

GENERAL PHYSICS TO ASTROPHYSICS VOL 5

$$\begin{aligned} G_{\mu\nu} &= 8\pi T_{\mu\nu} \\ G_{\mu\nu} &= \frac{8\pi G}{c^4} T_{\mu\nu} \\ R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R &= \frac{8\pi G}{c^4} T_{\mu\nu} \\ R &= g^{\mu\nu} R_{\mu\nu} \quad R = \sum_{\mu=0}^3 \sum_{\nu=0}^3 g^{\mu\nu} R_{\mu\nu} \\ R_{\mu\nu} &= \sum_{\sigma=0}^3 \sum_{\kappa=0}^3 g^{\sigma\kappa} R_{\sigma\mu\kappa\nu} \\ R_{\sigma\mu\nu}^{\rho} &= \partial_{\mu} \Gamma_{\nu\sigma}^{\rho} - \partial_{\nu} \Gamma_{\mu\sigma}^{\rho} + \Gamma_{\mu\lambda}^{\rho} \Gamma_{\nu\sigma}^{\lambda} - \Gamma_{\nu\lambda}^{\rho} \Gamma_{\mu\sigma}^{\lambda} \\ \Gamma_{\mu\sigma}^{\lambda} &= \frac{1}{2} g^{\lambda\kappa} \left(\frac{\partial g_{\kappa\mu}}{\partial x^{\sigma}} + \frac{\partial g_{\kappa\sigma}}{\partial x^{\mu}} - \frac{\partial g_{\mu\sigma}}{\partial x^{\kappa}} \right) \end{aligned}$$


Physicists enable qubits to chat in light at room temperature in a quantum leap

Researchers at the Institute of Science and Technology in Austria (ISTA) have achieved a major milestone in quantum computing after obtaining a complete optical readout of superconducting qubits.

This will help in building scalable quantum computers that are robust, operate at room temperature, and at a much lower cost, a press release said.

Quantum computers are the next frontier of computing, allowing calculations to occur at exponential rates compared to classical computers.

At the core of the quantum computer is the quantum bit or qubit that can occupy multiple states at once, allowing it to carry out multiple calculations at once, as against its binary counterpart, the bit.

To achieve this state, scientists use properties of materials, such as their superconductivity. However, these states can only be reached at temperatures

close to absolute zero, which then requires extensive cryogenic cooling infrastructure, increasing computational costs.

Using fiberoptics with quantum hardware

Even as work is ongoing on building [scalable quantum computers](#), some research groups are working to build the necessary network that it will need to operate. Just as the internet requires an extensive fiber optic network to operate, quantum computers also need a network that can transport qubits.

How Quantum Computing Will Redefine Our Future

Rolling out a cryogenically cooled network globally is impossible, so scientists are also working on using the existing fiber optic network to relay quantum information.

Superconducting qubits are electrical by nature but have low bandwidth. They can transmit little information over time and get easily overwhelmed by noise. On the other hand, optical signals are high-bandwidth signals that can propagate with minimal losses.

While this makes them ideal for qubit readouts, the challenge is communicating between these two and translating the optical signals to qubits and back.

Microwaves to the rescue

“Ideally, one would try to get rid of all electrical signals, as the required wiring transports a lot of heat into the cooling chambers where the qubits are. But this is not possible,” explained Thomas Werner, a PhD student at ISTA who was involved in the work.

The researchers turned to an electro-optic transducer that converts optical signals to microwave frequency, which qubits can understand. When the microwave is directed toward a qubit, the qubit reflects it back, thereby establishing communication with the transducer and connecting it to the outside world.

"We showed that we can send infrared light close to the qubits without making them lose their superconductivity," added Werner. The approach also helps overcome the limitations of conventional readout systems that are error-prone and need multiple corrections.

"By using the electro-optic transducer to disconnect the qubits from the electrical infrastructure, we were able to replace all the remaining parts of the setup with optics," said Werner, highlighting the efficiency and cost advantages of the approach.

"This new approach might allow us to increase the number of qubits so they become useful for computation. It also lays the foundation for building a network of superconducting [quantum computers](#) connected via optical fibers at room temperature," concluded Georg Arnold, former PhD student at ISTA, who was also involved with this work, in the press release.

