Berkeley Physics

FALL 2024

Eos:
The Dawn of a New Era in Neutrino Detection

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Berkeley Physics

ON THE COVER:
Associate Professor Gabriel Orebi Gann works on the Eos neutrino experiment with Assistant Project Scientist Leon Pickard

BACK COVER:
Students holding a 3D model of the campanile printed in the Student Machine Shop

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From the Chair

Our community at Berkeley Physics continues to flourish, in the laboratory and beyond 94720. This year we are delighted to report on the commissioning of a trailblazing neutrino detection effort led by Berkeley Professor Gabriel Orebbi-Gann. Eos–much like the namesake Titan goddess–signals the dawn of a new class of detection hardware that leverages both scintillation and Cherenkov radiation signatures. Featured in this issue, also on the theme of probing the most basic constituents of our universe, are experimental results obtained by the ALPHA team at CERN on an experiment proposed about a decade ago by Professors Joel Fajans and Jonathan Wurtele to test if antimatter would fall or levitate in our gravitational field. Spoiler alert: it falls!

Speaking of gravity, the grabbiest of objects might be loosening its grip...a bit–new calculations show that small islands in a black hole may protrude a (really) tiny bit out of the surface. The time may have arrived for experimentalists to go measure them! Nature does seem to be in the sharing mood, as Berkeley graduate student Claire Gasque recently proposed a mechanism for different types of Aurorae (dubbed Steve and picket fence) that to the untrained eye appear similar to the iconic Northern Lights but appear much further south on Earth. The team, including rocket scientists at SSL, have a model where these lights may not be caused by magnetic activity but rather by electric fields.

These vignettes only capture a tiny glimpse of the ongoing activities in the Department. We are excited to share the news of five new professors who are joining our faculty and will no doubt enrich our Physics family in so many ways. Meet three of them on page 13. Growth is also palpable in our teaching programs with new cohorts of BPIE students walking our halls, Beta physics thriving, and Reyes expanding its teaching activities. Our undergraduates will now also have a new space, the Physics Innovation Laboratory (PIL), where they can prototype their ideas in a cutting-edge design studio.

With that, I extend my best wishes for our collective success in the 2024-2025 academic year, on the scientific frontier, in our new initiative to improve upon our pedagogy, and our lasting commitment to inclusivity.

Irfan Siddiqi, Chair

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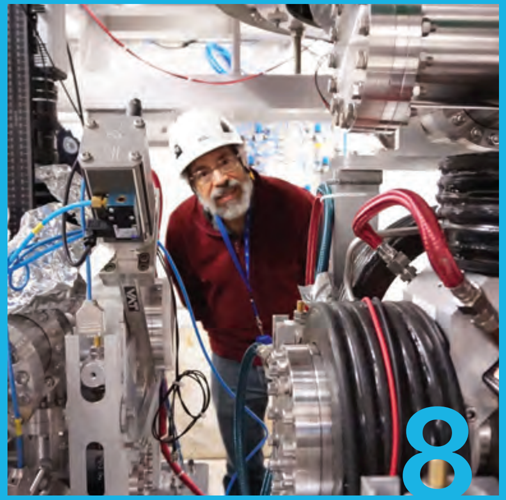

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EOS

The Dawn of a New Era of Neutrino Detection

View from the bottom of the Eos detector. The cylindrical inner vessel is surrounded by 168 ultra-fast photomultiplier tubes (PMTs), with dozens more above and below it–including 12 dichroicons below used to sort detected lightly by wavelength.

PHOTO: THOR SWIFT / BERKELEY LAB

Berkeley-led prototype detector evaluates hybrid technologies for the next generation of neutrino physics and applications

The bright yellow forklift crept forward, gracefully maneuvering the 20-ton steel tank through the entrance of Etcheverry Hall's basement with only two millimeters to spare. Relying on the expertise of Berkeley Lab riggers, this tight squeeze was by design to maximize the size of the outer vessel of the Eos experiment.

"Named for the Titan goddess of dawn, Eos represents the dawn of a new era of neutrino detection technology," says Gabriel Orebi Gann, a Berkeley Physics associate professor, Berkeley Lab faculty scientist, and the leader of Eos, an international collaboration of 24 institutions jointly led by UC Berkeley Physics and Berkeley Lab Nuclear Science.

Neutrinos are abundant, neutral, almost massless subatomic "ghost particles" created whenever atomic nuclei come together or break apart, including during fusion reactions at the core of the Sun and fission reactions inside nuclear reactors on Earth. Neutrinos are difficult to detect because they rarely interact with matter—about 100 trillion neutrinos harmlessly pass through the Earth and our bodies every second as if we don't exist.

Berkeley researchers are using Eos as a testbed to explore advanced, hybrid technologies for detecting these mysterious particles.

"While at Berkeley, we're characterizing the response of the detector using deployable optical and radioactive sources to understand how well our technologies are performing. And we're developing detailed simulations of our detector performance to make sure they agree with the data," says Berkeley Physics Postdoctoral Fellow Tanner Kaptanoglu. "Once we complete this validation, we hope to move Eos to a neutrino source for further testing."

Ultimately, the team hopes to use their experimental results and simulations to design a much larger version of Eos—named after the Titan goddess Theia, mother of Eos—to realize an astonishing breadth of nuclear physics, high energy physics, and astrophysics research.

The Eos collaboration is also investigating whether these technologies could someday detect nuclear security threats, in partnership with the funding sponsor, National Nuclear Security Administration.

"One nonproliferation application is using the absence of a neutrino signature to demonstrate that stockpile verification experiments are not nuclear," says Orebi Gann. "A second application is verifying that nuclear-powered marine vessels are operating correctly."

Unique, hybrid neutrino detector

Like a nesting doll, Eos comprises several detector layers. The inner layer is a 4-ton acrylic tank, filled in stages during testing with air, then deionized water, and finally a water-based liquid scintillator (WbLS).

The barrel of this inner vessel is surrounded by 168 fast, high-performance, 8-inch photomultiplier tubes (PMTs) with electromagnetic shielding. Attached above the vessel are two dozen 12-inch PMTs. And attached below it are three dozen 8-inch "front-row" PMTs, with another dozen 10-inch PMTs below them.

In January, this detector assembly was gently lowered inside the 20-ton steel outer vessel, with Berkeley Physics Assistant Project Scientist Leon Pickard operating the crane as other team members anxiously watched.

Left: Dr. Leon Pickard, Eos Installation Manager, working on the reverse osmosis (RO) component of the fluid handling system. The RO system is one step in a multi-stage purification process for the water that fills the inner acrylic vessel.

Right: Dr. Tanner Kaptanoglu, Eos Commissioning Manager, viewing triggers from the detector on an oscilloscope.

PHOTO: ELENA ZUKHOVA

"The big lift this was nerve-wracking. More than a year's worth of work, dedication, and time from lots of people and then I was lifting it all together into the outer tank," describes Pickard. "I knew the Berkeley Lab riggers taught me well so I was confident, excited, and definitely nervous."

The buffer region between the acrylic and steel vessels is filled with water, submerging the PMTs. The outermost Eos layer is a muon tracker system consisting of solid scintillator paddles with PMTs.

By combining several novel detector technologies, Eos measures both Cherenkov radiation and scintillation light simultaneously. Its main challenge is to separate the faint Cherenkov signal from the overwhelming scintillation signal.

When neutrinos pass through Eos, one very occasionally interacts with the detector's water or scintillator, transferring its energy to a charged particle. This charged particle then travels through the medium, emitting light that is detected by the PMTs.

When the charged particle travels faster than the speed of light in the medium, it creates a photonic boom—similar to the sonic boom created by a plane traveling faster than the speed of sound. This cone of Cherenkov light travels in the direction of the charged particle, making a ring-like image that is detected by the PMTs. In contrast, the scintillation light emits equally in all directions. Reconstructing the pattern of PMT hits helps distinguish between the two signals.

