STROBE

BUILDING THE MICROSCOPES OF TOMORROW

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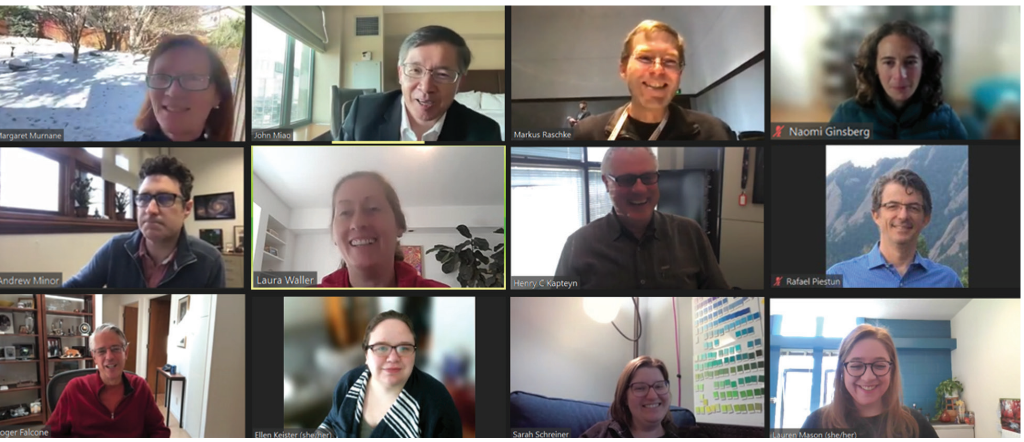


GREETINGS FROM STROBE

We hope that you are well and enjoying the holiday season. STROBE has been busy with community connections and exciting research advances in imaging science, as featured in this Newsletter. Research advances in 2023 include enhanced imaging using deep-learning and advanced algorithms, new methods to image spin textures in 3D at the nanoscale, new microscopes for capturing and understanding nanoscale transport in general geometries, enhanced imaging of highly periodic structures using vortex high harmonic beams, and new methods to image the solid-electrolyte interphase in a lithium ion battery.

Congratulations to all >240 graduates, fellowship, and award winners for your hard work and exciting discoveries in research, imaging science and technologies! Thank you to all of our STROBE and PEAQS graduate students, postdoctoral researchers, faculty and staff mentors for providing exciting projects and training for more than 35 student researchers this past summer. STROBE is also collaborating with K-12 teachers to encourage interest in STEM for the next generation by incorporating imaging science ideas and concepts into numerous outreach activities. It is wonderful to see the positive impact and broadening connections from the efforts of our community.

As we transition into winter, we look forward to the STROBE retreat in January 2024 at UCLA. The annual STROBE retreat is a great opportunity to meet new members, build networks, expand collaborations, participate in professional development training, and share STROBE research and activities from all nodes. There are many ways to get involved, including attending the fall and spring research advances seminar series and tutorials, professional development training such as research project management, social intelligence, and mentoring, or joining us at the STROBE retreat in January! We wish you a beautiful holiday season and we look forward to connecting with you soon.

University of Colorado Boulder

UCLA

Berkeley UNIVERSITY OF CALIFORNIA

UCI University of California, Irvine

FIU FLORIDA INTERNATIONAL UNIVERSITY

FORT LEWIS COLLEGE

PEAQS

NORFOLK STATE UNIVERSITY

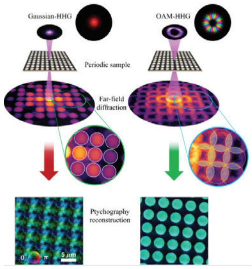
This material is based upon work supported by the National Science Foundation under STROBE Grant No. DMR 1548924, which began in 2016. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

BEST WISHES AND FAREWELL TO TING

We are excited to share that Dr. Chen-Ting (Ting) Liao has taken a position as Associate Professor of Physics at the University of Indiana Bloomington. Congratulations, Ting!

In 2021, Ting joined the STROBE leadership team as the Assistant Director of Research and Knowledge Transfer. Through this position, Ting supported STROBE collaborations with industry, national laboratories, and academia and organized the research advances seminar and tutorial series. Recently, Ting received research awards from the Air Force Young Investigator Program and from the Department of Energy Basic Energy Sciences Program. We wish Ting best wishes and a very fond farewell. We look forward to continued connection and research collaboration in his new role at UI!

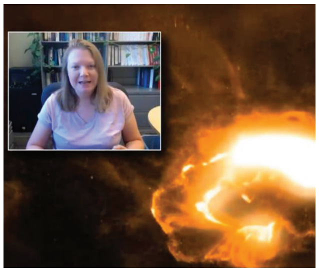
STROBE IN THE NEWS | JANUARY 2023 – DECEMBER 2023



High-Fidelity Ptychography of Highly Periodic Structures

December 1, 2023 | Optica: Optics & Photonics News

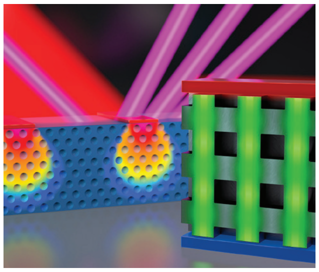
Lensless imaging based on ptychographic coherent diffractive imaging enables diffraction-limited microscopy at short wavelengths, overcoming the limits of imperfect optics.1,2 Ptychographic imaging of highly periodic structures has been challenging, however, due to the lack of diversity in the recorded diffraction patterns, which leads to poor convergence of the reconstructed sample images.



CU Students Become Solar Scientists

July 25, 2023 | 9news

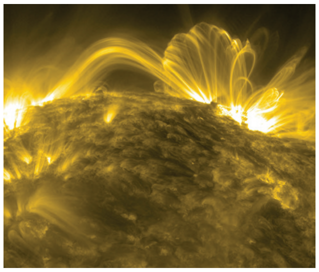
An unusual research project at the University of Colorado turned more than a thousand undergrad students into instant solar scientists.



Turning Up the Heat in Quantum Materials

June 12, 2023 | JILA, CU Boulder

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 . . .

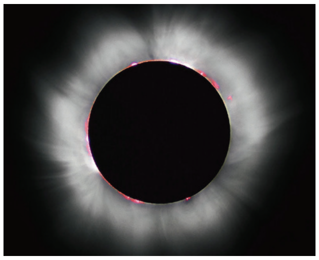


How hundreds of college students are helping solve a centuries-old mystery about the sun

May 17, 2023 | Popular Science

Astronomers-in-training spent thousands of hours peering at tiny solar flares that space telescopes missed. A team of more than 1,000 astronomers and college students just took a step closer to solving one of the long-lasting mysteries of astronomy: Why is the sun's outer layer, known as the corona, so . . .

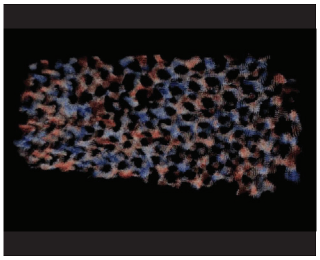
STROBE IN THE NEWS | JANUARY 2023 – DECEMBER 2023



How 1,000 undergraduates helped solve an enduring mystery about the sun

May 9, 2023 | CU Boulder Today

For a new study, a team of physicists recruited roughly 1,000 undergraduate students at CU Boulder to help answer one of the most enduring questions about the sun: How does the star's outermost atmosphere, or "corona," get so hot? The research represents a nearly-unprecedented feat of data analysis: From 2020 . . .



Imaging Topological Magnetic Monopoles in 3D

March 23, 2023 | Advanced Light Source, Lawrence Berkeley National Laboratory

Researchers created topologically stable magnetic monopoles and imaged them in 3D with unprecedented spatial resolution using a technique developed at the Advanced Light Source (ALS). The work enables the study of magnetic monopole behavior for both fundamental interest and potential use in information storage and transport applications. A bar magnet . . .

