LIGHT+MATTER

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Sizing Up an Electron's Shape
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JILA's PFC Awarded $25 million by the NSF
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JILA
CU Boulder and NIST

The annual JILA photo, taken in front of JILA's tower.
Credit: Steven Burrows/JILA

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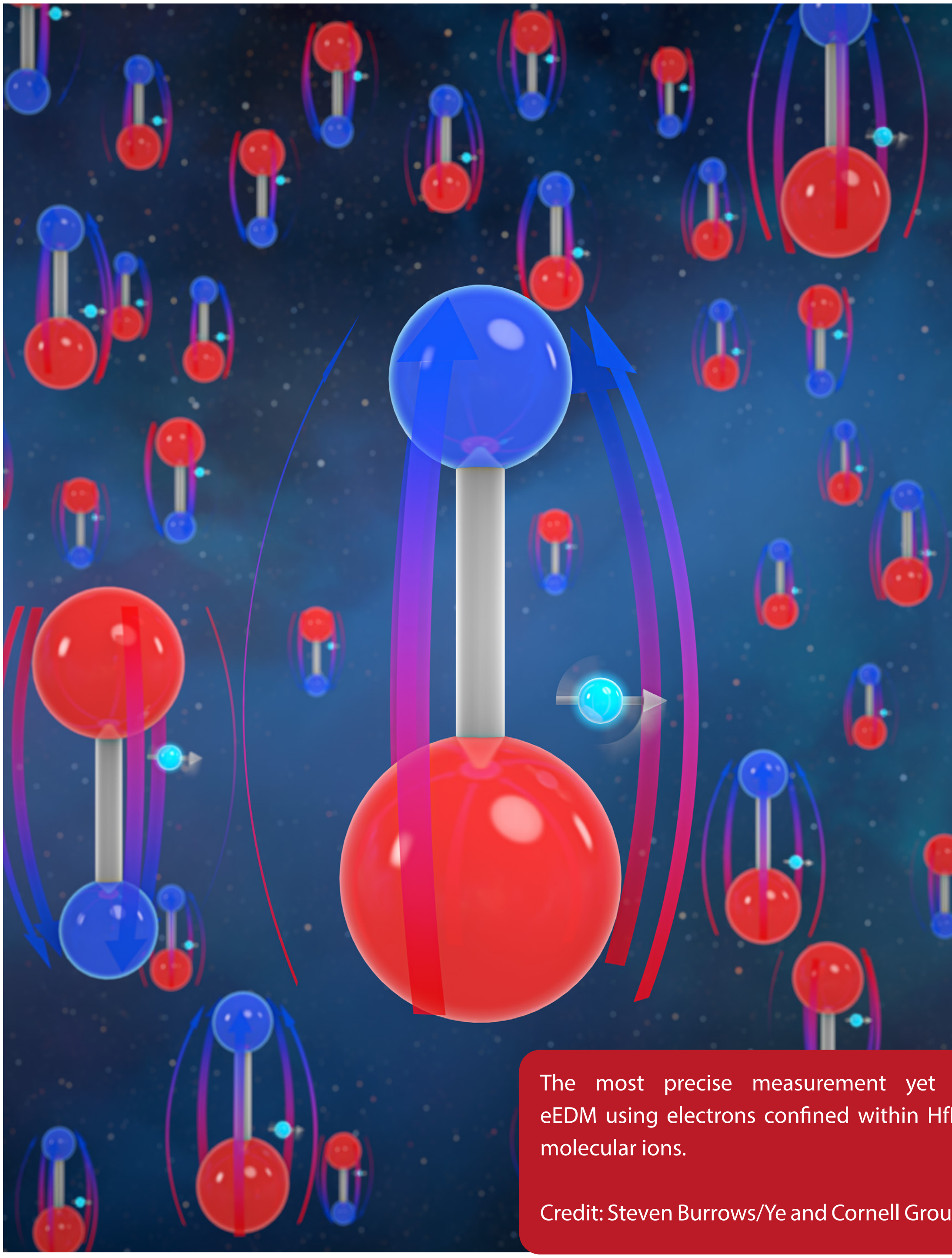
Sizing Up an Electron's Shape



The most precise measurement yet of eEDM using electrons confined within HfF+ molecular ions.

Credit: Steven Burrows/Ye and Cornell Groups

Some of the biggest questions about our universe may be solved by scientists using its tiniest particles. Since the 1960s, physicists have been looking at particle interactions to understand an observed imbalance of matter and antimatter in the universe. Much of the work has focused on interactions that violate charge and parity (CP) symmetry. This symmetry refers to a lack of change in our universe if all particles' charges and orientations were inverted. "This charge and parity symmetry is the symmetry that high-energy physicists say needs to be violated to result in this imbalance between matter and antimatter," explained JILA research associate Luke Caldwell. To try to find evidence of this violation of CP symmetry, JILA and NIST Fellows Jun Ye and Eric Cornell, and their teams, including Caldwell, collaborated to measure the electron electric dipole moment (eEDM), which is often used as a proxy measure for the CP symmetry violation. The eEDM is an asymmetric distortion of the electron's charge distribution along the axis of its spin. To try to measure this distortion, the researchers used a complex setup of lasers and a novel ion trap. Their results, published in *Science* as the cover story and in *Physical Review A,* leveraged a longer experiment time to improve the precision measurement by a factor of 2.4, setting new records.

Measuring the eEDM

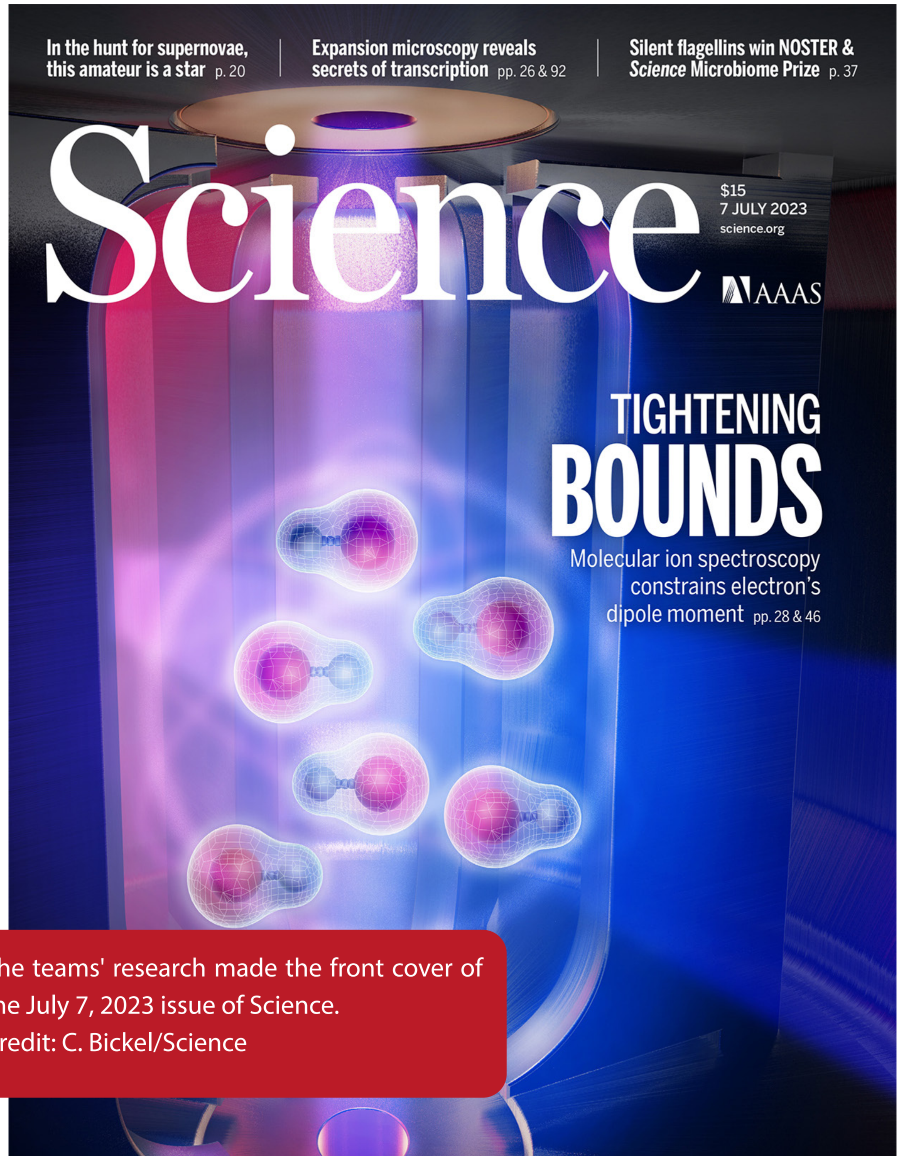
To understand how physicists measure the electron's electric dipole moment, it may be helpful to consider a clinical trial for a new medication. To ensure the trial is effective, doctors will run a study where half the sick participants take the drug in question and the other half take a placebo. If the doctors see an improvement in patients that took the drug compared with the placebo group, they can conclude that their medication is effective. This approach helps to control for effects that impact both groups. Now imagine an (admittedly dystopian) world where the researchers have created an 'anti-drug,' shown to make sick patients worse by the same amount as the regular drug improves their health. A new clinical trial could be organized, where half of the patients take the regular drug and the others take the anti-drug. The new trial would have all of the benefits of the previous trial but any effects of the drug would be even more clear. This drug and anti-drug analogy can then be applied to the electron symmetry.

As Caldwell explained: "We look for the energy shift of an electron subject to an electric field in one direction ["aligned" electron] by comparing it to an electron subject to an electric field in the opposite direction ["anti-aligned" electron], where the energy shift caused by the eEDM is equal and opposite. By measuring both simultaneously we are protected from effects which shift the energy of both electrons in the same direction." In measuring the difference between the aligned electron and the anti-aligned electron for each energy oscillation between the particles, the researchers could determine a value for eEDM.

To measure this energy difference, the researchers manipulated hafnium fluoride ions in an ion trap. The experiment began with a solid rod of hafnium in the experimental chamber. A pulsed laser was then used to isolate hafnium in the presence of sulfur hexafluoride gas, where the two react to create neutral hafnium fluoride molecules. Then the molecules flew down a tube where they enter the ion trap. "The entire cloud of gas enters the ion trap at about the same time," JILA graduate student Trevor Wright stated. "When it reaches the center of the trap, we turn on the ionization lasers. These lasers each emit a pulse of light that overlaps with the cloud of gas and are tuned to certain frequencies which resonate with hafnium fluoride. So, the hafnium fluoride molecules flying through get ionized, and lose one of their electrons. While this is happening, we turn on the voltages on our electrodes to stop the positively charged hafnium fluoride molecules, while the rest of the cloud will fly through the trap and out of the experiment." Using this process, the researchers could prepare the system for further studying hafnium.