In addition to topological differences, Cherenkov radiation is emitted almost instantaneously in a picosecond burst, whereas scintillation light lasts for nanoseconds. The PMTs detect this time difference.

Finally, the observable Cherenkov radiation has a longer, redder wavelength spectra than the bluer scintillation light, which inspired the creation of dichroic photosensors that sort photons by wavelength. These dichroicons consist of an 8-inch PMT with a long-pass optical filter above the bulb and a crown of short-pass filters surrounding it. A dozen of the 8-inch, front-row PMTs attached to the bottom of the inner vessel are dichroicons. The concept for these novel photosensors was developed under the leadership of Eos collaborator Professor Joshua Klein, with Kaptanoglu playing a central role as part of his PhD thesis at the University of Pennsylvania.

If the light's wavelength is above a certain threshold, a dichroicon guides Cherenkov light onto the central PMT. If the light is below that threshold, it passes through and is detected by the 10-inch, back-row PMTs.

"You effectively guide the Cherenkov light to specific PMTs and the scintillation light to other PMTs without losing light," says Orebi Gann. "This gives us an additional way to separate Cherenkov and scintillation light."

Another unique thing about Eos is its location.

"Although Eos is a Berkeley Physics project, the Nuclear Engineering department let us work in their space in the Etcheverry basement," says Orebi Gann. "It's unusual to work across departmental boundaries in this way. It's a sign of how great and supportive Nuclear Engineering has been."

> "We played a huge game of Tetris to get the detector put together."

Team work

Delivering the outer vessel into the building wasn't the only tight squeeze—the Eos installation was temporally and physically tight.

Neutrino experiments often struggle to get their steel tanks manufactured, so everyone was excited last June when the tank headed towards Berkeley. Unfortunately, Orebi Gann received an email the next morning saying the tank was destroyed in a non-injury accident when the truck collided with an overpass in Saint Louis. After immediately calling her sponsor with the bad news, she mobilized.

"I started sweating. They would have killed our three-year project if we had to wait for the insurance claim," says Orebi Gann. "Luckily, Berkeley Lab Nuclear Science Division Director Reiner Kruecken and others were really supportive, and we had enough contingency in the budget to buy another one. Within two weeks, we were under contract for a replacement. And the steel tank arrived three months later."

Despite this delay, the collaboration assembled the detector, acquired and analyzed the data, and finished developing the detector simulations during the last year of funding.

"That's the biggest setback you can have—your tank is crumpled. But with prudent planning, preparation, and scheduling agility, we were able to get right back on track," says Pickard, also the installation manager.

In addition to Orebi Gann, Pickard, and Kaptanoglu, the Berkeley Physics installation team included former Project Scientists Zara Bagdasarian, Morgan Askins, and Guang Yang, Junior Specialist Sawyer Kaplan, graduate students Max Smiley, Ed Callaghan, and Martina Hebert, and undergraduate students Joseph Koplowitz, Ashley Rincon, and Hong Joo Ryoo. They were assisted by Berkeley Lab Staff Scientist Richard Bonventre, Senior Scientific Engineer Associate Joe Wallig, mechanical engineer Joseph Saba, and machinist James Daniel Boldi.

Given the tight timeline and limited space, another installation challenge was where to put all the detector components. Eos collaborators across the country coordinated to bring everything in at just the right time, fully tested and ready to go for the build.

"Some of the deliveries stayed temporarily at Berkeley Lab. Gabriel let us use her office to store hundreds of PMTs for a while. And the Nuclear Science folks were phenomenally accommodating, allowing us to store muon paddles, PMTs, and other parts on the Etcheverry mezzanine," Pickard says. "We played a huge game of Tetris to get the detector put together."

Data acquisition and reconstruction

Once assembled, Eos acquired and analyzed data in three phases.

This March, it measured "first light" by flashing a blue LED into an optical fiber that points into the detector and then detecting this light with the PMTs. During initial tests, the inner vessel contained air while ensuring all the detector channels were working and the PMTs were measuring single photons.

Next, they filled the inner tank with optically-pure deionized water and took data using various radioactive sources, optical sources, a laser injection system, and cosmic muons to fully evaluate detector performance. During this phase, Eos operated as a water Cherenkov detector.

"In a water Cherenkov detector, you have only Cherenkov light so you can do a precise directional reconstruction of the event. This helps with particle identification at high energies and background discrimination at low energies," says Kaptanoglu, also the commissioning manager who helps identify the data needed. Among his other roles, he co-leads the simulations and analysis team with Marc Bergevin, a staff scientist at Lawrence Livermore National Lab.

PHOTO: ELENA ZUKHOVA

Lastly, the researchers turned Eos into a hybrid detector by injecting into the water a water-based liquid scintillator, which was supplied by Eos collaborator Minfang Yeh at Brookhaven National Laboratory. This allowed the team to explore the stability and neutrino detection capabilities of the novel scintillator. Adding WbLS improves energy and position reconstruction, but it makes event direction reconstruction difficult. A key goal was to show that Eos could still reconstruct the event direction with the WbLS—proving WbLS as a viable, effective, and impressive neutrino detection medium.

PHOTO: ELENA ZUKHOVA

Left (L to R): Associate Professor Gabriel Orebi Gann, Postdoctoral Fellow Tanner Kaptanoglu, Assistant Project Scientist Leon Pickard, Graduate Student Martina Hebert, MIT Undergraduate Emma Lynch, and R&D Engineer Sawyer Kaplan at the Eos experiment

Right: Schematic of a single dichroicon, showing the dichroic filters arranged in a conical form around the aperture PMT.

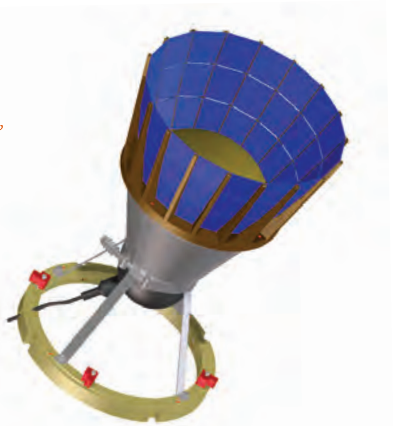


IMAGE: JOE WALLIG

"Our hybrid detector gives us the best of both worlds. We measure event directionality with the Cherenkov light, and we achieve excellent energy and position resolution and low detector thresholds using the scintillation light," says Kaptanoglu, "But by combining Cherenkov and scintillation, we get additional benefits. For example, we can better tell what type of particle is interacting in our detector—whether it's an electron, neutron, or gamma."

Eos data analysis combines traditional likelihood and machine learning algorithms to reconstruct events. These novel reconstruction algorithms simultaneously use the Cherenkov and scintillation light, finding a ring of PMTs hit by the Cherenkov light on top of the much larger isotropic scintillation light background. The team also compared the two methods to see if machine learning gave them any advantages.

> **"Our hybrid detector gives us the best of both worlds."**

"Our goal was to show that we can do this hybrid reconstruction and that we can simulate it well to match with the experimental data," says Kaptanoglu.

Their simulations entail microphysical modeling of every aspect of the Eos detector, characterizing in detail how the light is created, propagated, and detected. In addition to producing cool 3D renderings of the detector, Eos simulations will be used to help design future neutrino experiments.

"Our Monte Carlo simulations make predictions, and we compare those to our experimental data. That allows us to validate and improve the Monte Carlo simulations," say Orebi Gann. "We can use that improved Monte Carlo to predict performance in other scenarios. It's the step that allows us to go from the measurements we make at Berkeley to predicting how this technology would perform in different application scenarios."