Humans of JILA: Brendan McBennett

January 13, 2023 | JILA

Surrounded by some of the world's most advanced lasers, computers, and microscopes sits Brendan McBennett, a graduate student at JILA. McBennett has been working in the laboratories of JILA Fellows Margaret Murnane and Henry Kapteyn, as part of the KM group since 2019, excited to see his research advance significantly . . .

STROBE AWARDS | JANUARY 2023 – DECEMBER 2023

Congrats to Jessica Ramella-Roman for Being Elected as a 2024 Optica Fellow

October 30, 2023 | Optica

Jessica Ramella-Roman has been elected as a Fellow of Optica for her pioneering contributions to the study of polarized light transport in biological media through experimental and computational approaches. The Board of Directors of Optica (formerly OSA), Advancing Optics and Photonics Worldwide, recently elected 129 members from 26 countries . . .

Congrats to Jeremy Thurston for Receiving the Emil Wolf Outstanding Student Paper Award at Frontiers in Optics

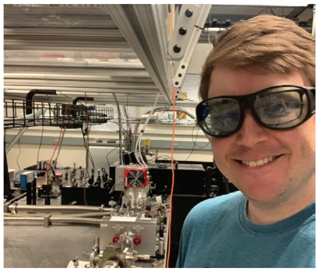
October 24, 2023 | Optica

Every year, the Frontiers in Optics conference holds the Emil Wolf Outstanding Student Paper Competition, acknowledging the excellence of students in presenting their work at the conference in both paper and poster form. This year, JILA graduate student Jeremy Thurston of the Murnane and Kapteyn research groups showcased his work . . .

Congrats to Drew Morrill for Receiving the Colorado Photonics Industry Association Poster Award

October 19, 2023 | Colorado Photonics Industry Association

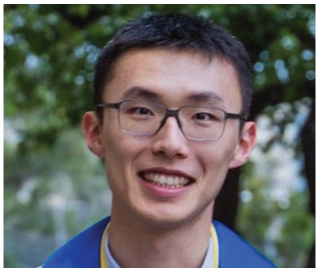
Drew Morrill's poster, titled: "High-harmonic generation from a 3 μm wavelength OPCPA," received an award from the Colorado Photonics Industry Association. The poster illustrates a method to generate soft X-rays using laser arrays. Congratulations, Drew!



Congrats to Daniel Carlson for Receiving the Best Paper Award at Optica International Conference on Advanced Solid State Lasers

October 12, 2023 | Optica

To honor students' abilities for clear and effective communication in quantum physics, Optica offers a yearly "best paper" award at its International Conference on Advanced Solid State Lasers. This year, JILA graduate student Daniel Carlson was among the list of winners, with his presentation "Carbon K-Edge Soft X-Rays Driven by . . .



Congrats to Ruiming Cao for Receiving best Student Paper Award at the Optica Imaging Congress

September 1, 2023 | Optica

Ruiming Cao received the Best Student Paper Award for his paper titled, "Speckle Structured Illumination of Dynamic Samples with a Neural Space-time Model" at the Optica Imaging Congress this fall. Congratulations, Ruiming!

Congrats to Colum O'Leary for Receiving a Poster Award at the 2023 Molecular Foundry User Meeting

August 21, 2023 | The Molecular Foundry, Lawrence Berkeley National Laboratory

Dr. Colum O'Leary received a poster award at the annual Molecular Foundry User Meeting at Lawrence Berkeley National Laboratory. Colum's poster was titled, "Visualizing embedded interfaces on the nanoscale via multislice electron ptychography".

Congrats to Vivian Wall for Receiving an NSF Graduate Research Fellowship

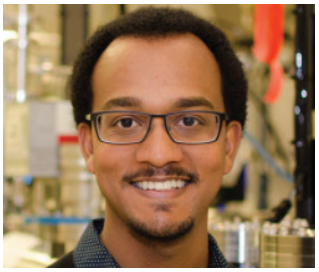
August 1, 2023 | National Science Foundation

The NSF GRFP recognizes and supports outstanding graduate students in NSF-supported STEM disciplines who are pursuing research-based master's and doctoral degrees at accredited US institutions. The purpose of the NSF Graduate Research Fellowship Program (GRFP) is to ensure the quality, vitality, and diversity of the scientific and engineering workforce of . . .

Congrats to Livia Belman-Wells for Receiving an NSF Graduate Research Fellowship

August 1, 2023 | National Science Foundation

The NSF GRFP recognizes and supports outstanding graduate students in NSF-supported STEM disciplines who are pursuing research-based master's and doctoral degrees at accredited US institutions. The purpose of the NSF Graduate Research Fellowship Program (GRFP) is to ensure the quality, vitality, and diversity of the scientific and engineering workforce of . . .



Congrats to Kwabena Bediako for Receiving a Heising-Simons Faculty Fellowship

July 1, 2023 | University of California Berkeley

The Heising-Simons Faculty Fellows Program catalyzes scientific discovery by investing in high-risk, high-reward research directions. The Program supports exceptional faculty working on topics in a diverse set of fields, including astronomy, physics, geology and geophysics, materials sciences (in both physics and engineering), and physical and materials chemistry.

Margaret Murnane is Awarded a Honorary Doctorate from the University of Salamanca

June 20, 2023 | University of Salamanca, JILA

Renowned scientist, JILA Fellow, and University of Colorado Boulder professor Margaret Murnane has been granted an honorary doctorate from the prestigious University of Salamanca, recognizing her outstanding contributions to the field of ultrafast laser science. As a trailblazer in her field, Murnane's groundbreaking research has revolutionized our understanding of light . . .

Congrats to Dr. Rachael Merritt for Receiving an NSF Mathematical and Physical Sciences Ascending Postdoctoral Research Fellowship

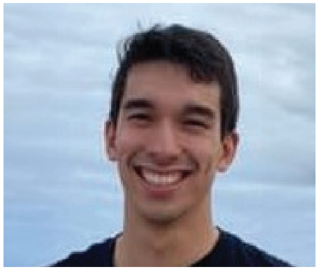
June 1, 2023 | National Science Foundation

The NSF Mathematical and Physical Sciences Ascending Postdoctoral Research Fellowships (MPS-Ascend) supports postdoctoral fellows performing impactful research in MPS fields while broadening the participation of groups that are underrepresented in the mathematical and physical sciences.

Congrats to Stephanie Hart for Receiving a Postdoctoral Fellowship in Chemical Sciences from the Arnold and Mabel Beckman Foundation

June 1, 2023 | Arnold and Mabel Beckman Foundation

Stephanie Hart has been awarded the Arnold O. Beckman Postdoctoral Fellowship for her project titled, "Nanoscale imaging of ultrafast energy flow in photosynthetic architectures." The Arnold O. Beckman Postdoctoral Fellowship in Chemical Sciences or Chemical Instrumentation Award Program supports advanced research by postdoctoral scholars within the core areas . . .



Congratulations to Nathan Brooks on a Postdoctoral Fellowship, Academia Sinica, Taiwan

May 31, 2023 | Academia Sinica, Taiwan

Congratulations to Nathan Brooks for receiving a Postdoctoral Fellowship from Academia Sinica in Taiwan!

Congrats to Ahyoung Kim for Receiving a Schmidt Science Fellowship

May 4, 2023 | Forbes

Eric and Wendy Schmidt have announced the Schmidt Science Fellows for 2023. This year's cohort of 32 Fellows are all recent PhD's who've been identified as some of the most outstanding early-career scientists in the world. The Schmidt Science Fellows was the first program supported by Schmidt Futures, a philanthropic initiative co-founded . . .

Congrats to Gordana Dukovic for Receiving a Guggenheim Fellowship

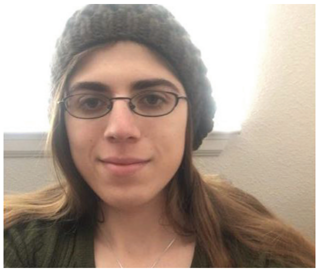
April 6, 2023 | John Simon Guggenheim Memorial Foundation

Congrats to Prof. Gordana Dukovic, who was named as one of the 2023 Guggenheim Fellows! The fellowship is a highly competitive award available to mid-career Americans and Canadians who have "demonstrated exceptional capacity for productive scholarship or exceptional ability in the arts and exhibit great promise for their future endeavors." . . .