New Records in Measurement

A new record was set for the length of "interrogation time" for the experiment—how long the researchers could trap and manipulate the electrons—at three seconds. While this may seem like a short amount of time, most quantum physics experiments run from femtoseconds (10^{-15} seconds) to nanoseconds (10^{-9} seconds), making three seconds seem like an eternity. Expanding on why the interrogation time is helpful in improving the measurement precision, Caldwell explained: "Think of a pendulum. If you wanted to measure the time period of a pendulum, you could just measure its swing once, and then stop its motion. But you'd have some error when you press stop. So, a better way to do it would be to let the pendulum swing 100 times, and then press stop, and then divide your answer by 100. Then, you get to divide your measurement error by 100, and you get a much better measurement of the pendulum's period. Our experiment is kind of similar, we are looking for an oscillation that corresponds to the electrons EDM. In our case, the measurement error doesn't come from when we press stop, but the same ideas apply. We get to divide our 'error bar' by how many periods of oscillation we measure. Compared to the previous generation of this experiment, and, to our competitor experiments, we can keep our molecules trapped for a very long time. So, we can measure lots and lots of oscillations." As previous experiments clocked interrogation times at three-quarters of a second, the expanded time of three seconds was a significant leap in advancing the interrogation time of this experiment and allowing for more flexibility in measurement. "We can hold on to our particles for a really long time as compared to previous experiments," Wright said. "And we can vary the hold time because we can stop the experiment whenever we want." Caldwell echoed this benefit: "Unlike other experiments, because our molecules are trapped rather than in a beam, we can control the length of the interrogation time. This allows us to better characterize and reject many types of systematic error that can affect the measurement."



The teams' research made the front cover of the July 7, 2023 issue of Science.
Credit: C. Bickel/Science

Thanks to this longer interrogation time, the researchers were able to make the most precise eEDM measurement yet. "Our result was consistent with zero and we used it to set an upper bound on the size of the eEDM," Caldwell stated. "Previous experiments have also measured the electron EDM, but with less precision. Because our error bar is smaller, we can say, with more confidence, that its value is below a certain level. Our limit is 2.4 times smaller than the previous limit." The researcher hope to continue pushing this measurement even further to reveal more about the quantum world.

Tanya S. Roussy, Luke Caldwell, Trevor Wright, William B. Cairncross, Yuval Shagam, Kia Boon Ng, Noah Schlossburger, Sun Yool Park, Anzhou Wang, Jun Ye, Eric A. Cornell. " An Improved bound on the electron's electric dipole moment." Science, 381, 46-50, 2023.

Luke Caldwell, Tanya S. Roussy, Trevor Wright, William B. Cairncross, Yuval Shagam, Kia Boon Ng, Noah Schlossberger, Sun Yool Park, Anzhou Wang, Jun Ye, Eric A. Cornell. " Systematic and statistical uncertainty evaluation of the HfF+ electron electric dipole moment experiment." Physical Review A, 108, 012804, 2023.

Written by Kenna Hughes-Castleberry,

Turning Up the Heat in Quantum Materials

Quantum materials, a fascinating class of materials that harness the power of quantum mechanics, are revolutionizing modern science and technology. Quantum materials often possess exotic states of matter, such as superconductivity or magnetic ordering, that defy conventional understanding and can be manipulated for various technological applications. To further enhance and manipulate the intriguing characteristics of quantum materials, researchers leverage nanostructuring—the ability to precisely control the geometry on the atomic scale. Specifically, nanostructuring provides the ability to manipulate and fine-tune the electrical and thermal properties of quantum and other materials. This can result, for example, in designer structures that conduct current very well, but impede heat transport. A related critical challenge for a broad range of nanotechnologies is the need for more efficient cooling so that the nanodevices do not overheat during operation. To better understand heat transport at the nanoscale, JILA Fellows Margaret Murnane, Henry Kapteyn, and their research groups within the STROBE NSF Center, JILA, and the University of Colorado Boulder, created the first general analytical theory of nanoscale-confined heat transport, that can be used to engineer heat transport in 3D nanosystems—such as nanowires and nanomeshes—that are of great interest for next-generation energy-efficient devices. This discovery was published in *Nano Letters*.

Harnessing Geometry

Understanding heat flow within the nanostructures of quantum and other materials unveils fundamental insights into thermal transport and paves the way for developing advanced thermoelectric devices and more efficient heat management systems. Thermoelectric materials can convert waste heat into useful electrical energy or regulate temperature differentials in electronic components. As Joshua Knobloch, a JILA and STROBE postdoctoral research associate, explained, "The main motivation for our work is the need for better thermal management strategies, which are very important for many devices, as the operating temperature of devices often determines their efficiency. For example, the rate at which a computer can do computations has been limited for about two decades because computer chips overheat. So, finding ways to increase heat dissipation, or to tailor the heat flow, is critically important."

To boost heat dissipation in these materials, Knobloch and graduate student Brendan McBennett highlighted two main strategies. "One option is to change the material composition of your device, that is, find a material with optimal thermal properties," stated Knobloch. While this strategy can boost the heat dissipation of a quantum material, it can also constrain other properties that this material may possess. Knobloch added, "Another option is nano-structuring, where you change the system's geometry while maintaining the composition. And because the structuring occurs on such a small scale, the geometry influences the fundamental physics at play, implying that you can tailor it for specific physical properties." For example, graphene, a well-known quantum material, is geometrically structured in flat hexagonal lattices. The structure of these lattices is what simultaneously gives the material high tensile strength, stability, and thermal conductivity.

Similarly, Knobloch and the other researchers wanted to understand how the geometry, or nano-structuring, of a common electronics material, such as silicon, influ-

Opposite: An artistic rendering of fluid-like heat flow in highly confined nanosystems.
Credit: Steven Burrows/Murnane and Kapteyn groups

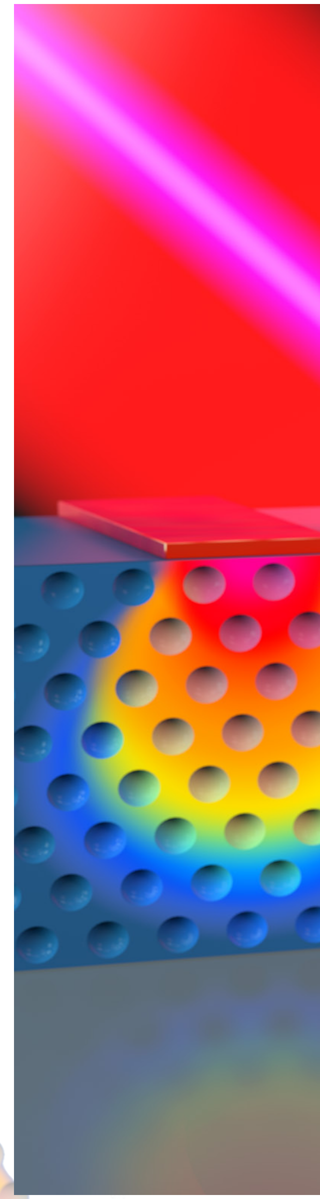
-fluences heat dissipation. Knobloch elaborated that "We studied silicon, which is widely used in electronic tronic devices. Specifically, the device was a nanostructured metalattice, containing periodically arranged holes carved out of solid material on a very small scale, a 10-nanometer scale, hundreds of times smaller than the thickness of a red blood cell."

Collaborators at Pennsylvania State University fashioned the nanostructured silicon material for the study. To understand the heat dissipation within the material, the researchers probed the silicon material with powerful extreme ultraviolet (EUV) lasers to observe heat flow within the material. "After laser-heating these metal structures, the heat is transported out of the metal structures and flows through the material below," elaborated Knobloch. "With the EUV probe, we are able to look at how the surface deforms. As the material heats up, it expands, and we observe the dynamics with our EUV laser with very high sensitivity to see how the material is deforming as the structure is cooling. Probing the heated metal structures as they cool down can tell us how the heat flows through the nanostructured material. That, in turn, can inform us on the fundamental behaviors within the system."