The research findings were published in the journal [Nature Physics](#).

Physicists achieve fully optical readout of superconducting qubits

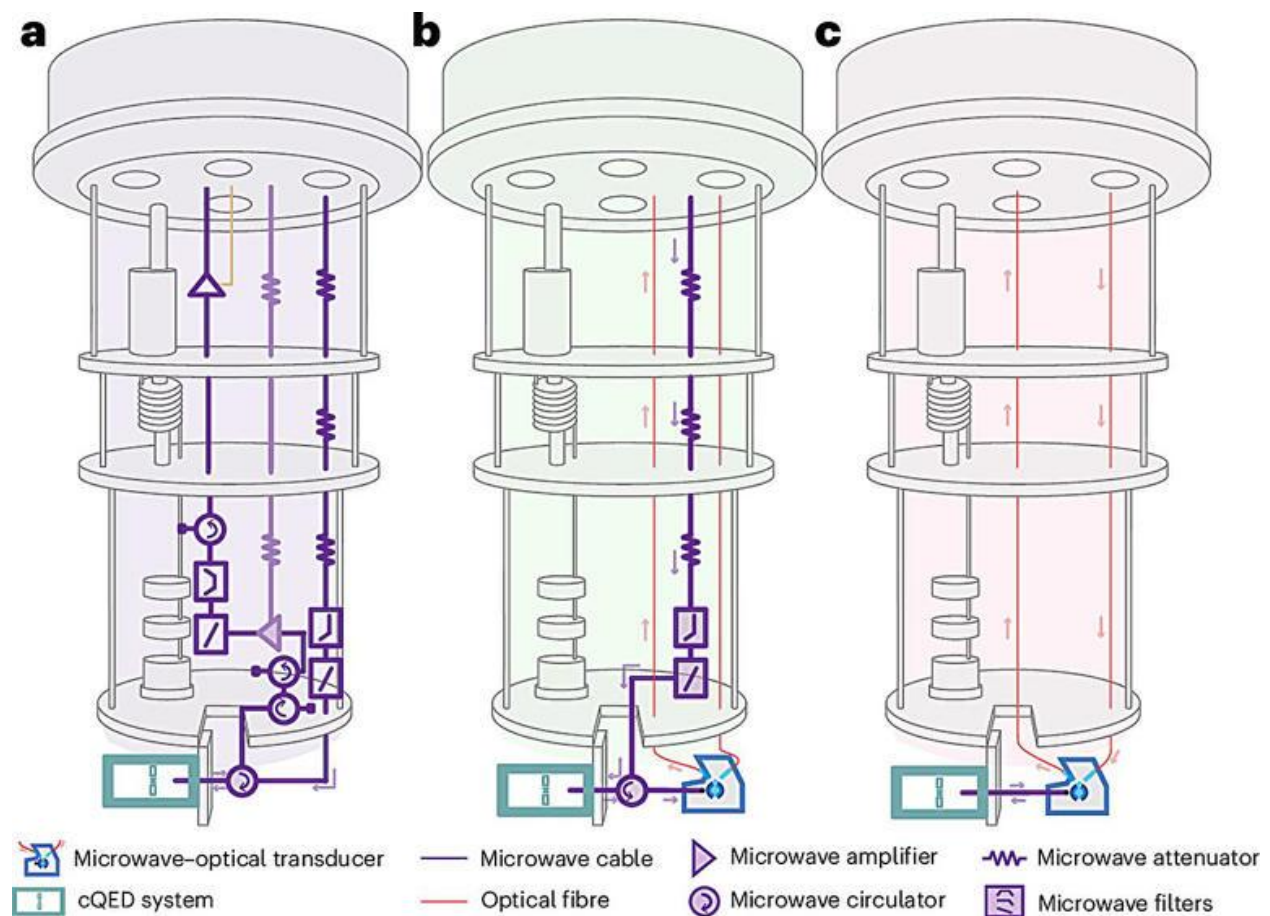
Qubits—the fundamental units of quantum information—drive entire tech sectors. Among them, superconducting qubits could be instrumental in building a large-scale quantum computer, but they rely on electrical signals and are difficult to scale.