Congrats to Naomi Ginsberg for Being Honored as Laird Lecturer at the University of British Columbia

April 3, 2023 | University of British Columbia

Professor Naomi Ginsberg has been named Laird Lecturer at the University of British Columbia. The Laird Lecturer brings to the general public some of the excitement that leading physicists from all over the world have as they understand fundamentals and apply their special talents to solving many of today's scientific . . .



Congrats to Olivia Bird for Receiving an NSF Graduate Research Fellowship

April 1, 2023 | National Science Foundation

The NSF GRFP recognizes and supports outstanding graduate students in NSF-supported STEM disciplines who are pursuing research-based master's and doctoral degrees at accredited US institutions. The purpose of the NSF Graduate Research Fellowship Program (GRFP) is to ensure the quality, vitality, and diversity of the scientific and engineering workforce of . . .

Congrats to Benjamin Hammel for Receiving an NSF Graduate Research Fellowship

April 1, 2023 | National Science Foundation

The NSF GRFP recognizes and supports outstanding graduate students in NSF-supported STEM disciplines who are pursuing research-based master's and doctoral degrees at accredited US institutions. The purpose of the NSF Graduate Research Fellowship Program (GRFP) is to ensure the quality, vitality, and diversity of the scientific and engineering workforce of . . .

Congrats to Emma Nelson for Receiving an NSF Graduate Research Fellowship

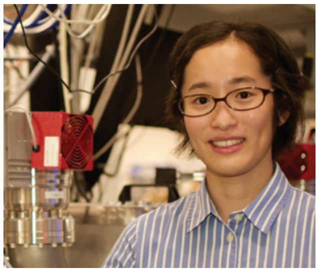
March 29, 2023 | National Science Foundation

The NSF GRFP recognizes and supports outstanding graduate students in NSF-supported STEM disciplines who are pursuing research-based master's and doctoral degrees at accredited US institutions. The purpose of the NSF Graduate Research Fellowship Program (GRFP) is to ensure the quality, vitality, and diversity of the scientific and engineering workforce of . . .

Congrats to Jessica Ramella-Roman for Being Named an AIMBE Fellow

March 27, 2023 | The American Institute for Medical and Biological Engineering

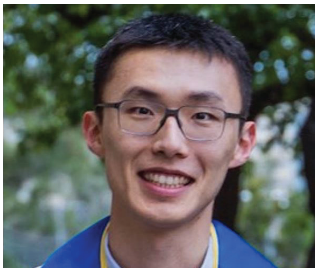
The American Institute for Medical and Biological Engineering (AIMBE) has announced the induction of Jessica C. Ramella-Roman, Ph.D., Associate Professor at Florida International University to its College of Fellows. Election to the AIMBE College of Fellows is among the highest professional distinctions accorded to a medical and biological engineer. The . . .



Congratulations to Yuka Esashi for Being Awarded the 2023 SPIE Karel Urbánek Best Student Paper Award

March 2, 2023 | SPIE

At the 2023 Advanced Lithography and Patterning Conference, Yuka Esashi was awarded the SPIE Karel Urbánek Best Student Paper Award for "Multi-modal tabletop EUV reflectometry for characterization of nanostructures." Congratulations, Yuka! The Karel Urbánek Best Student Paper Award recognizes the most promising contribution to the field by a student, based on . . .



Congrats to Ruiming Cao for Receiving the Hitachi High-Tech Best Presentation Award at the SPIE Photonics West Conference

January 27, 2023 | SPIE

Hitatchi sponsors two High-Tech Best Presentation Awards in High-Speed Biomedical Imaging and Spectroscopy at the SPIE Photonics West Conference. Congratulations to Ruiming Cao for receiving this award in 2023!

Congrats to Kwabena Bediako for Receiving an NSF Career Award

January 23, 2023 | NSF, The Daily Californian

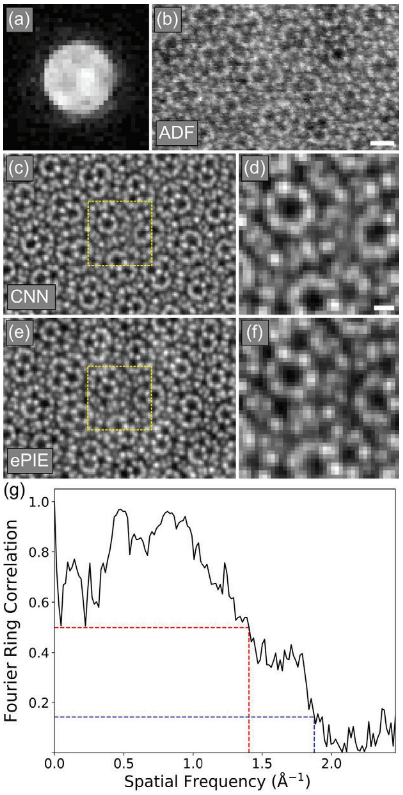
Kwabena Bediako, campus assistant chemistry professor, was awarded the National Science Foundation, or NSF, CAREER award for his ongoing research and outreach proposal. The CAREER award is a five-year grant open to assistant professors who are fairly early on in their careers, Bediako noted. This grant will help him . . .

Congrats to Markus Raschke for Receiving a Research Collaboration Award from the University of Bayreuth Centre of International Excellence

January 2, 2023 | University of Bayreuth

Markus Raschke received an award from the University of Bayreuth Centre of International Excellence to foster collaborations. The project is titled "Pico-cavity QED." The goal of this project between the Raschke group at the University of Colorado and the Lippitz group (Experimental Physics III) at the University of Bayreuth is . . .

SELECTED RESEARCH HIGHLIGHTS

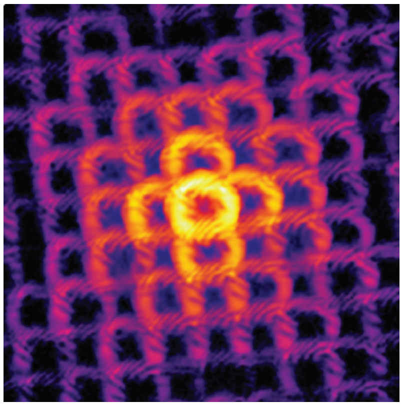


Deep-Learning Electron Diffractive Imaging

Coherent diffractive imaging (CDI) is revolutionizing the physical and biological science fields by first measuring the diffraction patterns of nano-crystals or non-crystalline samples and then inverting them to high-resolution images. The well-known phase problem is solved by the combination of coherent illumination and iterative computational algorithms. In particular, ptychography – a powerful scanning CDI method – has found wide applications with synchrotron radiation, high harmonic generation, electron and optical microscopy. However, iterative algorithms are not only computationally expensive, but also require practitioners to get algorithmic training to optimize the parameters and obtain satisfactory results. These difficulties have thus far prevented CDI from being accessible to an even broader user community. Here we demonstrated deep learning CDI using convolutional neural networks (CNNs) trained only by simulated data. The CNNs are subsequently used to directly retrieve the phase images of monolayer graphene, twisted hexagonal boron nitride and a Au nanoparticle from experimental electron diffraction patterns without any iteration. Quantitative analysis shows that the phase images recovered by the CNNs have comparable quality to those reconstructed by a conventional iterative method and the resolution of the phase images by the CNNs is in the range of 0.71-0.53 Å. Looking forward, we expect that deep learning CDI could become an important tool for real-time, atomic-scale imaging of a wide range of samples across different disciplines.

