mirror device and temporal shearing by a streak camera. Using a special algorithm, the system can extract the ultrafast sequence of frames.

A Single Pulse is Better Than Many

Peng Wang, a co-lead author of the paper and former Caltech postdoc who completed the work at the Institute, notes that previous imaging techniques used to study combustion dynamics relied on many laser pulses, repeatedly exciting PAHs and soot particles and then capturing individual frames. “But these nanoparticles are very delicate,” he says. “So, if you are exciting them continuously, you are heating them up and changing their optical properties. What we needed was a technology based on a single pulse. The single pulse induces the signal, and then the camera captures the entire decay of the signal. This is what we accomplished.”

In one video captured at 1.25 billion frames per second by the new technique, a green signal representing fluorescence appears, indicating the formation of PAH molecules in a flame. The green signal fades away within 35 nanoseconds. A short while later, a cloud of red soot particles forms and grows over hundreds of nanoseconds.

“We can watch the PAH molecules form before the cloud of soot particles grows,” Mishra says. Soot inception remains a highly debated topic within the combustion community, and our efforts mark just the beginning of unraveling the complexities of soot formation. To fully understand the species captured by fsLS-CUP, we need complementary optical methods for precise quantification as well as more advanced burner setups.”

Many Applications

The authors note that the work is relevant beyond combustion science. “Ultimately, fsLS-CUP has not only advanced our understanding of hydrocarbon and nanoparticle formation and growth in flames, but it also holds potential across multiple fields, making it a significant milestone in ultrafast imaging technology,” Mishra says. “This technique, which can capture some extremely fast phenomena in nature, has broad applications in physics, chemistry, biology, medicine, energy, and environmental science."

It is also relevant to astrophysical studies, the researchers say, given that PAHs make up some 10 to 12 percent of interstellar matter. "PAHs are robust molecules in interstellar space," says Murthy S. Gudipati, a senior research scientist at JPL and an author of the new paper. "Understanding the formation of PAHs and carbon soot expands our knowledge about their existence under astrophysical conditions as well."

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