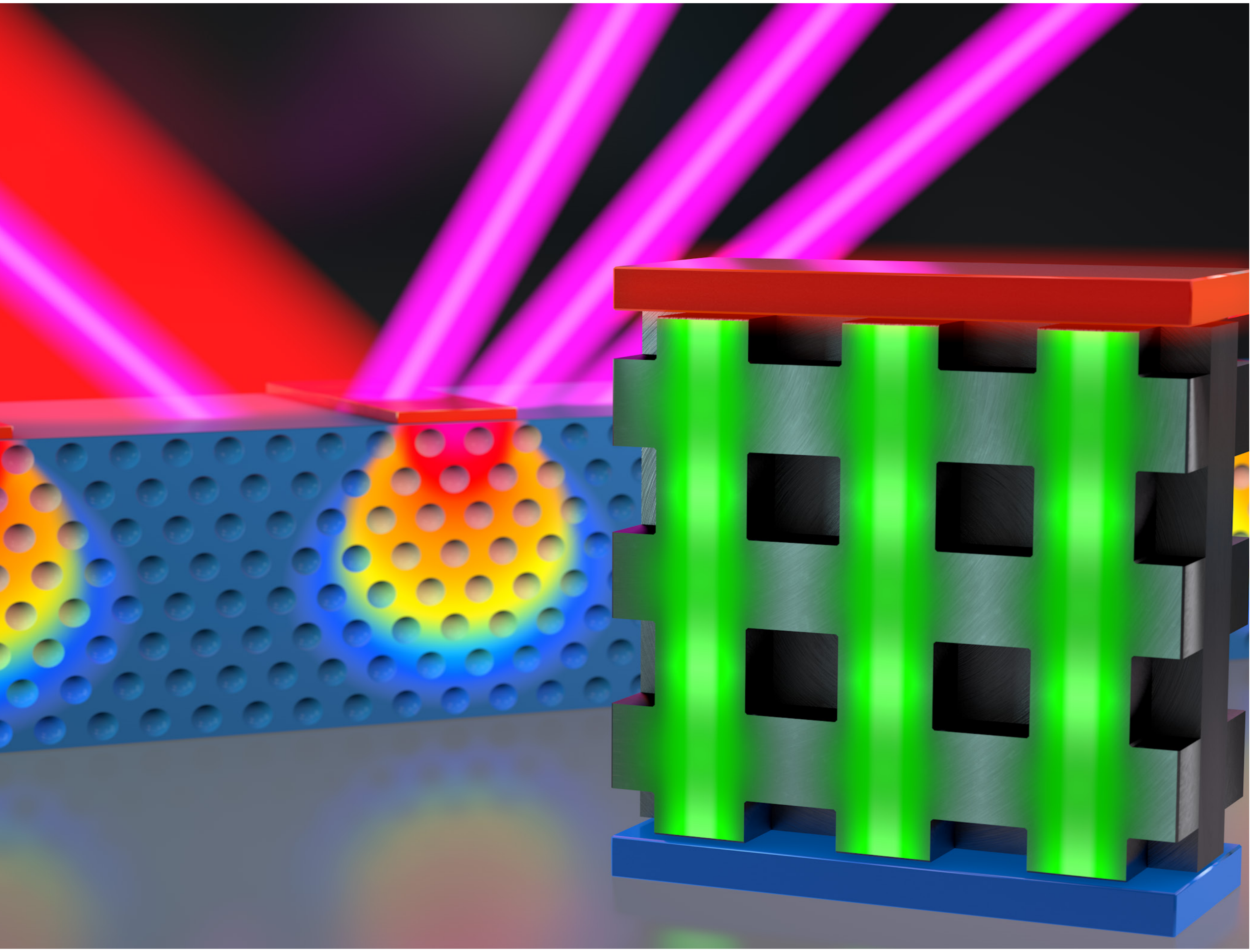
Following the (Heat) Flow

Historically, scientists thought nanoscale heat flowed away from a hot structure in straight lines under highly confined heat transport conditions, a property known as ballistic conduction or ballistic transport "It is common to think of phonons, the quantized vibrational energy packets responsible for thermal conduction in a material, as particles which travel ballistically, that is that they move in straight lines like pool balls bouncing around inside this material," Knobloch stated. Instead, the researchers took a more nuanced approach. "We consider heat to move hydrodynamically, a picture analogous to flowing water, where the heat flow adapts to the entire geometry of the structure and can flow in and out and around these pores," added Knobloch.

The researchers proposed a theoretical model of heat dissipation mimicking hydrodynamic effects, with collaborators from the University of Barcelona, including Albert Beardo, who is now at the University of Colorado Boulder. In an exciting discovery, this new model not only explained the study's results but also a wide range of data taken on different nanostructured silicon devices. "We found that when you take this hydrodynamic approach, you can derive a theory that could explain a broad range of experiments and predictions throughout the literature," stated Knobloch. "We took not only the data we measured with our EUV technique but also data from other studies in the literature, where we found that using this hydrodynamic perspective, thinking about heat flowing like water, we can explain a very broad range of these nanostructured materials, which has been out of reach for analytical theories for a very long time." These materials include things like nano-meshes, nanowires, and metalattices, all of which can be fine-tuned to exhibit specific properties.



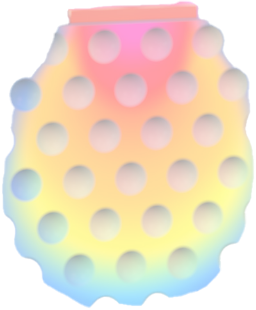
Even with the varying geometries of these materials, the researchers found they had similar hydrodynamic-like heat flow behaviors. "We do not yet understand why we are observing this universal behavior," Knobloch said. "Essentially, all of these systems contain an intrinsic phonon property called viscosity, which depends only on the material's porosity in a precise way. In other words, the ratio of air versus



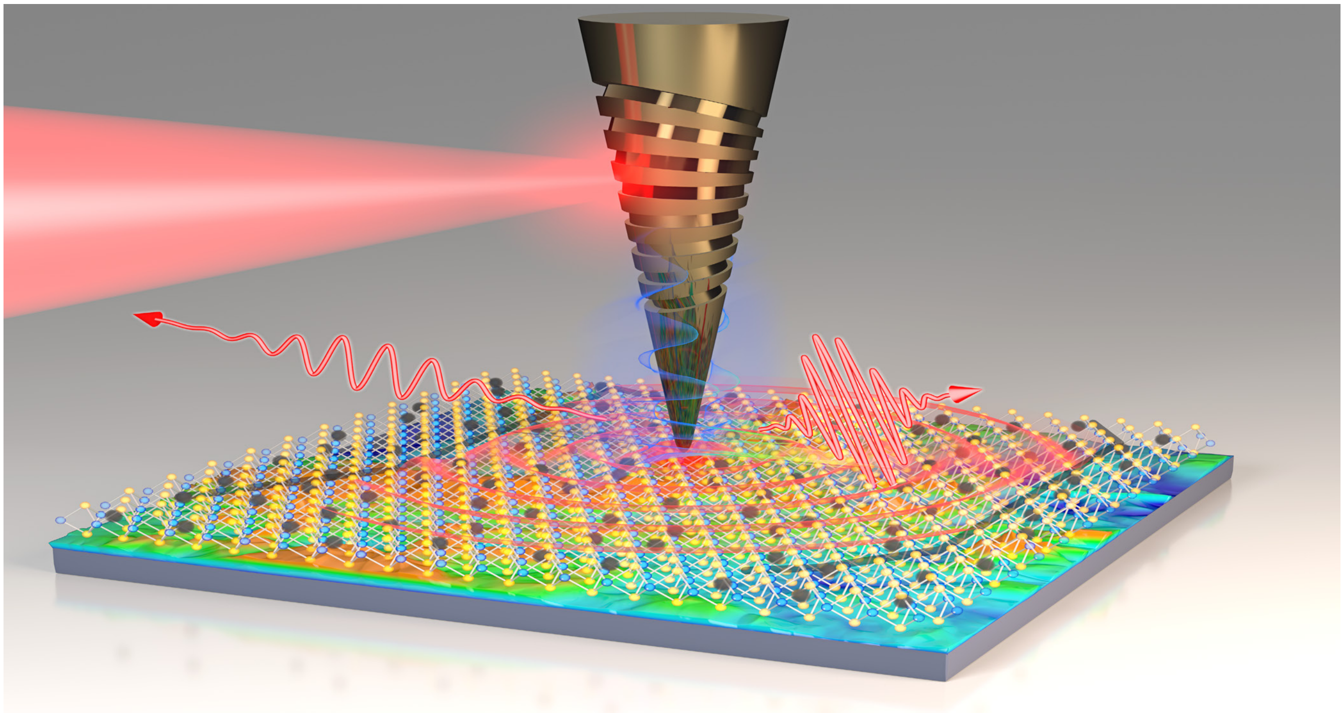
silicon [for this specific experiment] alters some intrinsic physics independent of the precise geometrical shape, and this is a deep concept we don't yet understand." As researchers leverage the different nanostructured geometries of all of these quantum materials, understanding the underlying relationship between geometry and heat flow can give a boost to creating these materials.

Brendan McBennet, Albert Beardo, Emma E. Nelson, Begona Abad, Travis D. Frazer, Amitava Adak, Yuka Esashi, Baowen Li, Henry C. Kapteyn, Margaret M. Murnane, and Joshua L. Knobloch. " Universal Behavior of Highly Confined Heat Flow in Semiconductor Nanosystems: From Nanomeshes to Metalattices" Nano Letters, 23(6), 2129–2136, 2023.

Written by Kenna Hughes-Castleberry



Imaging 2D Materials At a Smaller Scale



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

Two-dimensional materials, like graphene and 2D semiconductors, are an area of physics that has been growing tremendously in the last decade. According to JILA graduate student Ben Whetten, “That’s because they exhibit new spin and electronic physical phenomena and have much promise to build new miniaturized photonic or semiconductor nanoscale devices.” Researchers like Whetten, and his advisor, JILA Fellow, and University of Colorado Boulder professor Markus Raschke, develop methods to image these materials, giving a better understanding of their inner workings. In a new paper in *Nano Letters,* Raschke, and his team extended their ultrafast microscope to see nanometer-sized imperfections within a 2D semiconductor sample that created some surprising nonlinear optical effects.

The Promise of 2D Materials

2D materials are an exciting field to study as they exhibit remarkable electronic, optical, and mechanical properties that differ significantly from their 3D counterparts. For example, graphene, a single layer of carbon atoms, has exceptionally high electrical conductivity, mechanical strength, and flexibility, making it an ideal candidate for electronic and mechanical appli. cations. Yet, imaging these materials can be complex, as the small spatial scales of their features are beyond the resolution of conventional diffraction-limited optical microscopes.

To overcome these limitations, many researchers utilize atomic force microscopy (AFM) to provide information on topography, mechanical properties, and electrical conductivity of 2D materials with nanometer-scale resolution. However, AFM by itself limits what the researcher can study, constraining how much of the quantum interactions within the materials can be observed. So Raschke and his team devised a technique to use metallic AFM tips to focus laser light down to the 10-nm scale needed to be able to image optical and dynamic properties with the same resolution with which a typical AFM can image the static mechanical properties of a material.

Exciting Excitons

The specific material Raschke and his team studied is a monolayer of tungsten diselenide (WSe_2), a transition metal dichalcogenide that possesses unique electronic and photonic dynamics. "We are looking at the elementary processes of light-matter interaction in these systems," elaborated postdoctoral researcher, and first author, Wenjin Luo. "We then use ultrafast femtosecond laser pulses that we focus to the nanoscale to locally excite excitons." A femtosecond is 10^{-15}, or one quadrillionths of a second, which is astonishingly fast. The researchers then observed the excitons, which are a type of elementary quantum excitation of bound electrons specific to semiconductors. One of the long-unsolved puzzles in the field of 2D semiconductors has been how these excitons react to imperfections in the semiconductor material.

To study both the dynamic behavior of these excitons and how they respond to nanoscale defects in the material, the researchers utilized a nonlinear optical process known as four-wave mixing. As Luo explained: "It is a nonlinear optical effect in which three photons of light interact with the exciton coherently and generate a fourth signal photon which we detect. This process only occurs when we use short, coherent, and intense laser pulses." Coherence occurs when things move in sync, such as the excitons when driven by the laser field. When studying a large ensemble of excitons in conventional spectroscopy, the excitons rapidly lose their coherence due to scattering on the defects. However, "what we observe is that the coherence time of the excitons can be more than an order of magnitude longer when probing on the nanoscale," Raschke added.