> *D. J. Chang, C. M. O'Leary, C. Su, D. A. Jacobs, S. Kahn, A. Zettl, J. Ciston, P. Ercius, J. Miao, "Deep-Learning Electron Diffractive Imaging," Physical Review Letters, 130, 016101, (2023). DOI: 10.1103/physrevlett.130.016101*

SELECTED RESEARCH HIGHLIGHTS



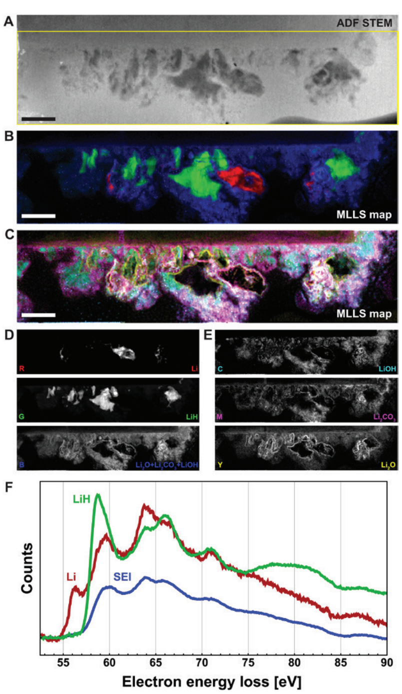
High-fidelity imaging of highly periodic structures enabled by vortex high harmonic beams

STROBE scientists solved a major imaging challenge by demonstrating high fidelity short wavelength imaging of highly-periodic structures for the first time, using engineered illumination via high harmonic extreme UV (EUV) beams carrying orbital angular momentum (OAM). This enables high-fidelity imaging and inspection of highly periodic structures for next-generation nano, energy and photonic devices.

Lensless imaging based on coherent diffractive imaging (CDI) enables near-perfect diffraction-limited microscopy at short wavelengths, overcoming the limits of imperfect and lossy optics. However, high fidelity imaging of highly periodic structures has been challenging. In CDI, a beam is scanned across a sample, and the scattered light is collected by a detector. A computer algorithm is then used to reconstruct an image of the sample. However, to retrieve high-fidelity images, the scatter patterns must change as the beam is scanned – which is not the case for highly periodic samples.

Graduate students Bin Wang and Nathan Brooks, working with Henry Kapteyn and Margaret Murnane, solved this long-standing challenge by using high harmonic beams carrying OAM. The high divergence and peak-intensity near their edges introduces strong interference fringes between adjacent diffraction orders in the far-field. These encode phase information into the scattered light as the beam is scanned, significantly enhancing diversity in the diffraction patterns so that the phase can be reliably retrieved. Moreover, defects in otherwise periodic grids can be more sensitively detected with improved signal-to-noise ratio > 100x, and with lower dose and sample damage than for scanning electron microscopy. Visible laser beams carrying OAM (i.e. donut-shaped) beams revolutionized visible super-resolution microscopy. Now there is a path forward for bringing these powerful capabilities to shorter wavelengths.

> *B. Wang, N. J. Brooks, P. Johnsen, N. W. Jenkins, Y. Esashi, I. Binnie, M. Tanksalvala, H. C. Kapteyn, M. M. Murnane, "High-fidelity ptychographic imaging of highly periodic structures enabled by vortex high harmonic beams," Optica, 10, 1245-1252, (2023). DOI: 10.1364/optica.498619*

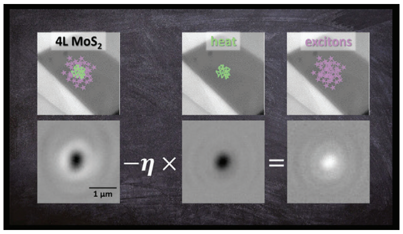


Operando Spectral Imaging of the Li-ion Battery's Solid-Electrolyte Interphase

Considering the scale of the lithium ion battery (LIB) industry, it is surprising how poorly the function of LIBs is understood at the molecular level. While much is certainly known, this knowledge has been gained via inference and expensive trial-and-error because it is difficult to look inside a functioning LIB to "see" what is going on. The battery is a bulk device with a liquid, air-sensitive organic electrolyte. With use, there forms on the LIB electrodes an almost magical solid-electrolyte interphase (SEI) that is an insulator for electrons but a conductor for Li+ ions. The main mysteries of LIB function involve the chemical composition and structure of this layer. We present the first images of the LIB SEI acquired under room-temperature operando conditions with high spatial and spectroscopic resolution. This combination gives us an unprecedented view of the SEI's development, where we can make chemical identifications localized to nanometer precision while the electrode is in the very act of intercalating. We image the bulk SEI, not just its surface, by contriving electrochemical fluid cells that are only 50 nm thick. With these thin cells we can map the Li itself by its unique spectroscopic fingerprint, an achievement described as "practically impossible" just a few years ago.

> *J. J. Lodico, M. Mecklenburg, H. Chan, Y. Chen, X. Ling, B. C. Regan, "Operando spectral imaging of the lithium ion battery's solid-electrolyte interphase," Science Advances, 9, (2023). DOI: 10.1126/sciadv.adg5135*

SELECTED RESEARCH HIGHLIGHTS

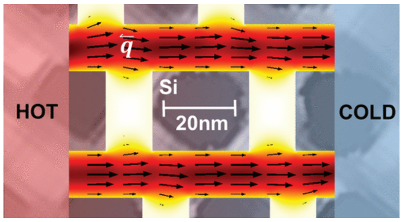


Detecting, distinguishing, and spatiotemporally tracking photogenerated charge and heat at the nanoscale

Since dissipative processes are ubiquitous in semiconductors, characterizing how electronic and thermal energy transduce and transport at the nanoscale is vital for understanding and leveraging their fundamental properties. For example, in low-dimensional transition metal dichalcogenides (TMDCs), excess heat generation upon photoexcitation is difficult to avoid since even with modest injected exciton densities, exciton-exciton annihilation still occurs. Both heat and photoexcited electronic species imprint transient changes in the optical response of a semiconductor, yet the distinct signatures of each are difficult to disentangle in typical spectra due to overlapping resonances. In response, it is necessary to simultaneously map both heat and charge populations in materials on relevant nanometer and picosecond length- and time scales.

By further honing stroboSCAT, a time-resolved optical scattering microscopy capable of capturing spatiotemporal energy flow in a wide range of materials, a STROBE team from UC Berkeley collaborated with Caltech to map both heat and exciton populations in few-layer TMDC MoS2 on the relevant length- and time scales and with 100-mK temperature sensitivity. We discern excitonic contributions to the signal from heat by combining observations close to and far from exciton resonances, characterizing photoinduced dynamics for each. Our approach is general and can be applied to any electronic material, including thermoelectrics, where heat and electronic observables spatially interplay, and lays the groundwork for direct and quantitative discernment of different types of coexisting energy without recourse to complex models or underlying assumptions. This work illustrates the ability to, finally, simultaneously observe and distinguish photogenerated heat from charge in a broad range of systems critical to the performance of next-generation energy conversion modules.

> *H. L. Weaver, C. M. Went, J. Wong, D. Jasrasaria, E. Rabani, H. A. Atwater, N. S. Ginsberg, "Detecting, Distinguishing, and Spatiotemporally Tracking Photogenerated Charge and Heat at the Nanoscale," ACS Nano, 17, 19011-19021, (2023). DOI: 10.1021/acsnano.3c04607*

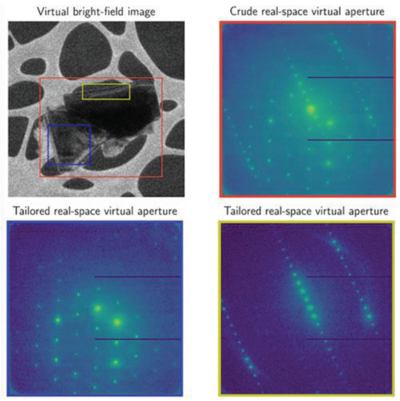


Predicting heat flow in 3D semiconductor nanosystems

Nanostructuring on length scales corresponding to phonon mean free paths provides control over heat flow in semiconductors and makes it possible, in principle, to engineer their thermal properties. However, this is currently not feasible because there is no general description for heat flow in 3D nanostructured semiconductors. In recent research, STROBE scientists used short wavelength extreme ultraviolet beams to study heat transport in a silicon metalattice with deep nanoscale features. They observed dramatically reduced thermal conductivity relative to bulk—about x50 times less than current model predictions. To explain this, they developed a new predictive theory that incorporates the idea that heat-carrying lattice vibrations can behave like a fluid—spreading out instead of just moving ballistically in straight lines. Moreover, this new theory of heat transport can be used to predict and engineer phonon transport in many other 3D nanosystems including nanowires and nanomeshes, that are of great interest for next-generation energy-efficient devices.