Next steps

Although their three-year project recently completed, Orebi Gann has applied for another three years of funding to extend Eos testing at Berkeley.

If funded, the team plans to explore different WbLS cocktails and various photosensor parameters. They are also considering upgrading to custom electronics.

During the additional three years, the team would also devise a plan for moving Eos to a neutrino source if they get follow-on funding. A likely location is the Spallation Neutron Source at Oak Ridge National Laboratory. This facility basically smashes neutrons into a target to produce a huge number of neutrinos.

"Moving Eos to the Spallation Neutron Source would allow us to demonstrate that we can see neutrinos with this technology, in a regime where it's not as subject to the low energy backgrounds that make reactor neutrino or fission neutrino detection challenging. It's a step on the road," says Orebi Gann.

According to Orebi Gann, the next step after that would be to move Eos to a nuclear reactor to prove it can detect neutrino signals in an operational environment with all relevant backgrounds.

Theia fundamental physics

However, the ultimate plan is to use Eos experimental results and simulation models to guide how to design Theia-25 (or Theia-100), a massive hybrid neutrino detector with a 25-kiloton (or 100-kiloton) WbLS tank and tens of thousands of ultrafast photosensors.

Orebi Gann is a lead proponent of Theia, a Berkeley-led "experiment in the making." If funded, Theia will likely reside at the Deep Underground Neutrino Experiment (DUNE) located in an abandoned gold mine in South Dakota.

Theia has two potential areas of fundamental physics research. The first is understanding the neutrinos themselves.

"In particle physics, we don't know of any fundamental property that differentiates neutrinos from antineutrinos, so they could in fact be incarnations of the same particle," she explains. "Understanding their fundamental properties and how they differ could, for example, help explain how the Universe evolved, including offering insights into why it is dominated by matter."

The second area of fundamental physics research uses the very weakly interacting neutrinos to probe the world around us.

"A large WbLS detector would enable us to look at solar neutrinos, supernova neutrinos, geo-neutrinos naturally produced in the Earth, and a vast array of other measurements," says Orebi Gann. "For example, solar neutrinos would give us a real-time monitor of the Sun."

"What's interesting about Theia is the breadth of its program. I can go on for an hour about the physics of Theia," Orebi Gann adds. "I think Eos, and the other R&D technology demonstrators around the world, will allow us to realize something like Theia, which would have a rich program of world leading physics across nuclear physics, high energy physics, and astrophysics."

Research Highlights

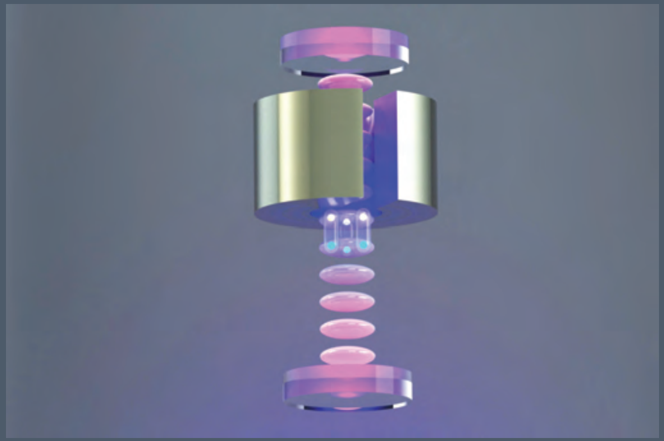


IMAGE: CRISTIAN PANDA/UC BERKELEY

Measuring Gravitational Attraction with Incredible Precision

Despite gravity being the dominant force on large scales, the quantum nature of gravity remains elusive. Now, Berkeley Physics Professor Holger Müller's group has built the most accurate instrument for measuring gravitational attraction between atoms and a small mass—enabling the search for deviations from Newtonian gravity due to quantum effects or hypothetical "fifth-force" dark energy.

This novel lattice atom interferometer exploits both the particle-like and wave-like properties of matter. Clouds of laser-cooled cesium atoms in a vacuum chamber are immobilized for up to 70 seconds using a vertical optical lattice, which passes through the center of a hollow tungsten cylinder. Each atom is then excited into a quantum superposition, where the atom exists as partial wave packets in two locations simultaneously. The wave packet closer to the tungsten experiences more gravitational pull, changing its phase. When the lattice is turned off, measuring the phase difference between the wave packets reveals their difference in gravitational attraction. The researchers made these precise measurements for atoms above and below the tungsten to reject systematic errors.

"Gravity pushes down the atoms with a force a billion times stronger than their attraction to the tungsten mass, but the restoring force from the optical lattice holds them, like a shelf," says Cristian Panda, a former postdoctoral fellow in Müller's lab. "We then split each atom into two wave packets, so now it's in a superposition of two heights. And then we take each of those two wave packets and load them in a separate lattice site, a separate shelf, so it looks like a cupboard. When we turn off the lattice, the wave packets recombine, and the quantum information acquired during the hold is read out."

Using improved laser systems and cooling with their optical lattice, the team achieved four times better accuracy than previous interferometry measurements that used "free-fall" atoms. Their results were consistent with Newtonian gravity and placed limits on dark energy candidate particles.

Above: Physicists at UC Berkeley split atoms into two wavepackets (split spheres) separated by microns that were then immobilized for many seconds in a vertical optical lattice (pink blobs). By recording the phase difference between the wavepackets that are closer and further to a tungsten mass (shiny cylinder), they were able to measure the weak gravitational attraction of the cylinder.

Right: Nothing escapes a black hole's immense gravity, but it may still be possible to detect what is going on in one.

Islands Protruding from Black Holes Are Key to Solving Paradox

Stephen Hawking showed a black hole constantly emits radiation that contains almost no information about its interior, causing the black hole to slowly evaporate. This suggests some information is irretrievably lost when the black hole dies. Theorists ever since have struggled to resolve the Hawking Information Paradox, which states information can neither be emitted from a black hole nor preserved inside it forever.

Based on Hawking's calculations, the radiation and black hole are quantum mechanically linked, and this entanglement keeps rising until the black hole evaporates with quantum information. But theorists later determined the entanglement peaks when the black hole is massive and then drops to zero—so information can escape.

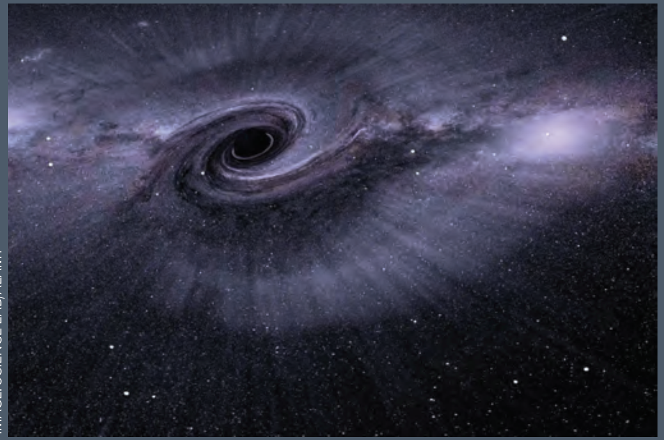


IMAGE: SCIENCE LAB/ALAMY

As part of this work, Berkeley Physics Assistant Professor Geoff Penington co-discovered "entanglement islands" sticking out of black holes, created when particles deep inside a black hole are reassigned to the radiation. Why this rearrangement occurs is a mystery, but entanglement islands may be the key to identifying how information escapes.

"Complementarity" theory hypothesizes information is stored in the black hole's surface while also passing inside, creating two copies of information representing different viewpoints that can't be simultaneously observed. "Firewall" theory hypothesizes everything falling into a black hole is incinerated by a physical firewall of energy surrounding an empty black hole, contradicting general relativity.