In a breakthrough, a team of physicists at the Institute of Science and Technology Austria (ISTA) has achieved a fully optical readout of superconducting qubits, pushing the technology beyond its current limitations. Their findings are [published](#) in *Nature Physics*.

Following a year-long rally, quantum computing stocks were brought to a standstill barely a few days into the [International Year of Quantum Science and Technology](#). The reason for this sudden setback was Nvidia CEO Jensen Huang's keynote at the CES 2025 tech trade show, where he predicted that "very useful quantum computers" were still two decades down the road.

Aside from stock markets and tech trade shows, the race continues fiercely toward scalable quantum computers that could perform some calculations

exponentially faster than "classical" computers. While this promising "quantum advantage" resulted in the rapid development of quantum hardware, many technical hurdles must still be overcome before quantum computers become "useful."



Comparison of conventional and optical qubit readout set-ups in a dilution refrigerator. Credit: Nature Physics (2025). DOI: 10.1038/s41567-024-02741-4

Now, a team of physicists from Professor Johannes Fink's group at the Institute of Science and Technology Austria (ISTA) has managed to overcome an important limitation, which could help scale up quantum computers. By ensuring the qubits understand the language of fiber optics, the team considerably reduced the amount of cryogenic hardware needed to measure them.

"This new approach might allow us to increase the number of qubits so they become useful for computation. It also lays the foundation for building a network of superconducting quantum computers connected via optical fibers at room temperature," says co-first author Georg Arnold, a former Ph.D. student in the Fink group at ISTA.

The challenges of applying fiberoptics to superconducting quantum hardware

While fiberoptics have revolutionized the telecom industry with their multiple advantages over electrical transmission and enabled high-speed communication, applying optics to quantum hardware is no easy task. Superconducting quantum computers, which use special physical properties of materials at temperatures near absolute zero, present a challenge of their own.

To realize superconducting qubits, tiny electrical circuits are cooled to extremely low temperatures where they lose all electrical resistance and can thus maintain a flowing current indefinitely.

"Thus, superconducting qubits are electrical by definition. To make them, we must reach temperatures of only a few thousandths of a degree above absolute zero. That's even colder than space," says Arnold.

However, electrical signals have a comparably low bandwidth, meaning they transmit little information per unit of time. Easily overwhelmed by noise, they are also prone to information loss. Also, the required wiring dissipates lots of heat. Thus, the "qubit readout," i.e., detecting and measuring qubits by sending an electric signal that they reflect, requires colossal cryogenic cooling as well as elaborate and expensive electrical components for filtering and amplification.

On the other hand, higher-energy optical signals—for example, at telecom wavelengths—propagate in thin optical fibers with minuscule losses. In addition, they have a considerably lower heat dissipation and much higher bandwidth. So, using them to push the limits of superconducting quantum hardware would be ideal, if only the qubits would understand their language.

'Translating' the optical signal to the qubits

To achieve a fully optical readout in superconducting quantum hardware, the team needed to find a way to 'translate' the optical signal to the qubits and back.

"Ideally, one would try to get rid of all electrical signals, as the required wiring transports a lot of heat into the cooling chambers where the qubits are. But this is

not possible," says co-first author Thomas Werner, a Ph.D. student in the Fink group at ISTA.

So, the researchers thought of using an electro-optic transducer to convert the optical signal to a microwave frequency—an electrical signal that the qubits can understand. In response, the qubits reflect a microwave signal that the transducer converts to optics.

Werner highlights the delicacy of the task, "We showed that we can send infrared light close to the qubits without making them lose their superconductivity." Using the electro-optic transducer as a switch allowed the team to connect the qubits directly to the outside world.

Overcoming the qubit barrier and other advantages

To do 'useful' computation with quantum computers, thousands or even millions of qubits are necessary. However, the infrastructure has difficulty keeping up because the cryogenic cooling requirements to detect and measure them are prohibitive.

"Our technology can decrease the heat load of measuring superconductive qubits considerably. This will allow us to break the qubit barrier and scale up the number of qubits that can be used in quantum computing," says Arnold.