> *McBennett, A. Beardo, E. Nelson, B. Abad, T. Frazer, A. Adak, B. Li, H. Kapteyn, M. Murnane, J. Knobloch, "Universal Behavior of Highly Confined Heat Flow in Semiconductor Nanosystems: From Nanomeshes to Metalattices," Nano Letters 23, 2129 (2023).*

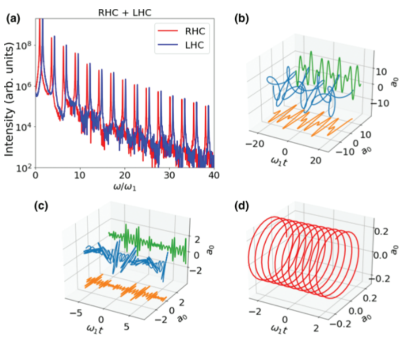
SELECTED RESEARCH HIGHLIGHTS



Ab initio structures from nanocrystal molecular lattices

Electron diffraction has dramatically increased in popularity amongst chemists given its renewed application for ab initio structure determination from molecular nanocrystals. In one implementation, popularly referred to as 3D ED or MicroED, crystals nanocrystals orders of magnitude too small for conventional X-ray analysis are interrogated by an electron beam to determine atomic structures. However, these approaches are thwarted by disordered, overlapping, or otherwise poorly diffracting domains. Spatially resolved diffraction mapping techniques can overcome some of these limitations, and have seen limited application in X-ray diffraction. In electron microscopy, such approaches, including 4D scanning electron microscopy (4D-STEM), have grown popular. We demonstrated that 4D-STEM can be used to determine ab initio structures of molecules by direct methods, from small ordered nanodomains of single microcrystals. In our approach 4D-STEM is used to generate diffraction scans that enable ex post facto reconstruction of digitally defined virtual apertures. The synthetic patterns derived from these scans are suitable for direct methods phasing of molecular structures. In addition, this approach unveils that coherently diffracting zones (CDZs) in molecular crystals form unpredictably distributed striations. The observation of these zones and our ability to determine structures from these regions of nanocrystals empowers us to explore their atomic substructure and their response to radiolytic damage.

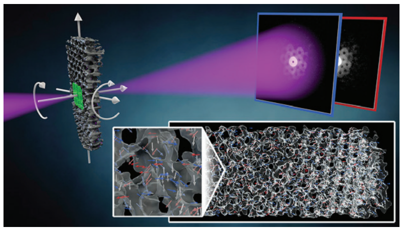
> *A. Saha, A. Pattison, M. Mecklenburg, A. Brewster, P. Ercius, J. Rodriguez, "Beyond MicroED: Ab Initio Structure Elucidation using 4D-STEM," Microscopy and Microanalysis, 29, 309-310, (2023). DOI: 10.1093/micmic/ozad067.143*



Two-color high-harmonic generation from relativistic plasma mirrors

Circularly polarized x-rays have a number of microscopy applications that leverage the rotational nature of some physical systems, one of the most common applications being magnetic dichroism of nanoscale magnetic devices. Generating circularly polarized x-rays, particularly coherent x-rays with ultrafast pulse durations is practically difficult and inefficient. One of the major successes of STROBE was the development of not just one, but two mechanisms for generating circularly polarized x-rays using light at moderate intensities in the strong field regime. In this work, we lay the foundation for scaling analogous mechanisms into the relativistic regime. In this regime, the energy cutoff can be much higher than in the strong field. Performing numerical simulations, we confirm that despite the physical mechanism being completely different at relativistic intensities, the same conservation laws observed in the earlier STROBE work are still valid in the relativistic regime. Experiments are being planned to demonstrate this mechanism in the lab, which can leverage new facilities such as the NSF ZEUS which would enable high single shot flux in dichroism experiments.

> *N. F. Beier, F. F. Dollar, "Two-color high-harmonic generation from relativistic plasma mirrors," Physical Review E, 108, 015201, (2023). DOI: 10.1103/physreve.108.015201*



The Swirling Spins of Hedgehogs

Though microscopes have been in use for centuries, there is still much that we cannot see at the smallest length scales. Current microscopies range from the simple optical microscopes used in high school science classes, to x-ray microscopes that can image through visibly-opaque objects, to electron microscopes that use electrons instead of light to capture images of vaccines and viruses. However, there is a great need to see beyond the static structure of an object—to be able capture how a nano- or biosystem functions in real time, or to visualize magnetic fields on nanometer scales. A team of researchers from the STROBE Center have been working together to overcome these challenges. STROBE is an NSF Science and Technology Center that is building the microscopes of tomorrow. A large multidisciplinary team from the Miao and Osher groups from UCLA, the Kapteyn-Murnane group at CU Boulder, Ezio Iacocca from CU Colorado Springs, David Shapiro and collaborators at Lawrence Berkley National Laboratory, and the Badding and Crespi groups from Pennsylvania State University. They developed and implemented a new method to use x-ray beams to capture the 3D magnetic texture in a material with very high 10-nanometer spatial resolution for the first time (published in Nature Nanotechnology, see reference below).

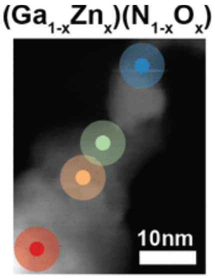
Hedgehogs and Anti-Hedgehogs

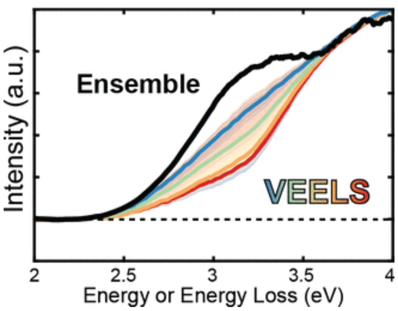
The team investigated a nanostructured magnetic sample, consisting of tiny spheres of nickel, only ~30nm across, connected together by slender few-nm "necks" of nickel, that together form a structure called a magnetic metalattice. This complex nanostructured magnet is expected to produce swirling magnetic fields with topological spin textures that are far more complex than in a uniform magnet. These are called 3D topological magnetic monopoles – or hedgehogs, due to their spiny shape in magnetic rotation – if the magnetic field points outward. Conversely, they can be thought of anti-hedgehogs if the magnetic field points inward. However, until recently, there was no experimental method to measure the 3D spin texture at the deep nanoscale. Using advanced algorithms to recover the image, and a microscope at the x-ray synchrotron light source at the Lawrence Berkley National Laboratory, the researchers overcame these challenges.

Imaging spin textures is extremely important, as it can help physicists to better understand magnetism at a fundamental level, and to design more energy-efficient data storage, memory, and nanodevices. Using electron microscopy, one can capture beautiful 2D images of a static spin-texture, but it is challenging to capture a full 3D image. In the past, other scientists were able to capture a 3D image at a spatial resolution of about 100 nanometers, but they had to make assumptions about the sample to extract the 3D image. With this new technique, researchers do not have to make any assumptions.

Armed with this new visualization technique, the team of researchers is excited to study spin textures further. STROBE is developing tabletop setups and helping with national facilities that can capture the static and dynamic spin texture in materials. All algorithms developed for this data analysis will be open-sourced soon. In this experiment, as with others, they found that collaboration is key for moving scientific progress forward.