New research by Berkeley Physics Professor Raphael Bousso and Penington suggests entanglement islands protrude further than initially thought—as much as an atom beyond a black hole's surface.

"Getting a scientific instrument within an atom's width of a black hole horizon requires far more advanced technology than our current spaceships," says Bousso. "But in principle we can tell which theory is correct by experimentally probing a black hole from the outside. This was a huge surprise."

A Collegial (Dis)Agreement On Gravity

Antimatter laser physics apparatus (ALPHA) resolves a friendly dispute, changes students lives, too

It all began with a friendly argument. As is not uncommon in academic science, Berkeley Physics Professors Joel Fajans and Jonathan Wurtele have had differing perspectives on what could be done to measure antihydrogen gravity.

But by working together over many years, the colleagues—while maybe not always exactly in agreement with one another—have recently achieved pathbreaking experimental results documenting the effects of gravity on antimatter. Perhaps as important, they have been able to involve undergraduate and graduate students in hands-on experimental work at one of the world's premiere science facilities.

As for the science itself, most notably, they have shown conclusively that antihydrogen—an antiproton paired with an antielectron or positron—is pulled downward by gravity and not pushed upward.

Of their collaboration, "Jonathan and I have actually been working together most of our professional lives," says Fajans with a hint of good-natured humor. "It started out very well. He came to give a talk where I was a graduate student, and afterwards, I came up to him and said, 'You're wrong.' It turns out perhaps I was wrong—though I don't concede the point."

Fast forward to 2010. Fajans and Wurtele found themselves working together on the Antimatter Laser Physics Apparatus (ALPHA) at the European Center for Nuclear Research (CERN) in Geneva, Switzerland. They were figuring out how to trap antihydrogen atoms—an exceedingly complex task.

By 2012, they were starting to get a reasonable amount of data, Fajans says. "And so, Jonathan said we should do something about gravity, and he scribbled some formulas on a whiteboard. I said 'go away. We can't.' After six months of him bothering me every week, I finally decided to look at the problem just to get him off my back. And I realized that, in fact, we could do something about gravity." Still, it took another four or five years, they say, to convince the broader ALPHA collaboration to move ahead with the gravity experiments. (It is no small feat for researchers to gain time for experiments using the tools and equipment available at large science facilities, including CERN.)

What Fajans, Wurtele, and their nearly 50 collaborators—including undergraduate and graduate students—did was show that the gravitational acceleration of antimatter is close to that for normal matter on Earth: 1 g or 9.8 meters per second per second, or one standard deviation from normal gravity. That's significant because an opposite result—antimatter moving upward in defiance of gravity—would have been inconsistent with the weak equivalence principle (WEP) of Einstein's theory of general relativity.

The work was published last year in Nature.

The results of their painstaking experiments, says Fajans and Wurtele, were not surprising to most physicists, though that is not to understate their significance, either. The theory of general relativity treats all matter the same, meaning that matter and antimatter respond the same to gravitational forces. All normal matter, including protons, electrons, and neutrons, have antiparticles bearing the opposite electrical charge. When antiparticles encounter normal matter counterparts, they annihilate completely.

The alpha-g machine

Fajans and Wurtele note that antihydrogen's properties are measured in one of ALPHA's magnetic traps. In 2018, the team designed the so-called ALPHA-g machine, a vertically oriented magnetic trap to study gravitation.

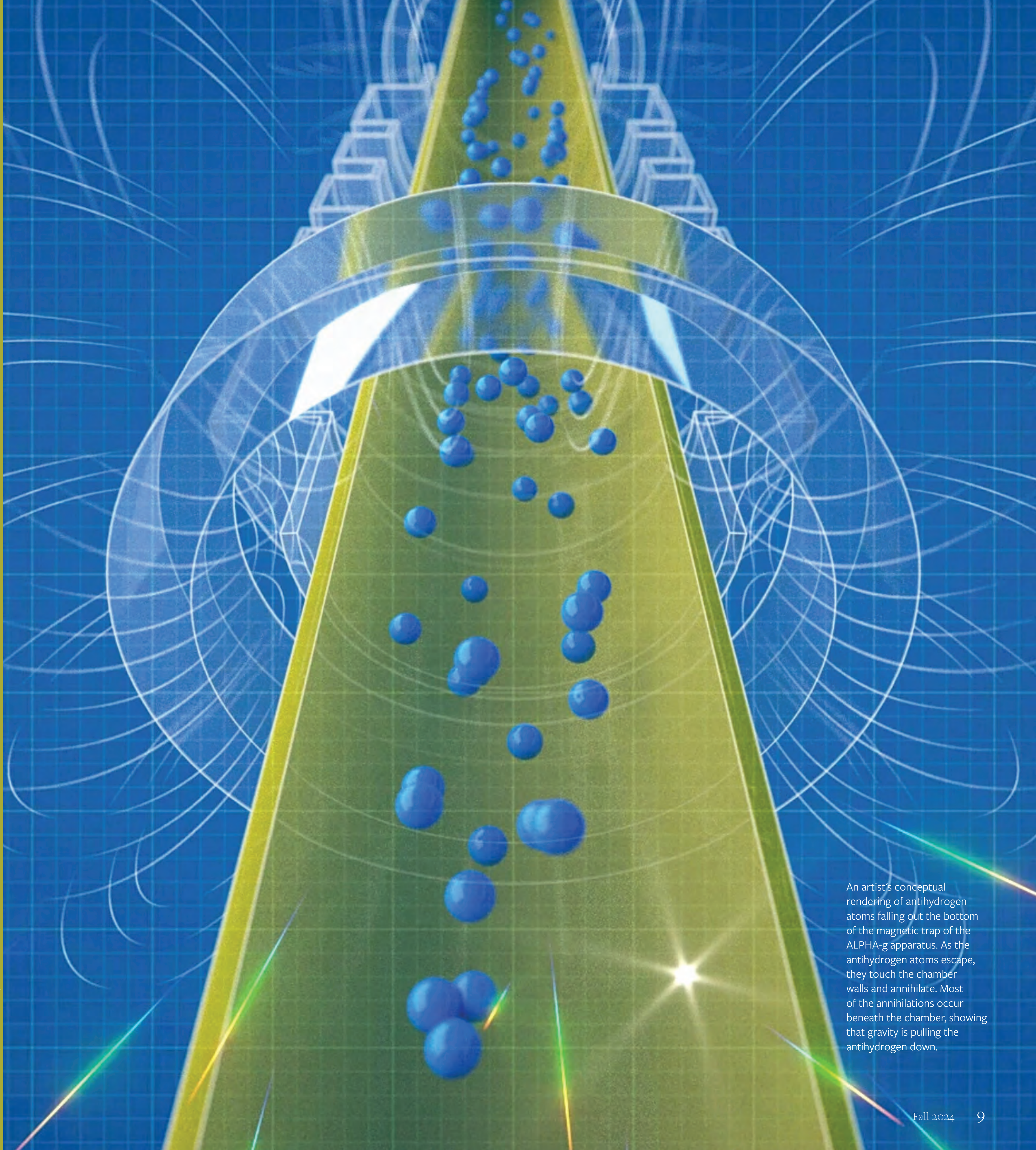
"The experimental strategy is conceptually simple: trap and accumulate atoms of antihydrogen; slowly release them opening the top and bottom barrier potentials of the vertical trap; and try to discern any influence of gravity on their motion when they escape and annihilate on the material walls of the apparatus," write Fajans et al., in their Nature paper.

The experiment took a long time to set up, Wurtele says. What's more, he says, "An exceedingly complicated magnet had to be put into place, and we needed a new particle detector which was designed and built by our Canadian colleagues. We also had to develop new plasma physics techniques to measure the magnetic field. And there was raising money for the project, which ultimately came from Canada, the US, and the EU."