Creating an Ultrafast Image

Besides the ultrafast laser system, the key component of the imaging system was the tiny tip of the AFM which the laser had to hit. As Whetten explained: "We fabricated these optical scanning probe tips ourselves. Those are unique optical devices in their own right. The tips are first etched electrochemically from a gold wire in a multi-step process. Then we used focused ion beam milling to write a grating onto the tip shaft to couple the femtosecond pulse [to the imaging]. Only once all that's prepared can we bring in the femtosecond pulse. We then illuminate this grating on the tip shaft, and the light pulse gets focused down to the apex. The image is then created when we measure the sample point by point."

With the point-by-point coherent imaging process, the researchers created a high-resolution image of the exciton coherence and how this coherence varies with the imperfections in the sample's surface. This process could give other scientists the information needed to develop more efficient 2D materials. "To measure their optical properties has conventionally been limited by the diffraction limit of light capping the resolution at about 500 nanometers or so," Whetten added. "This is insufficient to resolve [differences in the surface in] the optical properties associated with defects and grain boundaries. Our method can image with up to 100 times higher spatial resolution than was previously possible."

This "coherent nanoscope" allowed for better spatial resolution imaging of the sample, and thanks to the ultrafast lasers, it can measure excitons at the extremely fast time scales of the elementary processes of the motion of electrons. This has significant implications for imaging samples even at room tem temperature, where historically ex-

-periments are carried out at low temperatures to slow the motion of excitons down. With the coherent nanoscope's extremely high time resolution of just a few femtoseconds, Raschke, Luo, and Whetten could image the exciton dynamics even under conditions where 2D materials would typically be used in real-world applications.

Looking at Imperfections

The researchers found that the dynamics of excitons varied spatially within the material, losing the coherence fast in some areas, and with longer coherence time in others. "To get a visual picture of that, you can imagine a lawn, where the grass does not grow evenly, fast in some but slow in other areas," Raschke explained.

Because different surfaces in a 2D material can affect its performance, visualizing where these imperfections are can help scientists develop materials with fewer heterogeneities. "This is a burgeoning field where there are all these promises of amazing technologies and new semiconductor devices, and we can look at exactly what limits we can push them to," elaborated Whetten. "We can ask: How clean do they need to be, and what happens if they're not perfect? How does that affect the electronic and optical behavior of a semiconductor? And imaging the exciton coherence is the most elementary process allowing us to answer these questions."

When the team used their imaging system to study these imperfections, they discovered something surprising. "Another big takeaway was that we also saw a completely novel and nonintuitive behavior of the nonlinear optical signal itself associated with the defects," Whetten explained. "Normally, for sample regions with long [exciton] coherence, we would have expected the strongest signal because the longer the electrons oscillate in phase, the more coherent light they would radiate. But we saw the exact opposite. With the help of our theory collaborator from Texas A&M, Alexey Belyanin, we could explain this new effect. It has to do with spatial coherence, i.e., not just how the electrons start to oscillate out of sync as time progresses, but how their spatial correlation is modified due to defects and grain boundaries."

Incorporating Belyanin's theory, the researchers found new models to describe what affects the coherence time between excitons. "So, our work not only shows how defects limit coherence, leading to the desire to have samples with low defect densities," added Raschke. "But it also shows that through specific defect densities, we could engineer the interplay between coherence time and signal intensity in new ways as desirable for specific nano-photonic applications." Raschke and his team found that they could exploit the material's imperfections to tweak the coherency times between excitons. Raschke continued: "Unfortunately, we do not yet know the exact nature of the specific defects, and how different types of defect or disorder would influence the spatio-temporal coherence as it is called." This nature is what the team will try to discover in their future work while imaging different materials, semiconductors, and quantum devices to better understand the detrimental and beneficial effects of the different defects for improved materials function and device performance.

Wenjin Luo, Benjamin G. Whetten, Vasily Krastov, Ashutosh Singh, Yibo Yang, Di Huang, Xinbin Cheng, Tao Jiang, Alexey Benjamin, and Markus B. Raschke. " Ultrafast Nanoimaging of Electronic Coherence of Monolayer WSe_2." Nano Letters, 23(5), 1767–1773, 2022.

Written by Kenna Hughes-Castleberry

How to Bind with Metals and Water: A New Study on EDTA

Metal ions can be found in almost every environment, including waste water, chemical waste and electronic recycling waste. Because of the scarcity of some of these metals, such as rare earth elements or nickel, scientists are working to find ways to remove these ions from the waste and recycle the metals. One method used to remove these metals is to bind them to other molecules known as chelators or chelating agents. Chelators have multiple molecular groups that combine to form binding sites with a natural affinity for binding metal ions, making them a natural choice to extract metals from toxic waste. Ethylenediaminetetraacetic acid, or EDTA, is a chelator commonly used in metal removal and many other applications, including medicine. “EDTA is used to treat heavy-metal poisoning,” JILA graduate student Lane Terry explained. “So, if you have lead poisoning, you can take EDTA, which binds to the lead and then safely passes through your system. It's also used as a food preservative. So EDTA is everywhere. It's in one of my topical creams, etc.” EDTA is also commonly used in various laboratories, including many within JILA.

To understand how EDTA binds to these metal ions and water molecules, Madison Foreman, a former JILA graduate student in the Weber group, now a postdoctoral researcher at the University of California, Berkeley, Terry, and their supervisor, JILA Fellow J. Mathias Weber, studied the geometry of the EDTA binding site using a unique method that helped to isolate the molecules and their bound ions, allowing for more in-depth analyses of the binding interactions. They published a series of three papers on this topic. In their first paper, published in the *Journal of Physical Chemistry Letters*, they found that the size of the metal ion changes where it sits in the EDTA binding site, which affects other binding interactions, especially with water.

Binding to Metal Ions

EDTA is a chemical commonly found in a chemistry or biology laboratory. “EDTA is employed in many different contexts,” explained Weber. “Whenever you want to get rid of a metal ion in a solution, you throw EDTA into the solution. EDTA will bind to pretty much any metal ion across the periodic table. That's what makes it so widely used in chemistry and biochemistry.” Because of this, EDTA as a model system can reveal more about similar binding behaviors in proteins, including some found in the human body.

However, actually observing the mechanics of EDTA binding is rather tricky. “So, to see exactly what’s going on, you must isolate your target complex from other species,” explained Weber. “That's why we bring these ions into the gas phase, where we can control the number of solvent molecules they interact with—first without any solvent—then selectively start adding solvent one molecule at a time to see what changes.” To do this, the EDTA ions were coaxed into a gas phase. “We then cool them in a cryogenic ion trap to about 50 Kelvin,” Foreman added. “After that, we attach weakly bound nitrogen molecules, which act as messengers telling us later that a photon has been absorbed. We only let those [tagged EDTA] molecules into the second half of the experiment. nothing else, and we have only one sort of ion.”

The Manchester Ship Canal in the UK is a major hub for waste recycling.
Credit: Wikimedia Commons

These tagged ion clusters were then bombarded with light from a tunable laser, which helped detect the target clusters. "We hit that nitrogen-tagged EDTA complex with a photon, which ejects the nitrogen tag," added Foreman. "So now we have these two fragments flying along, the complex ion and the nitrogen, as well as some amount of undissociated cluster that still has the nitrogen on it." Thanks to this nitrogen eviction, the researchers can detect that light was absorbed. "After this, we do a second mass spectrometry step to distinguish the undissociated parent ions from the fragment ions," Weber clarified. "We selectively only measure the intensity of those fragment ions as we tune our laser. That's how we measure a photo-dissociation spectrum which is the analog of the infrared absorption spectrum of that complex."

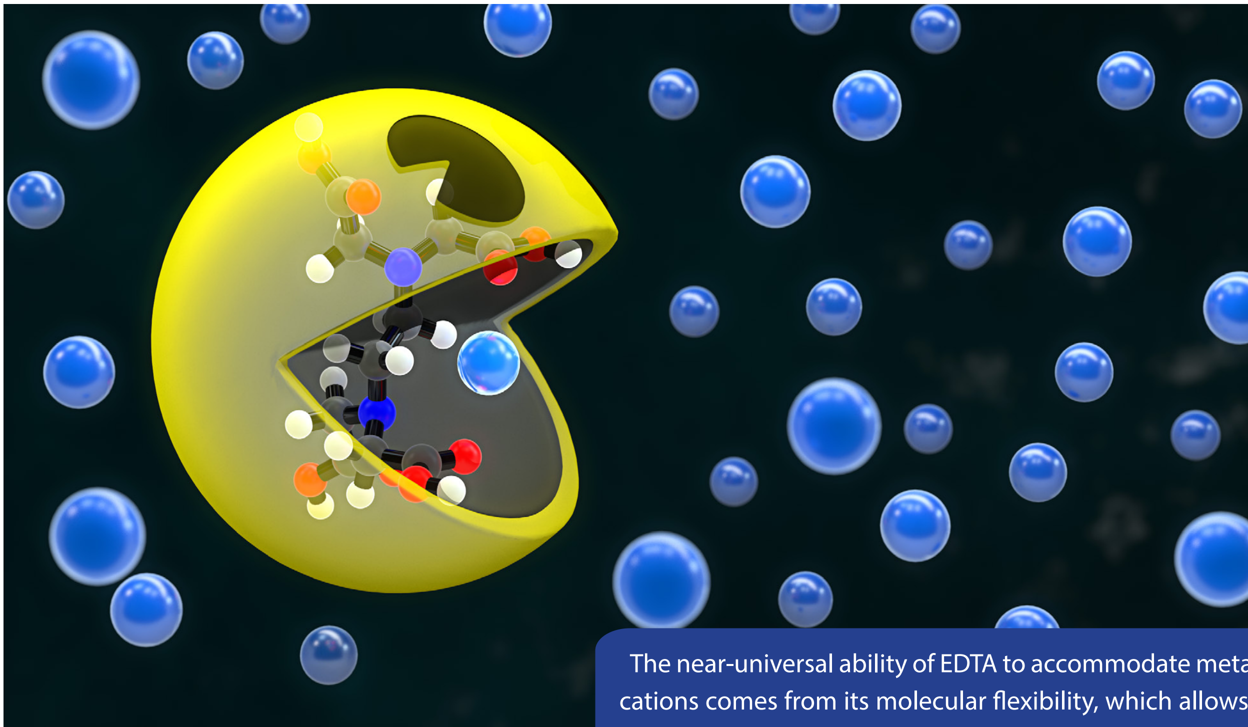
The infrared absorption spectrum of these complexes is something physicists and chemists often refer to, but because multiple atoms and molecules tend to contaminate a sample, this spectrum can be hard to isolate. With their gas-phase method, Weber and his team were able to create an analogous process to the infrared absorption measurements and understand more about the molecular behavior of EDTA. "Now, we can analyze the absorption features from that infrared spectrum to tell us something about the molecular structure," added Weber. "So encoded in this infrared spectrum is how the EDTA molecule interacts with that metal ion, how its functional groups are oriented, and how that orientation changes as you attach water to it or bring it into solution."