A. Rana, C. Liao, E. Iacocca, J. Zou, M. Pham, X. Lu, E. Subramanian, Y. Lo, S. A. Ryan, C. S. Bevis, R. M. Karl, A. J. Glaid, J. Rable, P. Mahale, J. Hirst, T. Ostler, W. Liu, C. M. O'Leary, Y. Yu, K. Bustillo, H. Ohldag, D. A. Shapiro, S. Yazdi, T. E. Mallouk, S. J. Osher, H. C. Kapteyn, V. H. Crespi, J. V. Badding, Y. Tserkovnyak, M. M. Murnane, J. Miao, ""Three-dimensional topological magnetic monopoles and their interactions in a ferromagnetic meta-lattice," Nature Nanotechnology, (2023). DOI: 10.1038/s41565-022-01311-0

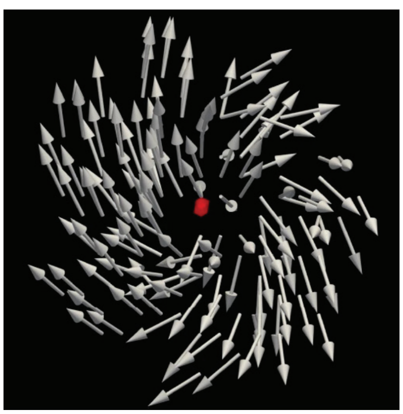


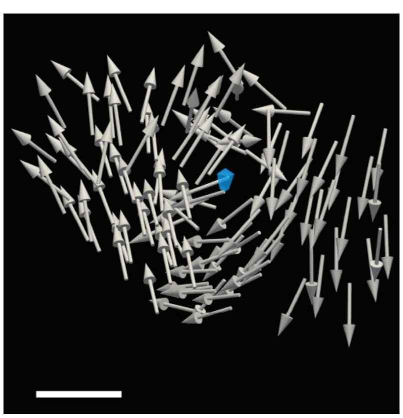


Relationships between Compositional Heterogeneity and Electronic Spectra of (Ga1–xZnx)(N1–xOx) Nanocrystals Revealed by Valence Electron Energy Loss Spectroscopy

Many ternary and quaternary semiconductors have been made in nanocrystalline forms for a variety of applications, but we have little understanding of how well their ensemble properties reflect the properties of individual nanocrystals. STROBE researchers at CU Boulder examined electronic structure heterogeneities in nanocrystals of (Ga1–xZnx)(N1–xOx), a semiconductor that splits water under visible illumination. They used valence electron energy loss spectroscopy (VEELS) in a scanning transmission electron microscope to map out electronic spectra of (Ga1–xZnx)(N1–xOx) nanocrystals with a spatial resolution of 8 nm. They examine three samples with varying degrees of intraparticle and interparticle compositional heterogeneity and ensemble optical spectra that range from a single band gap in the visible to two band gaps, one in the visible and one in the UV. The VEELS spectra resemble the ensemble absorption spectra for a sample with a homogeneous elemental distribution and a single band gap and, more interestingly, one with intraparticle compositional heterogeneity and two band gaps. They observe spatial variation in VEELS spectra only with significant interparticle compositional heterogeneity. Hence, they reveal the conditions under which the ensemble spectra reveal the optical properties of individual (Ga1–xZnx)(N1–xOx) particles. More broadly, they illustrate how VEELS can be used to probe electronic heterogeneities in compositionally complex nanoscale semiconductors.

> *B. F. Hammel, L. G. Hall, L. M. Pellows, O. M. Pearce, P. Tongying, S. Yazdi, G. Dukovic, "Relationships between Compositional Heterogeneity and Electronic Spectra of (Ga1-xZnX)(N1-xOX) Nanocrystals Revealed by Valence Electron Energy Loss Spectroscopy," The Journal of Physical Chemistry C, 127, 7762-7771, (2023). DOI: 10.1021/acs.jpcc.3c00572*





Three-dimensional topological magnetic monopoles and their interactions in a ferromagnetic meta-lattice

Topological magnetic monopoles (TMMs), also known as hedgehogs or Bloch points, are three-dimensional (3D) nonlocal spin textures that are robust to thermal and quantum fluctuations due to their topology. Understanding their properties is of fundamental interest and practical applications. However, it has been difficult to directly observe the 3D magnetization vector field of TMMs and probe their interactions at the nanoscale. Now, a STROBE team from UCLA, CU Boulder, UC Berkeley and LBNL collaborated with the Penn State MRSEC reports the creation of 138 stable TMMs at the specific sites of a ferromagnetic meta-lattice at room temperature. They developed 3D soft x-ray vector ptychography to determine the magnetization vector and emergent magnetic field of the TMMs with a 3D spatial resolution of 10 nm. This spatial resolution is comparable to the magnetic exchange length of transition metals, enabling them to probe monopole-monopole interactions. The team found that the TMM and anti-TMM pairs are separated by 18.3±1.6 nm, while the TMM and TMM, anti-TMM and anti-TMM pairs are stabilized at comparatively longer distances of 36.1±2.4 nm and 43.1±2.0 nm, respectively. They also observed virtual TMMs created by magnetic voids in the meta-lattice. This work demonstrates that ferromagnetic meta-lattices could be used as a new platform to create and investigate the interactions and dynamics of TMMs. Furthermore, it is expected that soft x-ray vector ptychography can be broadly applied to quantitatively image 3D vector fields in magnetic and anisotropic materials at the nanoscale.

> *A. Rana, C. Liao, E. Iacocca, J. Zou, M. Pham, X. Lu, E. Subramanian, Y. Lo, S. A. Ryan, C. S. Bevis, R. M. Karl, A. J. Glaid, J. Rable, P. Mahale, J. Hirst, T. Ostler, W. Liu, C. M. O'Leary, Y. Yu, K. Bustillo, H. Ohldag, D. A. Shapiro, S. Yazdi, T. E. Mallouk, S. J. Osher, H. C. Kapteyn, V. H. Crespi, J. V. Badding, Y. Tserkovnyak, M. M. Murnane, J. Miao, "Three-dimensional topological magnetic monopoles and their interactions in a ferromagnetic meta-lattice," Nature Nanotechnology, 18, 227-232, (2023). DOI: 10.1038/s41565-022-01311-0*

STROBE AND PEAQS ACTIVITIES

DECEMBER STROBE External Advisory Board Meeting

STROBE Research Advances Seminar Presents Prof. Rafael Piestun, University of Colorado Boulder

STROBE Research Advances Seminar Presents Dr. Henry Pinkard, Waller Group, UC Berkeley

2024

JANUARY STROBE Annual Retreat at UCLA

FEBRUARY STROBE & PEAQS 2024 Summer Undergraduate Research Program Applications Due

ONGOING Hosting visits and collaborations from industry, academe and national laboratories, STROBE seminars

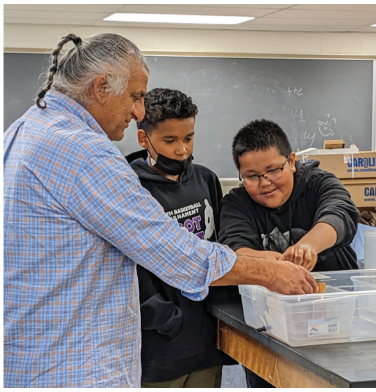
PROFESSIONAL DEVELOPMENT OPPORTUNITIES

STROBE offers a wide range of professional development workshops and trainings to participants at all nodes. Watch for emails about the programs listed below!