The team also had to deal with setbacks like the COVID-19 pandemic.

Nonetheless, step-by-step, "We made numerous tests to prove to ourselves that the apparatus was actually working," Wurtele continues. "But everything worked without any major problem. The first time we set it up with the hope of gravity measurement, we succeeded, which is a credit to all the people who were working on the experiment."

IMAGE: KEYI "ONYX" LI/U.S. NATIONAL SCIENCE FOUNDATION



An artist's conceptual rendering of antihydrogen atoms falling out the bottom of the magnetic trap of the ALPHA-g apparatus. As the antihydrogen atoms escape, they touch the chamber walls and annihilate. Most of the annihilations occur beneath the chamber, showing that gravity is pulling the antihydrogen down.

COURTESY JOEL FAJANS & JONATHAN WURTELE

Above (L to R): Graduate Student Eric Hunter, Professor Joel Fajans, Professor Jonathan Wurtele, Undergraduate Students Mike Davis, Dana Zimmer, Michael Mastalish, Dalila Robledo, Andrew Christensen, and Huws Landsberger, and Graduate student Celeste Carruth at the ALPHA experiment during summer 2018.

ALPHA-g "relies on detecting antihydrogen by looking at annihilations," says Danielle Hodgkinson who began her work on the project as a PhD student and is a co-author of the Nature paper. "We trap some antihydrogen, and we have it confined by this magnetic potential. And the way that we actually make the measurement is we have one magnetic confining barrier at the top and one at the bottom, and we gradually remove those. That allows the antihydrogen to escape. Because gravity drags the particles down, that means that you get more antimatter particles slipping out the bottom of the trap than the top. As we detect the annihilations, that's how we determine the gravitational acceleration of antihydrogen."

> "It was a very high-energy, intense environment. It was very motivating to be there around a big experiment.

For everyone who physically works at CERN, "a big fraction of what they do is operate the experiment," says Andrew Christensen, another co-author who worked on the project at CERN starting as an undergraduate and then as a PhD student. For ALPHA-g, he says, "the data taken for the antimatter gravity measurement took about a month and for most of the previous two years that I was there, I was implementing each step in the procedure."

Measuring the effect of gravity on antimatter, for example, "depended on measuring, with sensitivity, the magnetic field in our experiment, Christensen said. "I developed a new way of measuring magnetic fields, which we're calling magnetron phase imaging. I am working on a longer paper to explain the technique, which will be peer-reviewed."

COURTESY JOEL FAJANS & JONATHAN WURTELE

Below: Undergraduate Dana Zimmer works on the ALPHA experiment

Christensen, who lived in Switzerland for three years while working at CERN, was also part of a team that worked on and developed for the antimatter gravity experiments an existing form of magnetometry called electron cyclotron resonance.

"Being there for three years was somewhat unusual on ALPHA-g," Christensen says. "It was a very high-energy, intense environment. It was very motivating to be there around a big experiment. ALPHA-g was pushing really hard to get measurements."

Publication of the Nature paper garnered quite a bit of coverage in the popular press. Hodgkinson, who gave an interview about the project to the BBC, says she wasn't surprised. "I think it's an experiment which is kind of easy to understand, and easy to understand the impact. Antimatter has always been a popular physics topic. It was very cool to be there and be so involved with the media outreach."

Emphasizing women in research

Hodgkinson says there has been an increasing number of women scientists who are involved with the ALPHA project. "We're putting more and more emphasis on female researchers.... The contributions of female researchers were really highlighted in this work, and that's important to young, up-and-coming female researchers to see role models who are like them."

After working with Fajans and Wurtele at CERN, Hodgkinson says, "I ended up doing a postdoc here at UC Berkeley." Her work continues on the ALPHA-g project where she is devising experiments, for example, to look simultaneously at the effect of Earth's gravity on both hydrogen and antihydrogen.

Christensen has finished his PhD work and is moving on to a postdoctoral fellowship in the lab of Berkeley Physics Professor Holger Müller. He says he took some valuable insights from the work at CERN. "Everything I did at ALPHA involves precision measurements. I could broadly define a precision measurement as being a measurement where you need to account for a lot of things in order to get agreement between theory and experiment. It's exciting—and satisfying when you get it."

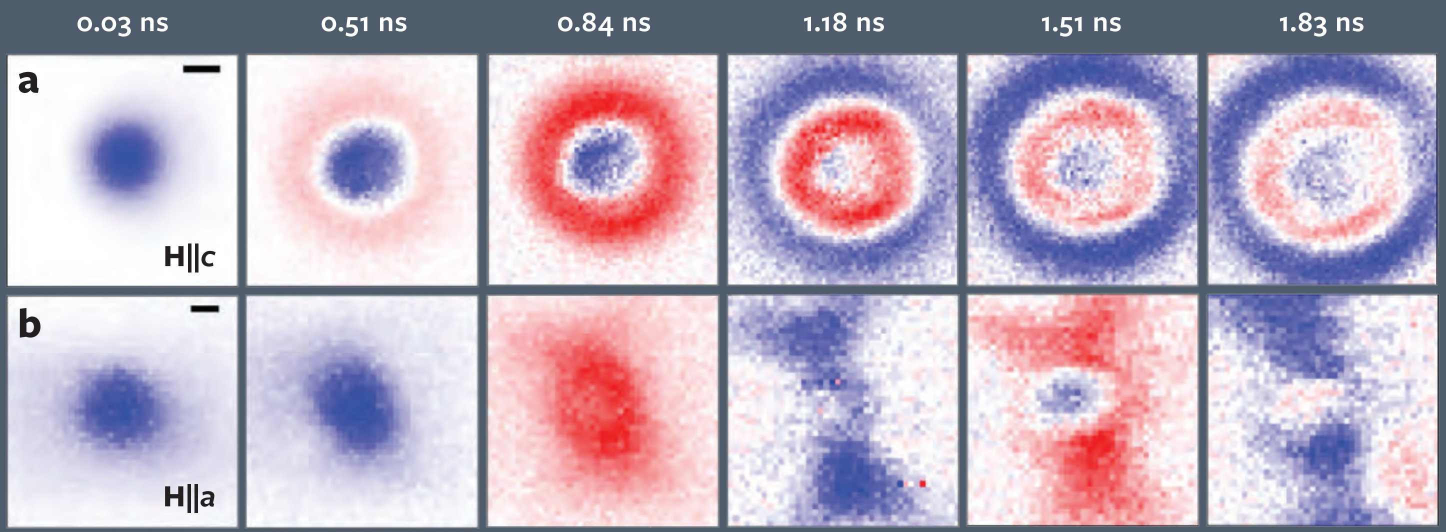
Fajans and Wurtele say they have sent dozens of undergrad and graduate students to work at CERN over the years, typically for a summer but sometimes two summers. Christensen, Fajans says, "made a remarkable measurement that he planned from the beginning, himself."

"This experiment was a great deal of fun," says Wurtele. "Nobody really had any expectation in our group that we would find something different from gravity. We tried to do everything we could to not have any bias, to just look at the data."

He says there was an enormous burden of publicity when the paper came out—"hundreds if not almost 1,000 articles about it. We certainly had some impact in the popular science world."

"We confirmed what everybody expected, or almost everybody was expecting," says Fajans, "so it's not that we revolutionized the world with this experiment, though it certainly matters a lot for science. I mean, it would have been more fun in some ways if the stuff [antihydrogen] did go upwards!"

ResearchHighlights



Above: Magnon wave packet propagation in an antiferromagnet is revealed in these snapshots obtained using pairs of laser pulses. Credit: Joseph Orenstein/ Berkeley Lab

Joseph Orenstein: Probing Nature's Perfect Quantum Bit

The spin of the electron is nature's perfect quantum bit, capable of extending the range of information storage beyond "one" or "zero," says Berkeley Physics Professor Joseph Orenstein. Exploiting the electron's spin degree of freedom—its possible spin states—is a central goal of quantum information science.