Achieving a fully optical readout of superconducting qubits also allowed the researchers to rid the setup of many of its cumbersome electrical components. The electrical signal in conventional readout systems is highly error-prone, requiring large-scale signal correction using many technically limiting and expensive electrical components that must also be cooled to cryogenic temperatures.

"So, by using the electro-optic transducer to disconnect the qubits from the electrical infrastructure, we were able to replace all the remaining parts of the setup with optics," says Werner. This makes the system not only more robust and efficient, but also reduces its costs.

Interfacing superconducting quantum computers via room-temperature links

This technology could help increase the number of usable superconducting qubits even further by allowing scientists to interface multiple quantum computers using light. Currently, quantum computers need so-called "dilution refrigerators" to provide cooling for the entire measurement setup, including any required connections between processor modules.

"But these dilution refrigerators also have practical limitations and can't be made infinitely large," says Arnold. In turn, the space and cooling restrictions limit the number of usable qubits. But now, connecting two qubits in two separate dilution refrigerators using an optical fiber might be within reach, according to the researchers.

"The infrastructure is available, and now we have the technology that allows us to build the first simple quantum computing networks," says Arnold.

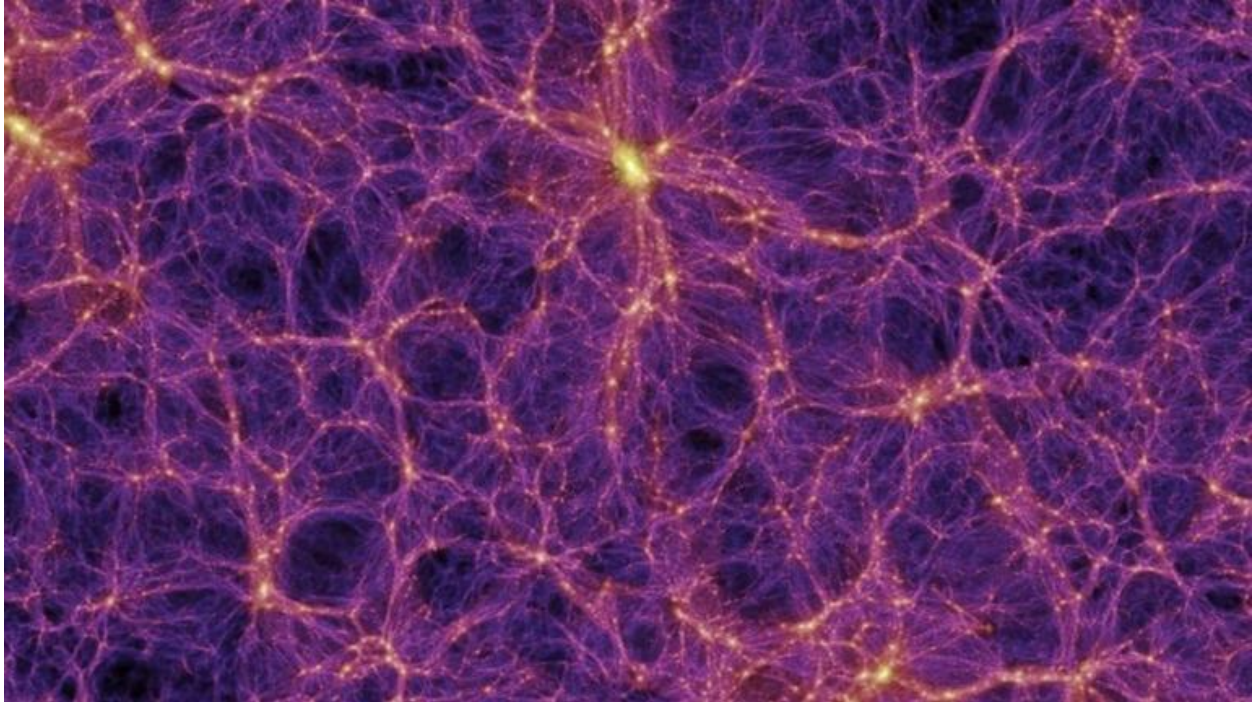
The ISTA physicists have reached a significant milestone in developing superconducting quantum hardware, but much more remains to be done.