Binding to Water Molecules

As there is usually water around EDTA and proteins, as in the human body, Weber and his team were curious to understand how EDTA's behavior changes when interacting with water. "These binding sites in proteins bind to metal ions like calcium or magnesium with similar functional groups as those in EDTA," Weber explained. "And in proteins, the interaction between the metal ion and the protein binding pocket often does not allow lots of water molecules around it. Instead, it allows one or two in the vicinity. So, one could argue that the behavior of EDTA in the gas phase is actually a good model for trying to understand how these binding sites work."

In one experiment, published in the *Journal of Physical Chemistry Letters,* the researchers added water to the metal-EDTA complex one molecule at a time to see how small amounts of water affected the EDTA. "Here you start with just the EDTA metal complex, and then you add one water molecule and see where it binds and how it deforms the metal-EDTA complex as a whole," Weber added. "Then you can add the second water molecule and see how it influences the complex. In our research, we contrasted it with full solvation, full hydration."

Studying how EDTA binds metals while in the presence of water can also help researchers better understand the binding processes happening within the human body. "One of the main proteins that EDTA is used to emulate is calmodulin, as its binding pockets are kind of similar," Foreman explained. "Calmodulin is part of a larger class of proteins. They're all over the body serving all sorts of different functions. But the primary function of calmodulin is as a calcium mediator, so it reacts to the presence of calcium and signals other proteins to perform their functions. This can have effects on everything from hormones to muscle contraction." Because calmodulin usually binds more to calcium than magnesium in water, the researchers wanted to see if EDTA mimicked this behavior in solution. "When we then look at EDTA in solution, we see a similar trend in binding affinity, [where EDTA] would prefer to bind calcium than magnesium," stated Foreman. "So then, by looking at it in the gas phase, or with just a few water molecules, we can see



The near-universal ability of EDTA to accommodate metal cations comes from its molecular flexibility, which allows it to respond to the chemical nature of the metal ion it binds.

Credit: Steven Burrows/Weber Groups

that the structure of the EDTA metal complex does change between magnesium and calcium. And that gives us a hint as to why these proteins might be more selective to some ions than others."

Recycling Metal Ions

Weber and his team first studied how the molecule binds to alkaline earth metals (such as magnesium, calcium, strontium, or barium) to understand EDTA's interaction with different metal ions. In a second paper, published in 2023 in the *Journal of Physical Chemistry A,* the researchers found geometric differences in bindings between transition metals, like manganese, cobalt, and nickel, and alkaline earth metals, like calcium or magnesium. "The alkaline earth ions are simple ions. They present a spherically symmetric charge distribution to the outside world," Weber elaborated. "So they're really round. The transition metals we published in the paper, their electronic structure brings directionality to their bonding with other molecules; they do not look like a spherically symmetric charge distribution. I usually phrase this where the alkaline earth metals are round and the transition metals are spiky. Their electronic structure produces 'arms' or 'spikes' in a structural template that allows other molecules to bind to them in a very structured way."

Understanding how EDTA binds to various metals can give Weber and other scientists insight into using molecules that are similar to EDTA in wider applications, such as metal recycling. "Imagine nickel, cobalt, or rare earth metals, everything that you need for things from electric vehicles to batteries to your cell phone," stated Weber. "These metals need to be removed from electronics waste during recycling; then they need to be purified. One way to do that is to grab them with something [like EDTA]. Lane gathered background information on using chelators for rare earth metal recycling. She actually wrote a proposal on that process. And there are other, very different kinds of ion receptors, too." They're hopeful that their results can help other scientists and engineers improve current metal chelation applications.

Madison M. Foreman, Lane M. Terry, and J. Mathias Weber. "Binding Pocket Response of EDTA Complexes with Alkaline Earth Dications to Stepwise Hydration and Structural Insight from Infrared Spectra." Journal of Physical Chemistry A, 127(25), 5374–5381, 2023.

Madison M. Foreman and J. Mathias Weber " Ion Binding Site Structure and the Role of Water in Alkaline Earth EDTA Complexes" Journal of Physical Chemistry Letters, 13(36), 8558–8563, 2022.

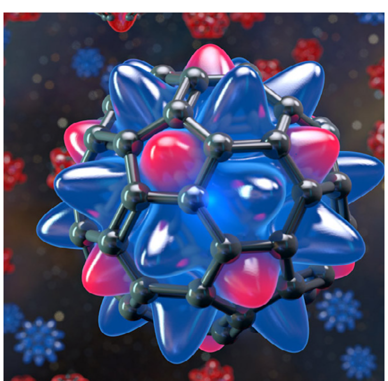
Madison M. Foreman, Maristella Alessio, Anna I. Krylov, and J. Mathias Weber " Influence of Transition Metal Electron Configuration on the Structure of Metal–EDTA Complexes" Jounral of Physical Chemistry A, 127(10), 2258–2264, 2023.

Written by Kenna Hughes-Castleberry

A New "Spin" on Ergodicity Breaking

In a recent *Science* paper, researchers led by JILA and NIST Fellow Jun Ye, along with collaborators JILA and NIST Fellow David Nesbitt, scientists from the University of Nevada, Reno, and Harvard University, observed novel ergodicity-breaking in C_{60}, a highly symmetric molecule composed of 60 carbon atoms arranged on the vertices of a "soccer ball" pattern (with 20 hexagon faces and 12 pentagon faces). Their results revealed ergodicity breaking in the rotations of C_{60}. Remarkably, they found that this ergodicity breaking occurs without symmetry breaking and can even turn on and off as the molecule spins faster and faster. Understanding ergodicity breaking can help scientists design better-optimized materials for energy and heat transfer.

Many everyday systems exhibit "ergodicity" such as heat spreading across a frying pan and smoke filling a room. In other words, matter or energy spreads evenly over time to all system parts as energy conservation allows. On the other hand, understanding how systems can violate (or "break") ergodicity, such as magnets or superconductors, helps scientists understand and engineer other exotic states of matter.



A C60 molecule examined by the researchers to understand ergodicity breaking.
Credit: Steven Burrows/Ye and Nesbitt Groups

In many cases, ergodicity breaking is tied to what physicists call "symmetry breaking." For example, the internal magnetic moments of atoms in a magnet all point in one direction, either "up" or "down." Despite possessing the same energy, these two distinct configurations are separated by an energy barrier. The "symmetry breaking" refers to the system assuming a configuration with lower symmetry than the physical laws governing its behavior would allow, such as all magnetic moments pointing "down" as the default state. At the same time, since the magnet has permanently settled into just one of two equal-energy configurations, it has also broken ergodicity.

Symmetry Breaking

To understand rotational ergodicity breaking, postdoctoral researcher and lead author, Lee Liu explained: "Consider a football thrown in a tight clockwise spiral. You would never see the football spontaneously flip 180 degrees end-over-end in mid-flight! This would require it to overcome an energy barrier. So a spiraling football maintains its end-to-end orientation in free flight, thereby breaking ergodicity and symmetry much like a magnet does."

However, unlike footballs, isolated molecules must obey the rules of quantum mechanics. Specifically, the two ends of an ethylene molecule (a quantum analog of a football) are indistinguishable. Thus, reorienting a spinning ethylene molecule 180 degrees end-over-end also entails overcoming an energy barrier; the initial and final states are indistinguishable. The molecule does not have two distinct end-to-end orientations to choose from, and symmetry and ergodicity are restored, meaning that the molecule's ground state is a combination, or the superposition, of both the final and initial states.

To probe the rotational dynamics of the C_{60} molecule, the researchers turned to a technique pioneered by the Ye group in 2016: combining buffer gas cooling with sensitive cavity-enhanced infrared spectroscopy. Using this technique, the researchers measured the infrared spectrum of C_{60} with 1000-fold higher sensitivity than previously achieved. It involved shining laser light on C_{60} molecules and "listening" to the frequencies of light they absorb. Rather than physically rotating the molecule faster and faster, the researchers probed a gas-phase sample of many C_{60} molecules in which some rotated rapidly and some slowly. The resulting infrared spectrum contained snapshots of the molecule at various rotation speeds. "Stitching of these traces together generated the complete spectrum, unraveling the full picture of the ergodicity evolution (or breaking) of the molecule," elaborated Dina Rosenberg, a fellow postdoctoral researcher in Ye's group.

Through this process, the researchers uncovered an astonishing behavior of C_{60}: spinning it at 2.3 billion GHz (rotations per second) makes it ergodic. This ergodic phase persists until 3.2 GHz when the molecule breaks ergodicity. As the molecule spins faster, it reverts back to being ergodic at 4.5 GHz. This peculiar switching behavior surprised the researchers, as ergodicity transitions typically occur only once the energy increases and in one direction. Curious, the team dove further into the spectrum to understand where this behavior originated.

By analyzing the infrared spectrum, the researchers could infer deformations of the molecule induced by its rotation. As Liu elaborated: "Just like drag race car's tires bulge more when rotated at a faster rate, the rotation rate of C_{60} dictates its structural deformation. The infrared spectra imply that two possibilities occur when the C_{60} rotation rate hits 2.3 GHz: It can flatten out into a frisbee shape or elongate into a football shape. The former occurs if it is rotating about a pentagon, and the latter if it is rotating about a hexagon." As it turns out, the peculiar ergodicity transitions of C_{60} could be attributed entirely to this sequence of deformations induced by the molecule's rotation.

Breaking Ergodicity Not Symmetry

In the gas phase, C_{60} molecules collide so infrequently that they behave as if they were isolated, meaning that the indistinguishability of each carbon atom in C_{60} becomes important. Therefore, spinning the molecule about any pentagon is equivalent to spinning it about any other pentagon. Likewise, spinning the molecule about any hexagon is equivalent to spinning it about any other hexagon. Just as in ethylene, the quantum indistinguishability of C_{60}'s carbon atoms restores the symmetry of the pentagonal and hexagonal rotational sectors. Nevertheless, the researchers' data showed that the molecule's rotation axis never switched between sectors.

The data showed two reasons for this rotational isolation around a single axis. At rotation rates below 3.2 and above 4.5 GHz, the pentagonal and hexagonal rotational sectors are isolated due to energy conservation. In this range, the C_{60} molecules are ergodic as the pentagonal and hexagonal sectors explore all possible states in distinct energy ranges, just as in the case of ethylene.