Recent work by Orenstein and collaborators Yue Sun, Jie Yao, and Fanghao Meng has shown the potential of so-called magnon wave packets—collective excitations of electron spins—to transport quantum information over substantial distances in the extremely small quantum realm in a class of materials known as antiferromagnets.

The work, published earlier this year in Nature Physics, upends conventional understanding about how electron-spin excitations propagate in antiferromagnets. Quantum technologies be they computers, sensors, or other devices will depend on transmitting quantum information with fidelity, over distance. Orenstein and coworkers hope the work moves researchers a step closer to these goals.

Electron spins can be thought of as tiny bar magnets responsible for magnetism in materials. When neighboring spins are oriented in alternating directions, the result is antiferromagnetic order, which produces no net magnetization.

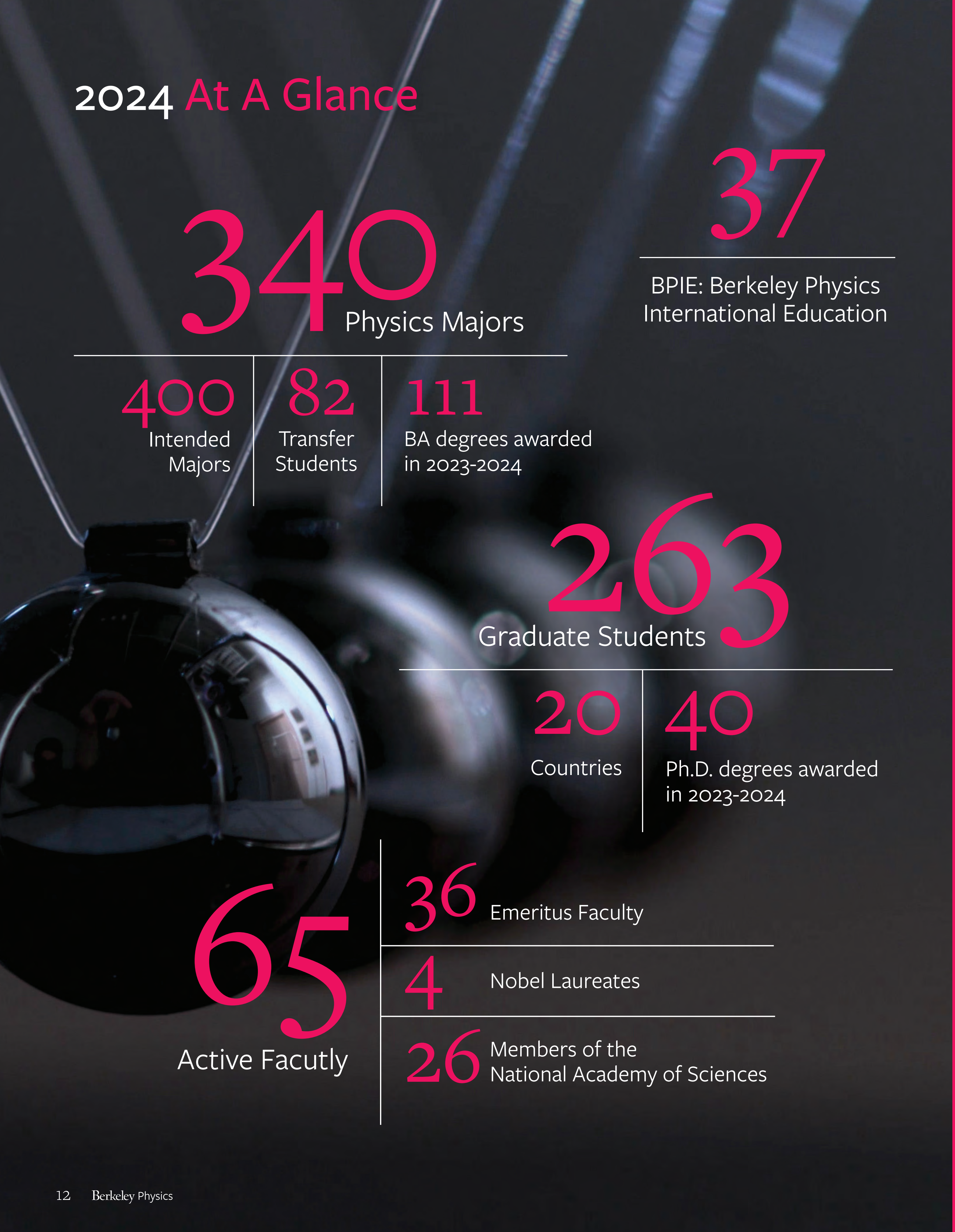
Orenstein is a condensed matter physicist who uses extremely short bursts of laser light lasting only about one-trillionth of a second to track how phenomena like electron spin propagate from one location to another. The recent work on magnon wave packets is part of a more-than-20-year exploration of electron-spin phenomenon by the Orenstein group.

Using ultra-short laser pulses, they have been able to develop time-resolved (as opposed to frequency-resolved) optical spectroscopies ranging from the very far-infrared to the visible region of the spectrum. This, in turn, has enabled studies of a variety of spin-related phenomena, unlocking basic-science understanding and pointing to ways electron spin might be applied, for example, building more energy-efficient transistors.

To understand how magnon wave packets move through an antiferromagnetic material, Orenstein's group used pairs of laser pulses to perturb the order in one place while probing at another. Doing so yielded snapshots revealing that magnon wave packets propagate in all directions. A good analogy would be ripples on a pond from a dropped pebble.

Orenstein's team also showed that magnon wave packets in an antiferromagnet propagate remarkably faster and over longer distances than existing models would predict. The models assume that each electron spin couples only to its neighbors. Imagine a system of spheres connected to near neighbors by springs, says Orenstein. Displacing one sphere from its preferred position produces a wave of displacement that spreads with time.

"However, recall that each spinning electron is like a tiny bar magnet. If we imagine replacing the spheres by tiny bar magnets representing the spinning electrons, the picture changes completely," Orenstein says. "Now, instead of local interactions, each bar magnet couples to every other one throughout the entire system, through the same long-range interaction that pulls a refrigerator magnet to the fridge door. It is this long-range interaction that accounts for the remarkable speed of electron spin propagation."



2024 At A Glance

340 Physics Majors

37

BPIE: Berkeley Physics International Education

400 Intended Majors

82 Transfer Students

111 BA degrees awarded in 2023-2024

263 Graduate Students

20 Countries

40 Ph.D. degrees awarded in 2023-2024

65 Active Faculty

36 Emeritus Faculty

4 Nobel Laureates

26 Members of the National Academy of Sciences

Introducing 3 new Physics Faculty

Luca Iliesiu

Luca is a high-energy theorist interested in quantum field theory, quantum gravity, and their relation to particle and condensed matter physics. He received his BA in physics from Princeton University in 2015, and remained there to earn his PhD in 2020. He then became a postdoctoral fellow at Stanford University, where he was part of the Simons Ultra Quantum Matter Collaboration, before starting as an assistant professor at Berkeley Physics in January 2024.

Chiara Salemi

Chiara is an experimentalist developing new techniques to search for axion dark matter. She received her BS in physics and mathematics from the University of North Carolina at Chapel Hill in 2017, and her PhD in physics in 2022 at the Massachusetts Institute of Technology, where she built the first lumped-element axion search, ABRACADABRA. She then became a postdoctoral fellow at Stanford University and SLAC National Accelerator Laboratory. Chiara will join the Berkeley Physics faculty as an assistant professor in January 2025.