- Mentoring Training (curriculum developed by CIMER)
- Project Management (co-developed with IIL)
- Programming in Python and version control (curriculum developed by Software Carpentries)
- Social Intelligence (offered in partnership with CU Boulder Human Resources)
- Interviewing
- Resume writing (and other common job and school application documents)
- Networking

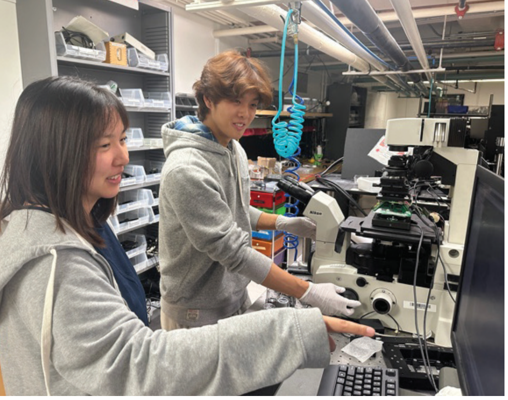
STROBE OUTREACH UPDATE

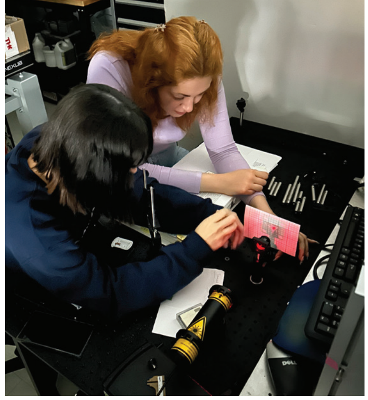
Every year, STROBE collaborates with CU Science Discovery and the teachers in the Four Corners region to develop hands on activities for middle school students. In spring 2023, the activities focused on "Water in the West". STROBE, Science Discovery, and PEAQS undergraduates from Fort Lewis College implemented these workshops in May 2023 for students from middle schools around the Four Corners region, including Tse Bit Tai Middle School on the Navajo Nation and Ignacio Middle School on the Southern Ute reservation. Students learned about how different types of concrete and materials impact water absorption into the land, how clouds form and what causes rain, and how we can use solar energy, water, and gravity to create a renewable hydro-pump energy storage system to power our cities during the day and night. The hydro-pump activity was such a hit with students and teachers, that STROBE Director of Outreach and Broadening Participation and Director of Education, Drs. Sarah Schreiner and Ellen Keister, built 25 hydro-pump boards to provide all teachers with a classroom kit to continue that workshop into their curriculum for years to come.



STROBE ACROSS THE NATION: COLLABORATIVE EXCHANGES

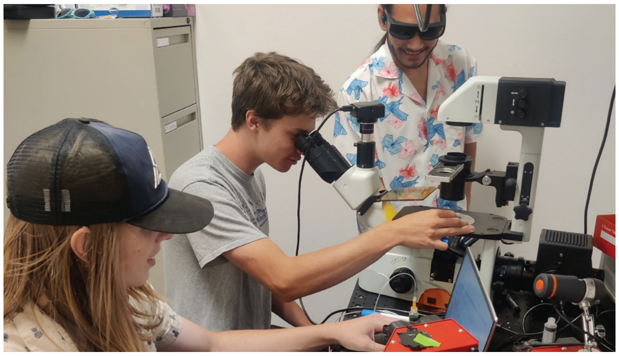
STROBE and PEAQS continued to strengthen cross-node connections as well as participant professional development via in-person visits and workshops this fall. Drs. Sarah Schreiner and Ellen Keister visited Fort Lewis College, Norfolk State University, and Florida International University to offer workshops including financial literacy, applying to summer research programs, and programming in Python, as well as to connect individually with faculty and students. Additionally, Drs. Schreiner and Keister visited the NSF Center for Integration of Modern Optoelectronic Materials on Demand (IMOD) at the University of Washington Seattle. They met with IMOD faculty, staff, students, and labs to build community with the goal of expanding undergraduate research opportunities for the STROBE and PEAQS students.





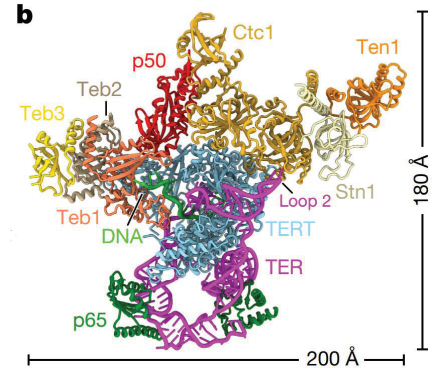
2023 SUMMER UNDERGRADUATE RESEARCH SCHOLARS

STROBE and PEAQS welcomed 36 undergraduate research scholars into our laboratories during the summer of 2023 to work on exciting imaging science research projects with graduate student, postdoc, and faculty mentors. Through projects such as designing circuit boards for advanced laser systems, etching silicon for use as a membrane in biological systems, and learning about the quantum properties of water within crystalline structures, students received hands-on technical training in research. They also participated in professional development training to complement their research experience, including workshops on how to present talks and posters, preparing for interviews, and building professional networks. Each student prepared a presentation about their project, including a project summary, current research challenges, and contextualizing their project within the field. Thank you to Drs. Ellen Keister and Sarah Schreiner for organizing and implementing this program, and all of the graduate students, postdoc, and faculty mentors and program staff for all of your work with the outstanding 2023 undergraduate student cohort.



THE 2023 PREM RESEARCH SCHOLARS SYMPOSIUM: PEAQS AND STROBE UNDERGRADUATE STUDENTS SHINE AT MRS

Each year, NSF supports a symposium at the Materials Research Society (MRS) conference to welcome undergraduate students from NSF PREM (Partnership for Research and Education in Materials) programs to the materials science community. Dr. Sarah Schreiner collaborated with a team of NSF and PREM faculty members to develop and organize the MRS PREM Research Scholars Symposium at the 2023 MRS Spring Meeting in San Francisco. This symposium hosted almost 100 undergraduate PREM Research Scholars from around the United States for two days (see photo). Scholars participated in professional development and networking activities, and the symposium ended with a poster session for all participants to share their materials research projects with the community. Dr. Schreiner offered two workshops at the symposium on *Networking at Conferences* and *Turning Your Science into a Story*. The STROBE-PREM partnership, called PEAQS, supported 10 students from Fort Lewis College and Norfolk State University at the symposium.



STROBE PUBLICATIONS | JANUARY 2023 – DECEMBER 2023

Relativistic ultrafast electron diffraction at high repetition rates
K. M. Siddiqui, D. B. Durham, F. Cropp, F. Ji, S. Paiagua, C. Ophus, N. C. Andresen, L. Jin, J. Wu, S. Wang, X. Zhang, W. You, M. M. Murnane, M. Centurion, X. Wang, D. S. Slaughter, R. A. Kaindl, P. Musumeci, A. M. Minor, D. Filippetto, Structural Dynamics, **10**, 064302, (2023).

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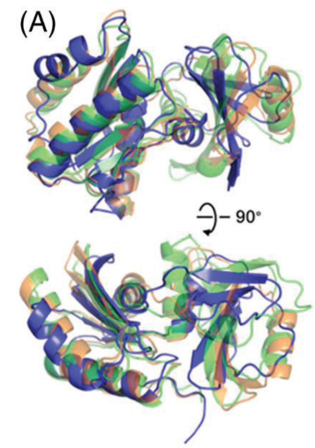

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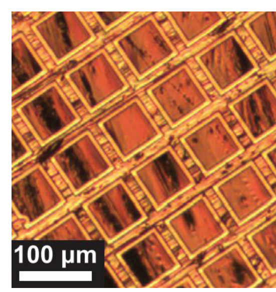

Imaging the electron charge density in monolayer MoS_2 at the Ångstrom scale
J. Martis, S. Susarla, A. Rayabharam, C. Su, T. Paule, P. Pelz, C. Huff, X. Xu, H. Li, M. Jaikissoon, V. Chen, E. Pop, K. Saraswat, A. Zettl, N. R. Aluru, R. Ramesh, P. Ercius, A. Majumdar, Nature Communications, **14**, 4363, (2023).

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Two-color high-harmonic generation from relativistic plasma mirrors
N. F. Beier, F. F. Dollar, Physical Review E, **108**, 015201, (2023).

Structural basis of gRNA stabilization and mRNA recognition in trypanosomal RNA editing
S. Liu, H. Wang, X. Li, F. Zhang, J. J. Lee, Z. Li, C. Yu, J. J. Hu, X. Zhao, T. Suematsu, A. L. Alvarez-Cabrera, Q. Liu, L. Zhang, L. Huang, I. Aphasizheva, R. Aphasizhev, Z. Hong Zhou, Science, **381**, eadg4725, (2023).