At rotation rates between 3.2 and 4.5 GHz, pentagonal and hexagonal sectors exist in the same energy range. "This is because spinning a hexagonal and a pentagonal football can take the same amount of energy," said Liu. "Nevertheless, C_{60} still fails to switch between the two rotational sectors because of an energy barrier—the same barrier that prevents a football from flipping end-over-end mid-flight. In this regime, therefore, C_{60} has broken ergodicity without breaking symmetry. This mechanism of ergodicity breaking without symmetry breaking, which can be understood simply in terms of deformations of a spinning molecule, was a total surprise to us," said Liu. These results reveal a rare example of ergodicity breaking without symmetry breaking, giving further insight into the quantum dynamics of the system.

Lee R. Liu, Dina Rosenberg, P. Bryan Changala, Philip J.D. Crowley, David J. Nesbitt, Norman Y. Yao, Timur V. Tscherbul, and Jun Ye " Ergodicity breaking in rapidly rotating C_{60} fullerenes." Science, 381, 778–783, 2023.

Going for Gold: New Advancements in Hot Carrier Science

In a new *ACS Nano* paper, JILA and NIST Fellow David Nesbitt, along with former graduate student Jacob Pettine and other collaborators, developed a new method for measuring the dynamics of specific particles known as "hot carriers," as a function of both time and energy, unveiling detailed information that can be used to improve collection efficiencies.

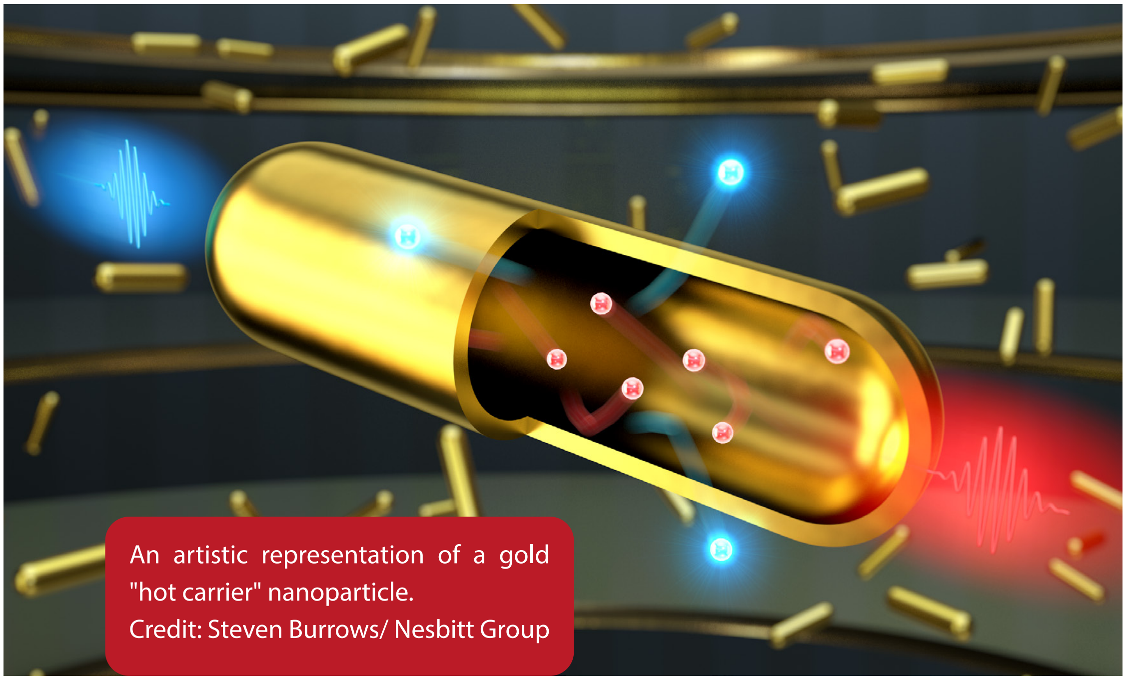
Within nanoscience, gold nanoparticles have emerged as fascinating building blocks for numerous applications, ranging from catalysis and sensing to biomedicine. Among their remarkable properties is the ability to generate large numbers of "hot carriers" upon light absorption. Hot carriers refer to highly energetic charge carriers, such as electrons, which bounce around inside the gold nanoparticles. If the kinetic energy stored in these hot carriers could be fully collected, it would lead to significant efficiency boosts and new capabilities in photovoltaics, photochemical catalysis, nanophotonics, and nanoelectronics.

Hot carriers can be collected for energy harvesting in several applications, such as solar cells. However, how to achieve technologically useful collection efficiencies in systems incorporating nanoscale metals remains unclear. "Whereas solar cells can exhibit energy collection efficiencies over 30%, many gold nanoparticle studies show less than 1% efficiencies," explained former JILA graduate student Jacob Pettine, now a Director's Postdoctoral Fellow at Los Alamos National Laboratory. "But, if we can boost these underlying collection efficiencies, then nanoparticles have the added bonus of operating across a broader range of the solar spectrum than silicon. There is room for growth; in some cases, hot electron extraction from these nanoparticles has even exceeded 10%. The challenge is understanding what exactly is happening at these tiny length scales and very fast time scales."

As Good as Gold: A Study of Metals

Gold has played a significant role in human history, captivating civilizations for centuries due to its inherent beauty, rarity, and versatility. "Gold is an amazing material," Nesbitt elaborated. "In macroscopically large 'chunks,' gold behaves in a way that is essentially chemically inert." However, at a nanoscale, gold behaves differently. "At the nanoscopic level, 'small' clusters of gold (say 10–10,000 atoms) can exhibit exceptionally high chemical reactivity, for example, in developing catalysts for oxidation/reduction of CO (carbon monoxide) to/from CO_2," added Nesbitt. "Of even greater interest, these small gold clusters are extremely good at absorbing visible solar light, with many orders of magnitude higher absorption per unit area than the 'blackest' materials like carbon soot. That's 'ironic' for a metal like gold, which we typically think of as highly reflective and not absorbing!"

Thanks to their ability to absorb sunlight, the gold nanoparticles can be filled to the energetic "brim" with hot carriers. Pettine, the study's lead author, and Nesbitt wanted to study the hot carrier dynamics and needed a method to track the energy decay of these hot carriers throughout their short lifetimes. "When you come in with a photon, and that light gets absorbed inside of these particles, the question becomes, how does the electron's energy decay after being excited?" Nesbitt stated. "How does this energy spill out? Does it simply instantaneously heat up the gold



An artistic representation of a gold "hot carrier" nanoparticle.
Credit: Steven Burrows/ Nesbitt Group

atoms (which is not terribly useful) or keep the energy in hot electron currents bouncing around inside a gold cluster?" To answer these questions, Pettine and Nesbitt realized they would have to develop a novel procedure to dive deeper into these nanomaterials.

Nanoscale Games of Darts

In their experimental setup, Pettine and Nesbitt combined two laser beams to excite, and then detect, the hot carriers. According to Pettine, "The system we built up in the Nesbitt Lab has allowed us to perform time-resolved studies on single nanoparticles. This is a totally unique capability, which we use with a technique called photoemission spectroscopy to resolve how fast the electrons decay or jump down from a higher to lower energy level, as a function of excitation energy." Photoemission spectroscopy has a rich historical legacy within physics. "It is based on the photoelectric effect," Pettine added. "The idea for our study is to kick electrons out of the system, detect them, and reconstruct what they were doing in the nanoparticle."

To capture and measure the hot carrier dynamics, the researchers first excited their gold nanoparticles with a red laser, transforming them into hot carriers. Then, a blue laser probed the system and ejected the cluster of hot carriers out of the nanoparticles. Using a series of copper plates at various voltages as a lens for these electrons, the researchers could focus them onto a detector. Similar to a game of darts, the electron "splatter" on this detector could then be used to measure their energy dynamics. "The general idea is that you're taking a snapshot of the system," Pettine elaborated. "The idea is to come in and knock it out of equilibrium with the first pulse, then we come in with a second pulse and see what the electrons are up to. We can do several things with this second pulse, like measure the absorption or reflectivity of the nanoparticle, but in our case, we can use it to kick out electrons so we can see how fast they move and in what direction."

From their new method, Pettine and Nesbitt found some unexpected results. "Our findings help us shed light on a few more basic ideas," said Pettine. "Amazingly, we still don't fully understand the dynamics in simple metals like gold when you shine a light on them. In fact, our recent work, including this paper, teaches us a few new things about gold in general. In nanoscale gold, whereas you might expect the surface to play a huge role due to the huge surface-to-volume ratio, we find that it plays almost no role! So, everything we're looking at really comes from the bulk of the material, and by studying these nanoparticles, we can actually get a remarkably accurate view of what likely happens in macroscopic bulk metal, like a chunk of gold."

Jacob Pettine, Paolo Maioli, Fabrice Vallee, Natalia Del Fatti, and David J. Nesbitt. " Energy-Resolved Femtosecond Hot Electron Dynamics in Single Plasmonic Nanoparticles" ACS Nano, 17(11), 10721–10732, 2023.

Written by Kenna Hughes-Castleberry

JILA's Physics Frontier Center (PFC) Awarded $25 Million by the National Science Foundation

The JILA Physics Frontier Center (PFC), an NSF-funded science center within JILA (a world-leading physics research institute), has recently been awarded a $25 million grant after a re-competition process. This science center brings together 20 investigators within JILA to collaborate to realize precise measurements and cutting-edge manipulations to harness increasingly complex quantum systems. Since its establishment in 2006, the JILA PFC's dedication to advancing quantum research and educating the next generation of scientists has helped it to stand out as the heart of JILA's excellence.

While the PFC includes about 20 JILA researchers, it is led by a much smaller executive committee. "We sometimes call it an oligarchy," stated JILA and NIST Fellow, and former PFC Director, Eric Cornell. "As the executive committee decides things by consensus, the Director is not especially important. However, the NSF does need a point of contact for the grant, so the Director does play a role in government relations."

One of the distinguishing features of the PFC is its commitment to fostering interdisciplinary collaboration. By bringing together physicists, chemists, biologists and other scientific experts, the PFC enables a unique environment for innovation and cross-pollination of ideas. The center encourages researchers to step outside their comfort zones and tackle complex scientific challenges from multiple perspectives, leading to breakthrough discoveries that would be difficult to achieve in isolation. "The JILA PFC, in my point of view, is the spinal cord of JILA," explained PFC Co-Director, and JILA and NIST Fellow, Ana Maria Rey "The reason is that the center serves as a connecting tissue among JILA investigators with different but complementary research interests. We all understand the added value of the center and are excited about the scientific barriers we can overcome as a team. We are willing to take risks and commit to very challenging problems that have long-term horizons which are only possible by the joint and synergistic capabilities of the investigators."