Victoria Xu

Victoria works on precision measurements to explore fundamental physics. She received her BS in physics from UC Santa Barbara in 2013, and her PhD in physics from UC Berkeley in 2020. For her PhD, she worked with Professor Holger Müller on trapped cavity atom interferometers for precision measurements and fundamental physics. She then joined the MIT LIGO Laboratory as a postdoctoral associate. In January 2025, Victoria will become a Berkeley Physics assistant professor.

PHOTO: SARAH WITTMER

Berkeley Physics Pre-Core Program Boosts Skills, Comfort for Transfer Students

The cultural shift and academic rigor at Berkeley can feel daunting for undergraduate students who transfer to Berkeley Physics from other institutions. The Berkeley Pre-Core Transfer Summer Program aims to give transfer students a sense of belonging even before they enroll in their first academic semester.

The program offers math, coding, data analysis, and experimental preparation skills as well as an opportunity for directed group study to help students bolster technical skills for upper-division courses in physics, astrophysics, and earth and planetary sciences.

Pre-core isn't only about academics though. Students receive academic planning tips and advice; familiarity with campus resources for academic support and student wellness; information about graduate school and industry jobs, including hearing from guest speakers; information about finding research opportunities, clubs and activities; and community building with fellow transfer students in physical sciences.

Rising senior Michael Speights, who transferred to Berkeley Physics from a Sacramento-area Community college, now serves as something of an ambassador for students in the program. "We try to let them know that, while transferring to Berkeley Physics can be hard, it's completely doable," he says. "If anything, Berkeley surprised me by how supportive it is. In the physics department, your professors really do care about you."

Berkeley Physics' REYES: A STEM Education Shining Star

When the COVID-19 pandemic forced Professor Raul Briceno in 2020 to offer his Python4Physics course online, something unexpected happened: He recognized the possibility for lowering barriers to science careers for more students—mostly high schoolers—from anywhere in the world.

Briceno seized the opportunity and transformed his Python programming course and related activities, originally at Virginia's Old Dominion University, into an online STEM-education shining star that now also offers mentorship opportunities. In 2023, it was relaunched as the Berkeley Physics REYES (Remote Experience for Young Engineers and Scientists) program.

Today, via word of mouth and social media, more than 11,000 learners in 135 countries have registered for REYES. "I've talked to students who tell me that they found out about REYES because it was on a WhatsApp chat and somebody sent them a link," Briceno says.

Python4Physics remains central to REYES. "It's a full-blown class, and students learn quite a bit," Briceno says. With the pandemic over, the Python course is now hybrid, drawing some 20 Bay area students to in-person classes.

REYES mentorships, which are separate from the online Python course, provide an opportunity to participate in a research project. Volunteer mentors can post with REYES information about their research projects. Students in REYES can access that information and list their top three choices. It's competitive, and only about 20 students are paired with mentors, but Briceno hopes REYES can continue to grow and offer more opportunities to more students.

Upper Left: Assistant Professor Raul Briceno teaches a class as part of the REYES program

Bottom Right: Pre-Core student Michael Speights in the Physics Undergraduate Reading Room

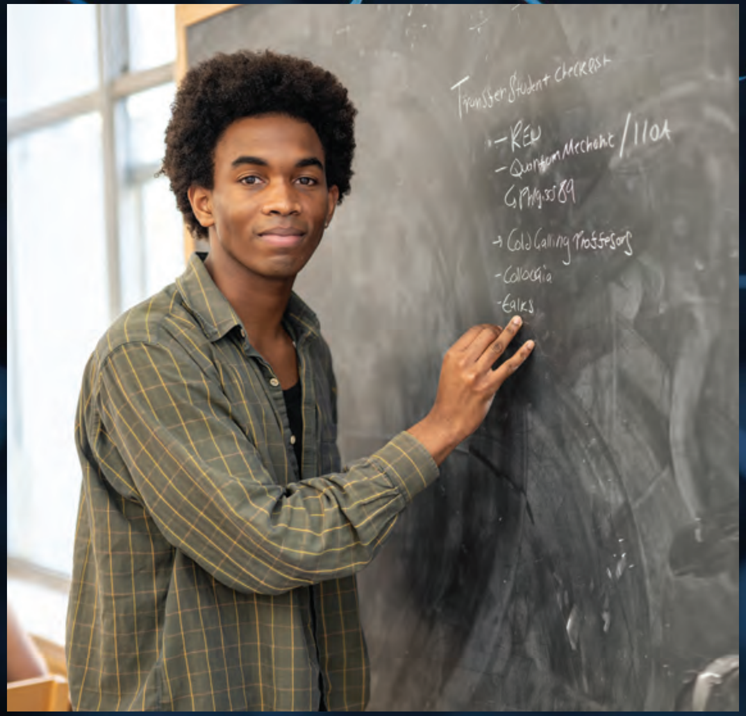


PHOTO: KEEGAN HOUSER

Hands-On Creativity Defines the Spirit of the New Physics Innovation Lab

PHOTO: KEEGAN HOUSER

Above: The newly completed Paul L. Richards Physics Innovation Laboratory. The space will soon hold tools for computer-aided design, circuitry stations, and more.

Below: (L to R) PIL Student Manager Vivian Frisk, Assistant Professor Eric Ma, and Student Machine Shop Manager Jesse Lopez

A new experience awaits Berkeley Physics and Astronomy undergraduate students this fall with the opening of the Paul L. Richards Physics Innovation Lab (PIL). The new facility will offer students up-to-date tools for automated processing and computer-aided design, 3D printers and laser cutters, and soldering and circuitry stations.

The lab is partly funded by Berkeley's Physics Innovators Initiative (Pi2). The idea is to give students hands-on experience with the types of equipment and projects they are likely to encounter in post-baccalaureate studies.

The new facility is named in honor of Emeritus Professor Paul Richards, a pioneer of infrared and millimeter wave physics. The Richards family is supporting the PIL to honor his belief that prototyping in the lab, making needed equipment, is an important bridge to learning.

"It's somewhere that students can go and work safely and not have to have lengthy training," says Student Machine Shop Manager, Jesse Lopez. Additional lab equipment, he says, will include basic hand tools, voltmeters, oscilloscopes and other diagnostic equipment for electronics, and an optics table with lasers.

"We'll start simple. We'll start basic," Lopez says. "And then we'll let the students kind of show us what they need."

The PIL is not for any precision or industrial-type machining work, says PIL Student Manager Vivian Frisk.

"The Physics Innovation Lab is a great way for students with no research or no experimental background to get involved," she says. "I'm really excited to see a lot more undergraduate students be able to experiment and see if that's something that they want to do—hands-on, experimental physics." Frisk says her involvement with the machine shop and with the PIL has helped her find a comfort-zone in the Physics Department.

Indeed, the PIL will address a catch-22 situation for undergraduates, especially students from underrepresented backgrounds, says Assistant Professor Eric Y. Ma. That is, most principal investigators require candidate undergraduate research assistants for Berkeley Physics laboratories to have had some prior research experience.

"But a lot of undergrad students don't have research experience," says Ma. "Student experience in the PIL, however, would impart some of that needed experience, and likely reach a much wider student body."

The PIL is meant to give students agency, says Astronomy Professor Eugene Chiang. "In real life, and in scientific research, there are no recipes. You have to create it from scratch."

PHOTO: KEEGAN HOUSER

AlumniStories


PHOTO: JACQUELINE MCBRIDE/NEWSLINE

Luisa Hansen: Longtime Advocate for Women in Science

For 64 years and counting, Berkeley Physics alum **Luisa Hansen** (PhD ’59) has been a proud employee of Lawrence Livermore National Laboratory (LLNL)—and she has no plans to retire. The Chilean born nuclear physicist, and self-described “rare bird,” began her work at LLNL at a time when its science workforce was nearly 100 percent male. She says her biggest challenge at that time was convincing male colleagues of her talent and capabilities.