STROBE PUBLICATIONS | JANUARY 2023 – DECEMBER 2023

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Structure of LARP7 Protein p65–telomerase RNA Complex in Telomerase Revealed by Cryo-EM and NMR
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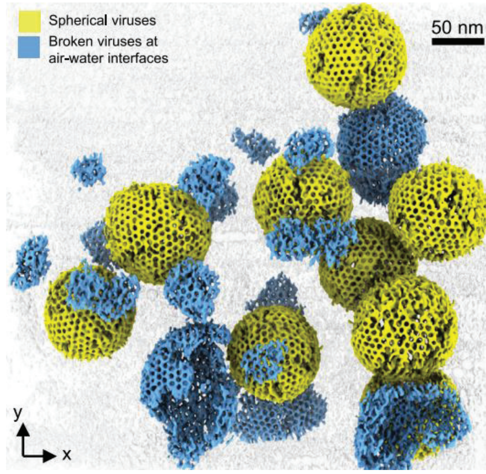

Coronal Heating as Determined by the Solar Flare Frequency Distribution Obtained by Aggregating Case Studies
Y. Wang, Y. He, Y. Wang, Y. Yang, M. Singh, C. D. Eichhorn, X. Cheng, Y. Jiang, Z. Hong Zhou, J. Feigon, The Astrophysical Journal, **948**, (2023).

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T. Carbin, X. Zhang, A. B. Culver, H. Zhao, A. Zong, R. Acharya, C. J. Abbamonte, R. Roy, G. Cao, A. Kogar, Physical Review Letters, **130**, 186902, (2023).

Nonadditive Interactions Unlock Small-Particle Mobility in Binary Colloidal Monolayers
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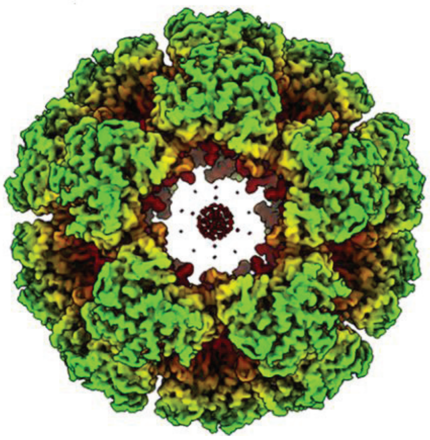
Relationships between Compositional Heterogeneity and Electronic Spectra of (Ga1-xZnX)(N1-xOX) Nanocrystals Revealed by Valence Electron Energy Loss Spectroscopy
B. F. Hammel, L. G. Hall, L. M. Pellows, O. M. Pearce, P. Tongying, S. Yazdi, G. Dukovic, The Journal of Physical Chemistry C, **127**, 7762–7771, (2023).



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Cryo-EM structure of amyloid fibril formed by α-synuclein hereditary A53E mutation reveals a distinct protofilament interface
C. Sun, K. Zhou, P. DePaola, W. Shin, T. Hillyer, M. R. Sawaya, R. Zhu, C. Peng, Z. Hong Zhou, L. Jiang, Journal of Biological Chemistry, **299**, 104566, (2023).

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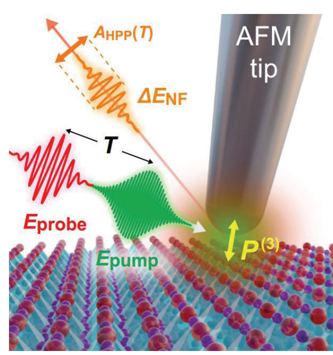

Operando Label-Free Optical Imaging of Solution-Phase Ion Transport and Electrochemistry
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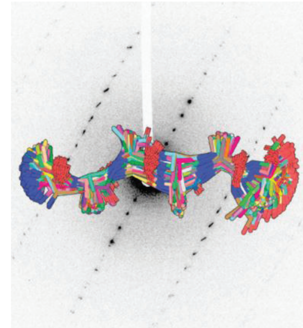

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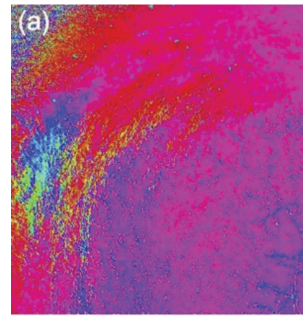

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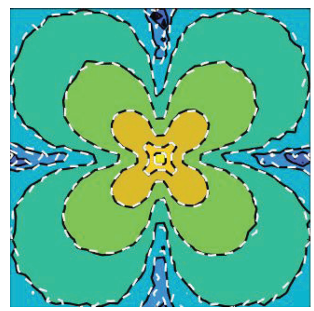

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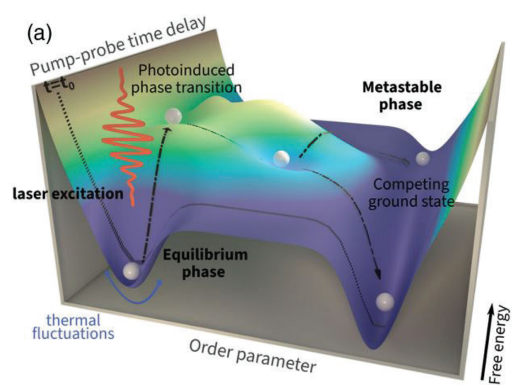

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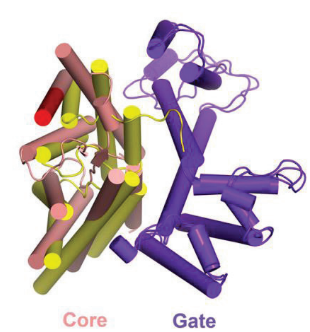

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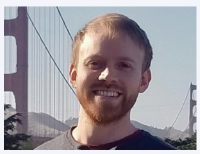

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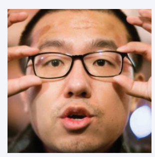

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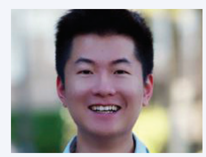

Chaoyi Zhu
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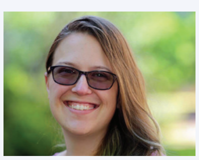
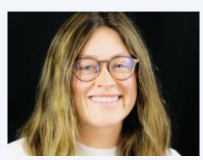


Emma Cating-Subramanian
TBD

Paul Denham
TBD



Kristen Parzuchowski
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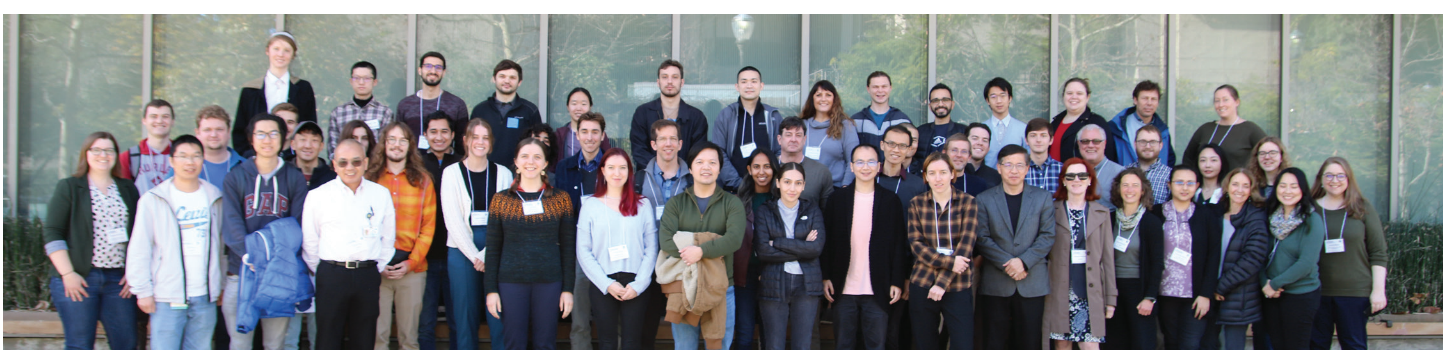

We look forward to seeing you in person soon!