"The performance of our prototype is still quite limited—in particular with regard to the amount of optical power needed and dissipated. Nevertheless, it serves as a proof of principle that a fully optical readout of superconducting qubits is even possible. It will be the industry's role to push the technique further."

More information: Georg Arnold et al, All-optical superconducting qubit readout, *Nature Physics* (2025). DOI: [10.1038/s41567-024-02741-4](https://doi.org/10.1038/s41567-024-02741-4)

Provided by Institute of Science and Technology Austria

Largest Structure In The Near Universe Discovered – 130,000 Times More Massive Than Our Galaxy



In simulations of the universe like this one, you can find humongous structures like the one discovered. - Image Credit: Springel et al. (2005)© IFL Science

Mapping the distribution of matter in the universe is an important quest for cosmology and astrophysics. There is a battle going on between the universe's accelerated expansion and gravity trying to keep things all together. Some absolutely enormous structures have been found in the distant universe, but even closer to us there are gargantuan ones. Meet Quipu.

Quipu is a structure spanning 1.3 billion light-years. That means it would fit 13,000 galaxies like the Milky Way one after the other. It has a total mass of 2×10^{15} solar masses or as much as 130,000 Milky Ways. The two numbers reveal it couldn't possibly be a conga line of galaxies. There is one main strand of clusters of galaxies from which many strands depart.

This structure reminded the discoverer of the [Quipu](#), the Incan system used for counting, primarily, but also record keeping. There is the occasional hypothesis that there might be more language in it than we currently understand. It involves

color-coded cords all attached to a larger strand. Each strand has knots tied in certain locations to deliver numerical information. Similarly, Quipu the cosmic structure has over-densities with larger clusters along its strands.

Quipu is one of five large cosmic structures discovered between 424 million and 815 million light-years from Earth. Together, they contain 45 percent of all galaxy clusters, 30 percent of all galaxies, and a quarter of all matter within that region of the near Universe – but they occupy only 13 percent of its volume, making them clear over-densities with respect to the rest of the region.

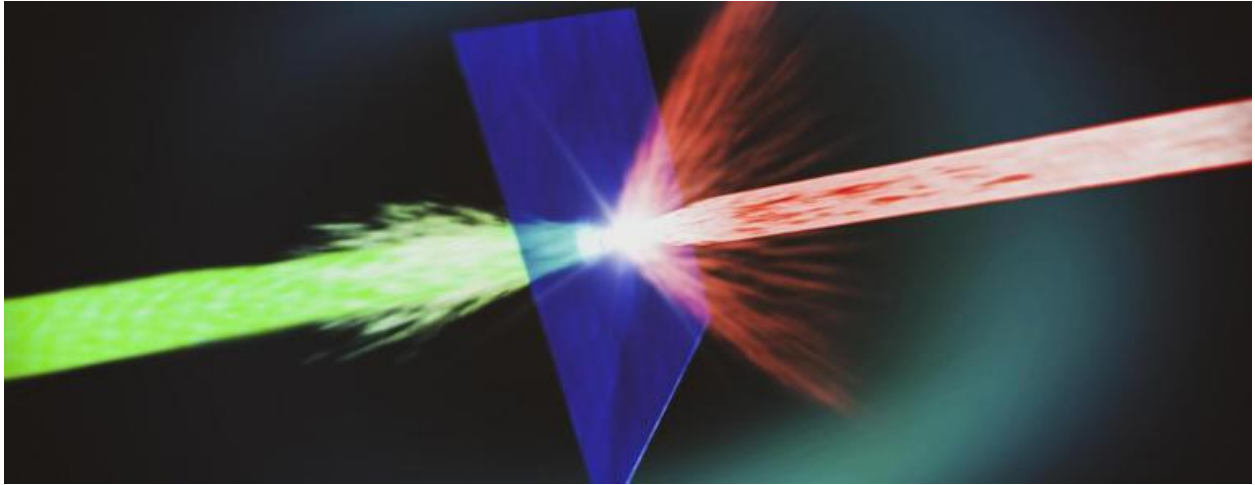
It is not surprising that there are regions that are more densely populated by galaxies, and regions that are less populated. The whole universe is organized in the so-called [cosmic web](#), where galaxies and clusters are organized in strands and nodes, with mostly empty space in between. Those regions are called the voids.