They became convinced. Over the course of her career, Hansen has published some 184 papers, and delivered them in places like France, Germany, Russia, Japan, and China. In 1989, she was named a Fellow of the American Nuclear Society for work relevant to the LLNL weapons program.

Hansen once said, “No woman has to defend her right to a place in her field, except by her work.”

Indeed, she has been a longtime activist for increasing the participation of women in science at LLNL, where she began working just seven years after the lab opened. She is a member of the laboratory’s Women’s Association and served as its president. She worked with others in the group to expose salary differences of 15 to 30 percent between professional men and women at the lab—a tally that LLNL moved to correct.

“If you enjoy what you are doing, work hard to succeed,” Hansen has said. ”Be honest and open to hearing new opinions. If you think that something is not right, don’t be afraid to speak up.”

> **“If you enjoy what you are doing, work hard to succeed”**
> – Luisa Hansen

Alum Pamela Caton likes to get her hands dirty

Pamela Caton (BA ’92) has always been a “maker.” As a young person, she took jewelry, machining, and programming classes. When her radio broke, her dad suggested, “Try to fix it. It’s already broken, so what’s the worst that can happen?” Working on hardware brings her joy, and she is especially drawn to multidisciplinary projects.

Caton has primarily worked on micro-electromechanical systems (MEMS). MEMS engineers use the same tools that an electrical engineer would use to build silicon chips, but they build electronically-controlled mechanical structures with moving parts.

As an optical MEMS engineer at AEye, Caton is helping to develop a light detection and ranging (lidar) sensor for automotive and smart infrastructure applications. For example, self-driving car companies could use AEye’s sensors to detect and identify the features of an object on the freeway, allowing the car to understand if it needs to avoid the object—is it a brick or a plastic bag?

A lidar sensor measures the distance to a target by sending out a short laser pulse, reflecting it off an object, and recording the time between the outgoing and reflected light pulses. By doing an array of laser measurements, engineers create a big map of distance information. Caton works on developing and testing the MEMS mirrors used for laser scanning.

Caton credits some of her success in industry to her Berkeley Physics training. “I have a really solid understanding of the fundamentals. Physics is a fantastic basis for all types of engineering,” she says.

Her favorite classes were the advanced physics labs. “Professor Sumner Davis was fantastic. And I loved Physics 111 because it was so hands-on. You couldn’t get through the lab without understanding the theory, but you got your hands dirty too.”

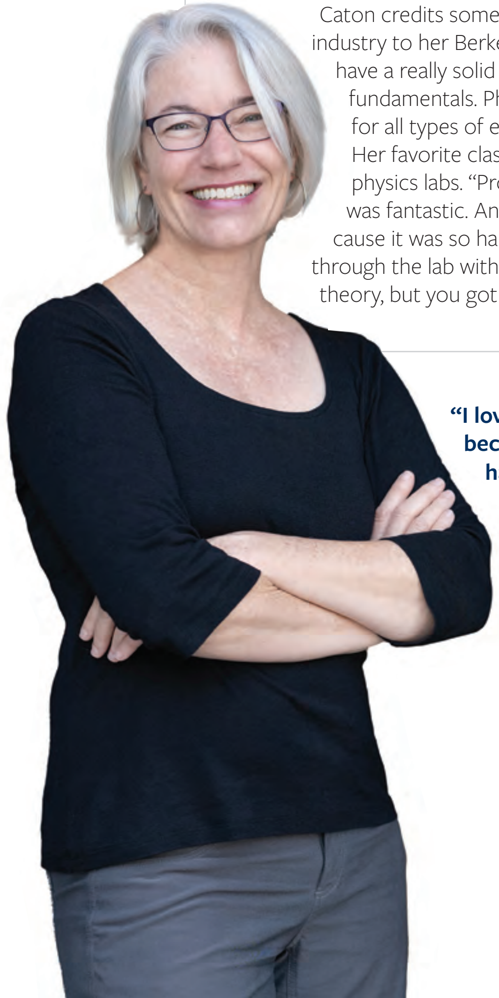


PHOTO: BROOKE SHATTUCK

> **“I loved Physics 111 because it was so hands-on.”**
> –Pamela Caton

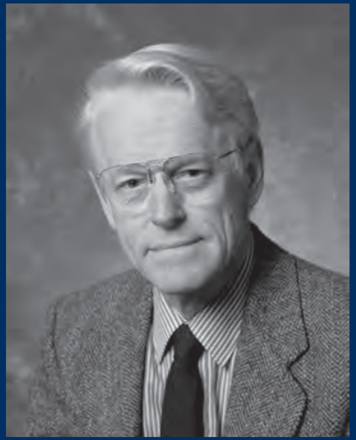
Astro/Physics Alum Wins MacArthur Genius Award

Every year the John D. and Catherine T. MacArthur Foundation announces a class of two dozen or fewer fellows, better known as the “Genius Grant” awards. Astronomy and Physics alum **Keivan Stassun** (BA ’94) is a 2024 recipient. He will receive $800K to spend however he wants over five years. While here at UC Berkeley, he worked in the lab group of Gibor Basri and organized a club for astronomy majors. And he delivered the valedictory address at graduation. He went on to do his Astronomy PhD at the University of Wisconsin. Following a postdoc as a NASA Hubble Fellow, Stassun joined the faculty at Vanderbilt University in Nashville, rising to full professor in 2011 and becoming Senior Associate Dean for Graduate Education & Research in 2015. Most notably, he is currently founder and director of the Frist Center for Autism and Innovation. This reflects his long advocacy for increasing diversity in STEM research and education. Inspired by his experience in the physics community here at Berkeley, Professor Stassun is especially proud of building a Bridge Program that expands the STEM student pipeline into higher education.


PHOTO: JOHN D. AND CATHERINE T. MACARTHUR FOUNDATION

InMemory

Paul Richards



Paul L. Richards (1934-2024), Berkeley Physics Professor Emeritus and a pioneer in cosmic microwave background (CMB) research, passed away on September 16, 2024. Originally a solid-state physicist, Richards shifted to astrophysics after the discovery of the CMB. He developed highly sensitive instruments that helped confirm the Big Bang theory and measure CMB radiation. His balloon-borne experiments, including MAXIMA, played a pivotal role in establishing the universe’s flatness and supporting inflation theory. A respected mentor and collaborator, Richards was recognized with numerous prestigious awards.

Korkut Bardakci

Korkut Bardakci (1936–2024), Berkeley Physics Professor Emeritus, passed away on March 16, 2024. After studying as an undergraduate at Robert College in Turkey and as a PhD graduate student in axiomatic quantum field theory at the University of Rochester, Bardakci worked as a postdoctoral fellow at the University of Minnesota and the Institute for Advanced Study. He joined Berkeley Physics as an assistant professor in 1966, making seminal contributions to quantum chromodynamics and string theory. Together with Martin Halpern, Bardakci discovered a new type of mathematical structure within string theory, Affine Lie Algebras, which had far-reaching applications.

Rainer Sachs

Rainer “Ray” Sachs (1932–2024), a Berkeley Professor Emeritus of Mathematics and Physics, passed away on April 16, 2024. Sachs’s early work focused on general relativity and cosmology. Among other pivotal contributions, he provided a general proof that positive-energy-carrying gravitational waves are a consequence of general relativity, which was experimentally observed 50 years later in 2016. In the 1980s, Sachs moved on to the challenge of applying his mathematical skills to the field of radiation biology. His research provided many insights into the formation and repair/misrepair kinetics of radiation-induced chromosome aberrations. His modeling of radiation carcinogenesis challenged the central paradigm that cancer arises from a single aberrant cell.

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