Over the years, the PFC, and JILA's group grant before it, have embarked on numerous research projects that have pushed the boundaries of physics. From exploring the properties of ultracold molecules to developing advanced precision measurement techniques, the PFC has consistently been at the forefront of pioneering research. Researchers at the center have significantly contributed to areas such as quantum information science, atomic and molecular physics, quantum optics, ultrafast science, and condensed matter physics.

The PFC has achieved several significant milestones and breakthroughs throughout its history. Most notably, in ultracold physics, JILA Fellows Eric Cornell and Carl Wieman won the Nobel Prize in Physics in 2001 for creating the first Bose-Einstein Condensate—a remarkable state of matter with extraordinary properties. This groundbreaking achievement opened up new avenues for exploring quantum phenomena and laid the foundation for subsequent research in ultracold physics.

The PFC has also made significant strides in quantum information science. In 2017, JILA scientists successfully created a long-lived quantum memory for photons, a crucial step towards developing quantum computers and secure quantum communication networks. These advancements have the potential to revolutionize computing and information processing, opening up a new era of technology. Furthermore, the PFC helped to push forward many new ideas in the development of ultrafast lasers, a technology used collaboratively in many PFC labs. Most recently, the path towards polarization control of ultrashort laser light pulses over a broad wavelength regime, led by PFC investigators Margaret Murnane and Henry Kapteyn, was supported using PFC funds.

“While the money is useful, the PFC has become greater than the sum of its parts,” Cornell stated. “It’s much more of a way to keep us thinking about research collaborations and to wish each other well in our projects. It’s about making it a place that good students want to come to and good staff wants to stay at.” For Rey and PFC Co-Director and JILA Fellow Andreas Becker, the feeling is similar. “We are nevertheless excited and proud to report that in this re-competition, in contrast to prior ones, NSF provides an increase of the JILA PFC budget,” said Rey. “This is exciting and will allow us to attract an even larger poll of fantastic and productive students and postdocs and undertake broader outreach activities that will benefit our community.”

When examining how the PFC has impacted JILA’s community and culture, JILA’s Chief Operations Officer Beth Kroger agreed with Cornell. “The NSF PFC funding enables JILA to provide critical infrastructure in support of the transformational research done at JILA,” she stated. “A key component of JILA’s infrastructure is the JILA Shop. The JILA Shops are instrumental in advancing research and providing mentoring and hands-on applied learning for scientists-in-training. This is just one example of the impact of the PFC.”

The PFC's contributions to the field of physics extend beyond groundbreaking discoveries. It has nurtured numerous scientists, providing an environment fostering creativity, collaboration, and scientific excellence. The center has trained numerous graduate students and postdoctoral researchers, equipping them with the knowledge and skills to make a lasting impact in their respective fields. “During the next PFC grant period we plan to initiate new training and mentoring programs at JILA which should further help our graduate students and postdocs in preparing them for their future careers in academia and industry”, said Becker.

Furthermore, a key part of the PFC has been its outreach program, “Partnerships for Informal Science Education in the Community," or PISEC, a semester-long afterschool program where CU volunteers work with K–12 students on inquiry-based physics experiments. It is mainly targeted to students from underrepresented groups in STEM: primarily Hispanic/Latinx with low income. The goal is to cultivate in the students involved an interest in science, and facilitate pathways into STEM degrees. PISEC is a very important part of the JILA-PFC. Jessica Hoehn is the current full-time PFC director for public engagement. In collaboration with executive members Heather Lewandowski and Eric Cornell, Hoehn is envisioning exciting new directions in which the PISEC can further expand and become even better during this funding period. Thanks to the $25 million grant awarded to JILA’s PFC, its vision and ongoing projects can continue to push the boundaries of quantum science and influence JILA’s culture and community.

A compilation of the many researchers and projects funded by the PFC.
Credit: Andreas Becker and Ana Maria Rey.

Remembering JILA Fellow James "Jim" Faller

JILA Fellow James E. Faller recently passed away at age 89.
Credit: JILA

Dr. James E. Faller passed away on June 14, 2023 at the age of 89, after a series of strokes. He was an experimental physicist who made significant contributions to precision measurements, experimental relativity, and innovative instrumentation, and he mentored many students and postdocs. Dr. Faller was an internationally renowned physicist in the Quantum Physics Division of the National Institute for Standards and Technology and a Fellow of JILA (University of Colorado Boulder and NIST).

James Elliot Faller was born January 17, 1934 in Mishawaka, IN where he spent his childhood. He graduated with an A.B. in Physics (summa cum laude) from the University of Indiana in 1955. He obtained his M.S. (1957) and Ph.D. (1963) degrees in the storied Princeton physics group led by R.H. Dicke.

After an initial postdoctoral appointment at JILA (1963–1966), Dr. Faller held faculty appointments at the Wesleyan University Department of Physics from 1966 until 1972 when he returned to JILA as a Fellow and NIST staff scientist. After serving terms as Chairman of JILA (1995–6) and Chief of the NIST Quantum Electronics Division (1996–2004), Dr. Faller retired in 2006. He enjoyed a position as a Visiting Professor at the University of Glasgow from 2001 until 2023.

Dr. Faller's scientific career spanned precision measurement of physical constants, fundamental tests of basic laws and innovative instrumentation. Starting with his doctoral thesis at Princeton, and continuing with numerous graduate students, he developed a succession of absolute gravimeters for measuring the Earth's gravitational acceleration '*g*.' The core idea of his doctoral thesis was interferometrically measuring the descent of a dropped object. He improved on that original idea with the incorporation of a stabilized laser, a reference mass on a suspension with long-period vibration isolation (aka, superspring), and a throwing system that measured both upward and downward travel with a high repetition rate. The gravimeters were all more-or-less portable to facilitate gravity mapping and side-by-side comparisons at reference locations. Both research and commercial versions became standards for gravimetry, geodesy and fundamental tests of 'fifth force' and Newton's Law of Gravitation.

One of Dr. Faller's most enduring research contributions was the proposal for precision ranging to the Moon using lasers and retroreflector arrays left on the Moon by the Apollo 11, 14 and 15 missions. He originally proposed the concept while still a graduate student, supported the refinement of the design and carried out the first successful ranging at Lick Observatory with Joe Wampler. Initial ranging accuracy of centimeters, and now millimeters, enabled unique lunar science, geophysics and fundamental tests of Newtonian gravity and General Relativity.

In another career-spanning endeavor, Dr. Faller developed multiple torsion pendulums for improved Eötvös experiments. Most were based on test masses floating in liquids with electrostatic and magnetic torsion springs. These torsion pendulums were primarily used to test the Equivalence Principle.

In the field of gravitational waves, Dr. Faller made important contributions to the quartz-fiber final suspensions and the active seismic isolation systems incorporated into Advanced LIGO. He collaborated with students and faculty at the University of Glasgow in developing silicate bonds for final suspensions. The active seismic isolation system is critical for the low-frequency response of the instrument that enables detection of merging stellar-mass black holes which make up the bulk of the revolutionary detections.

In 1981 Drs. Faller and Peter Bender proposed the first workable concept for a space- based, gravitational-wave detector that would operate in the millihertz band where the richest array of sources is found. Working with Dr. Bender and others, he pioneered the conceptual design that became the Laser Interferometric Space Antenna (LISA). LISA promises to detect massive black hole binary systems throughout the Universe and other gravitational-wave sources that are undetectable by ground-based instruments.

LISA is now a major space mission in the European Space Agency's program, with an anticipated launch date in the latter half of the 2030s. Dr. Faller recognized that laser frequency noise could be canceled in an unequal armed interferometer by suitable combinations of time-delayed signals.

Dr. Faller performed other notable precision measurements, such as a test of Coulomb's Law and upper limit on the photon rest mass, a measurement of the Newtonian Gravitational Constant ('G'), and a test of the anisotropy in the speed of light.

Many of Dr. Faller's students will remember him for his persistent concern for their motivation and his empowerment of them. He was extraordinarily successful at engaging students in creative instrumental solutions to major experimental challenges in ways that transformed their careers. For example, he was justifiably proud of achieving the first successful laser ranging to the Moon with a coterie of undergraduates and one graduate student, all of whom went on to earn doctorates in physics. In his later years, he frequently spent his summers at the University of Glasgow coaching graduate students on how to tackle experiments, how to choose, build and operate the right instrumentation, and how, in the right circumstances, to transfer that knowledge to industry.

Dr. Faller received many prizes over his illustrious career, including: the National Bureau of Standards Precision Measurement Award (1970), the Arnold O. Beckman Award of the Instrument Society of America (1970), the NASA Group Achievement Award (1973), the NASA Exceptional Scientific Achievement Medal (1973), the Department of Commerce Gold medal (1990), and the Joseph F. Keithley Award (2001). He was a Fellow of the American Physical Society, Optica, the American Geophysical Union and the American Association for the Advancement of Science.

Dr. Faller was a passionate devotee of Medieval, Renaissance and Baroque music and played the recorder for many decades. He was also an avid sports fan, particularly of tennis and basketball. He lectured occasionally on the nexus of sports and physics.

Dr. Faller is survived by his wife, Jocelyne Bellenger, his brother Larry Faller and his two sons, William and Peter Faller.

Written by Robin "Tuck" Stebbins, former JILAn

Remembering JILA Founder Lewis M. Branscomb

(January 17, 1926–May 31, 2023)

It is with heavy hearts that the JILA and NIST communities mourn the loss of renowned physicist Lewis Branscomb, who passed away on May 31, 2023, leaving behind an indelible legacy in the world of science and a profound impact on JILA. Branscomb, a brilliant mind and a cherished member of JILA will forever be remembered for his groundbreaking contributions to the field of physics and his unwavering commitment to advancing scientific knowledge. His dedication to founding JILA, and serving as its first Fellow Chair, will remain forever in JILA's collective memory. His insatiable curiosity and intellectual prowess paved the way for a remarkable career that spanned over six decades.

Born on August 17, 1926, in Asheville, North Carolina, Lewis Branscomb's thirst for knowledge led him on a remarkable journey through the realms of scientific discovery. Educated at Duke University, he earned his bachelor's degree in physics in 1945, summa cum laude, (at age 19) and a doctorate degree in mathematical physics in 1949 from Harvard University. In the years between his bachelor's and his Ph.D. degrees, Branscomb served as a U.S. Naval Reserve Officer in the Philippines during World War II as part of an accelerator program at Duke to train scientists. After receiving his Ph.D. in 1949, Branscomb was appointed a Junior Fellow in the Harvard Society of Fellows.

In 1951, Branscomb joined the National Bureau of Standards (NBS, later to become the National Institute of Standards and Technology or NIST) as a research scientist. Branscomb's research focused on astrophysics and precision measurement. In the book *JILA: the First 50 Years*, Branscomb stated, "At the National Bureau of Standards, Steve Smith and I were exploiting new spectroscopy tools to study negative hydrogen ions that control the temperature of the solar photosphere." During this time, Branscomb began collaborating with physicist and later co-founder of JILA, Richard "Dick" Thomas, to create a research institute focused on laboratory astrophysics.

In the early 1960s, few institutes offered astrophysicists laboratories to study outer space phenomena. This forced many scientists to change their career trajectories or focus on other topics entirely. Seeing these issues, Branscomb and Thomas approached then NBC Director Allen Astin with a proposal to create a new institute focused solely on laboratory astrophysics. Astin agreed to their proposal and suggested partnering with a university to share in funding and talent. While Branscomb and Thomas toured various universities, the University of Colorado Boulder seemed the most appealing, as several CU administrators were enthusiastic about a future institution.

Once Branscomb and Thomas decided on CU Boulder, and several university faculty, Astin, and other NBS members raised funds to build a new building. In 1962, the Joint Institute for Laboratory Astrophysics (JILA) was officially born, erecting a tower on the western part of CU Boulder's campus. Branscomb helped create the by-laws for JILA and served as its first Fellow Chair. As founding member, Steven J. Smith later stated: "There would have been no JILA without the leadership of Lewis Branscomb…" At JILA, Branscomb's intellect and innovative thinking flourished, and he became an influential figure, inspiring generations of scientists to push the boundaries of human understanding. His collaborations with other JILA scientists and his dedication to mentoring young researchers significantly impacted the development of atomic clocks, quantum optics, and precision metrology.

Beyond his exceptional scientific achievements, Branscomb was known for his kindness, generosity, and passion for teaching. He nurtured an environment of collaboration and encouraged interdisciplinary research, bringing together physicists, chemists, and engineers to explore uncharted territories. His wisdom and guidance were invaluable to countless scientists, fostering an atmosphere of innovation and intellectual rigor at JILA.

While at JILA, Branscomb sat on the Presidential Advisory Committee for President Lyndon B. Johnson. His expertise in astrophysics was influential in helping the Committee oversee NASA's Apollo program in the 1960s. Branscomb chaired the Committee's Panel on Space Science and Technology.

In 1969, Branscomb transitioned from JILA to the NBS, where President Richard Nixon named him the Director of the NBS. Branscomb would hold this position until 1972.

In 1972, Branscomb decided to move to the private sector and joined IBM as their Chief Scientist and later as member of the IBM Corporate Management Board. His vast knowledge and keen insights were influential in helping IBM during the period when the company was developing space shuttle components and creating personal computers.

After his time at IBM and the National Science Board, Branscomb became a professor at Harvard University and Director of the Science, Technology, and Public Policy Program at Harvard's John F. Kennedy School of Government. In 1996, he retired.

JILA founder and astrophysicist Lewis M. Branscomb recently passed away at age 96.
Credit: Wikimedia Commons

On May 31, 2023, Branscomb passed away at the age of 96 from natural causes, around four years after suffering from severe brain trauma following a tragic fall in 2019.

Awards and Recognitions

Lewis Branscomb's contributions to science were widely recognized and honored. He received numerous prestigious awards and accolades throughout his career, including the Okawa Prize in 1998 "for outstanding contributions to the progress of informatics, scientific and technological policy, and corporate management" and the Vannevar Bush Award from the National Science Board in 2001 "for his distinguished public service in the development of U.S. science and technology policy; a scientist, teacher, scholar, business leader and author who has influenced policies of recent Administrations, he has been an inspiration to students and colleagues and a valuable asset to the Nation." Branscomb was also awarded honorary doctorates from fifteen universities. He also was a member of all three National Academies: of Sciences, of Engineering and of Medicine. Branscomb also served as President of the American Physical Society in 1979 and as the Editor of the Reviews of Modern Physics from 1963–1969. He was also the author of over a dozen books and hundreds of scientific papers.

While the loss of Lewis Branscomb leaves a void in the scientific community, his remarkable legacy will continue to inspire future generations of physicists and scientists. His unwavering dedication to knowledge, his commitment to excellence, and his relentless pursuit of understanding the fundamental nature of the universe will forever guide the scientific endeavors at JILA.

Written by Kenna Hughes-Castleberry

Humans Of JILA: Rachael Merritt

While many researchers within JILA focus on pushing the limits of particles in the quantum realm, others, like Rachael Merritt, look at how physics is currently being taught and ways to improve this process. Known as physics education research (PER), this field is crucial in enhancing the quality of physics education by providing evidence-based insights into teaching and learning practices. As a postdoctoral researcher in JILA Fellow Heather Lewandowski's group, Merritt helps to lead some of the most cutting-edge research in PER in the United States.

PER investigates different teaching methods and their impact on student learning outcomes. In her own research, Merritt focuses on physics laboratory experiments in particular. "Since I've been here, I've been validating the modeling assessment for physics laboratory experiments, also known as MAPLE, which is an assessment to measure students modeling proficiency in upper-division optics along with electronics courses," stated Merritt. "So the American Association of Physics Teachers has identified modeling as an essential skill students need to have in undergraduates and physics programs. Previously there wasn't a research-based assessment instrument to evaluate this modeling. So, MAPLE was developed."

Rachael Merritt, a postdoctoral research associate at JILA.

To validate MAPLE's effectiveness, Merritt and her fellow researchers work to understand the personas of the students involved in these specific laboratory experiments and the assessment guidelines involved. While looking through more qualitative data can seem confusing or overwhelming, Merritt and her team use special coding to help transform the qualitative data into quantitative results. Yet, they also study the qualitative results to get a holistic picture of the entire process. "There definitely is a social science part of it," said Merritt. "Because you're working with people, so there has to be. But then, once you have the data, it is a very methodical and scientific process as you're analyzing this. That's one thing that I've really appreciated about working with Heather is that she holds us all to a very high standard about how we analyze the data and what results we put out."

Merritt's work in PER has been recognized by Lewandowski and her team and, more recently, the National Science Foundation (NSF). "I'm very excited to say that I have been awarded a National Science Foundation, Mathematical, and Physical Sciences ascending Postdoctoral Research Fellowship, or an NPS Ascend Fellowship," she added. "The purpose of this program is to support postdoctoral fellows, who will broaden participation of groups historically excluded and currently underrepresented in NPS or math or physical sciences, in the United States." Through this fellowship, Merritt plans to transform physics education into more hands-on, engaging processes that could help persuade more individuals to learn more about physics. "If you think about everything good about a traditional undergraduate research experience, you pick that up, you take it, and you drop it into a classroom setting, where you're having all of the authentic research experiences where students are doing teamwork, they're learning scientific skills, that will be transferable for whatever they decide to do," explained Merritt. Classes in biology already have these hands-on infrastructures in place, but it's much more difficult for physics and math courses. "The goal of my fellowship is to actually come up with a framework for discipline-specific challenges and benefits of running [these infrastructures] in physics departments. Then from the framework, we hopefully will be able to distribute that across the country."

News and Awards

Above: The JILA Postdoc Group Career panel. (Seated, left to right): Postdoc Group co-chair Rachael Merritt, former Keck Lab Director J. Curtis Breimborn II, JILA Fellow Margaret Murnane, JILA Fellow Graeme Smith, and Postdoc Group co-chair Jake Higgins; (on screen): JILA Fellow Shuo Sun
Credit: Kenna Hughes-Castleberry/JILA

News

JILA's Postdoc Group Hosts Career Panel. JILA's Postdoc Group, an internal organization supporting postdoctoral researchers within JILA, held a career panel titled: "Insights for Applying for Faculty Positions as a Postdoctoral Researcher." The panel featured three JILA Fellows: Margaret Murnane, Shuo Sun, and Graeme Smith, and J. Curtis Beimborn II, at the time the Director of the W.M. Keck Laboratory at JILA, who recently accepted a faculty position on the East Coast.

JILA Graduate Student Enrique Segura Carrillo is highlighted in an APS Physics article. JILA graduate student and Los Alamos National Laboratory (LANL) researcher Enrique Segura Carrillo has been highlighted in the July/August issue of the American Physical Society's (APS Physics) newsletter. Segura Carrillo, whose research focuses on quantum science, is part of the APS's Industry Mentoring Program (IMPact), which began in 2015.

JILA Fellow and University of Colorado Boulder Physics Professor Heather Lewandowski is interviewed by Colorado 9News. Lewandowski discussed a recent paper with over 1,000 authors. This recent paper, published in *the Astrophysical Journal,* focused on solving the mystery of the Sun's corona, a ring of significantly hotter temperatures surrounding the Sun compared to its core.

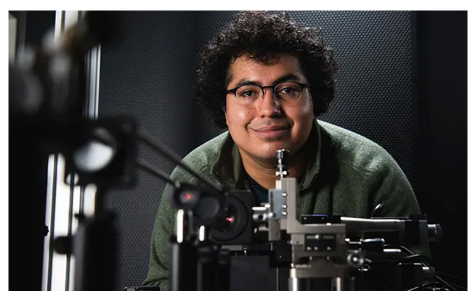
JILA Fellow and University of Colorado Boulder physics professor Daniel Dessau's research was recently highlighted in an article from The Washington Post *focusing on the recent room-temperature superconductor and its controversial science.*

JILA and NIST Fellow Jun Ye's Research is Highlighted in a New University of Colorado Boulder Start Up Program. Entrepreneur Eva Yao will help market a breathalyzer capable of detecting molecules in breath or air samples invented by Ye for fast detection of diseases and contaminants.

Awards

Margaret Murnane is Awarded a Honorary Doctorate from the University of Salamanca. A trailblazer in her field, this esteemed recognition from one of the oldest universities in the world serves as a testament to Murnane's remarkable achievements and lasting impact on the scientific community.

JILA and NIST Fellow Ana Maria Rey is Awarded a 2023 Vannevar Bush Faculty Fellowship from the Department of Defense. The Vannevar Bush Faculty Fellowship, named after the visionary American engineer and science administrator, aims to support exceptional researchers with outstanding scientific and technological leadership.



Above: JILA and Los Alamos National Laboratory (LANL) researcher Enrique Segura Carrillo, who was highlighted in a recent ASP Physics article.
Credit: APS Physics

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

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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