Quipu is the largest of these structures in the near universe. [Much larger structures](#) have been found in the far universe that have called into question our models. Quipu instead is perfectly sized for it. Simulations of the cosmos expect the presence of structures like Quipu out there.

The presence of such a large structure could affect cosmological measurements. This has been suggested as a possible solution to the famous Hubble tension, the disagreement between multiple methods to estimate the expansion rate of the universe. The team looked for the effect in the data, but they feel that statistical confidence on the finding is too poor.

The paper is accepted for publication in the journal *Astronomy & Astrophysics* and can be read on the [arXiv](#) preprint server.

Innovative target design leads to surprising discovery in laser-plasma acceleration



Researchers studying laser-driven proton acceleration introduced an innovative, self-replenishing water sheet target to address the inefficiency of replacing targets after each laser pulse. The target had a surprising side effect, resulting in a naturally focused, more tightly aligned proton beam. Credit: Greg Stewart/SLAC National Accelerator Laboratory

Scientists have developed a method for generating fast, bright proton beams using a high-repetition-rate laser-plasma accelerator. This work, [published](#) in *Nature Communications*, resolves several long-standing challenges and ushers this technology to the threshold of real-world applications—all thanks to a stream of water.

"These exciting results pave the way for new applications of relativistic high-power lasers for applications in medicine, accelerator research, and inertial fusion," said Siegfried Glenzer, professor of photon science and the director of the High Energy Density Science division at the Department of Energy's SLAC National Accelerator Laboratory.

The need for new types of proton beams

Proton beams are high-speed streams of charged particles known for their ability to damage or alter the materials they interact with. They deposit their energy in specific locations, providing precision that is not possible with other sources such as X-rays. This characteristic makes them valuable for diverse applications from

treating tumors to etching tiny features on microchips and semiconductors. But generating these ultrafast, energetic beams is challenging.

Conventional particle accelerators, such as synchrotrons, rely on a series of electromagnets to accelerate, steer and focus particle beams. Though these accelerators have driven countless discoveries in fundamental science, their size limits their ability to be deployed in industrial and clinical applications.

For example, some advanced medical centers use proton beams to target cancerous tissues, damaging tumors while sparing healthy cells. Developing smaller, more affordable proton beam sources could expand the range of medical treatments offered by such centers and open entirely new fields for this technology.

The promise of laser-plasma acceleration

Enter laser-plasma accelerators (LPAs). LPAs use high-intensity lasers to strike a target, generating charged particle beams that reach comparable speeds to those produced using traditional accelerators—but at a fraction of the distance. Scientists are exploring LPAs as a compact, cost-effective way to generate proton beams, but several technical challenges have hindered their progress.

One challenge arises from the high-intensity laser, which destroys the targets after each pulse, requiring a new target for every shot. Another issue is the beam divergence—proton beams produced by LPAs typically spread out like a floodlight rather than maintaining a narrow focus. Both the need for target replacement and the beam divergence significantly reduce the efficiency of LPA systems.

Just add water

In this recent study, researchers made an unexpected breakthrough, simultaneously resolving multiple problems although they had only aimed to address one.

Working at the STFC Rutherford Appleton Laboratory's Central Laser Facility, the team tested a novel target, developed by researchers at SLAC, to tackle the

inefficiency of replacing targets after each laser pulse. Instead of using a traditional solid target, they introduced a thin sheet of water—a self-regenerating stream that replenishes after each shot. When the laser struck the water, it generated a proton beam as anticipated.

But then, something surprising happened. The evaporated water formed a vapor cloud around the target, which interacted with the proton beam to create magnetic fields. These fields naturally focused the beam, resulting in a brighter, more tightly aligned proton beam.

Compared to similar experiments with solid targets, the water sheet reduced the proton beam's divergence by an order of magnitude and increased the beam's efficiency by a factor of 100. The proton beam exhibited remarkable stability, consistently operating at five pulses per second over hundreds of laser shots.

"This effect was completely unexpected," said Griffin Glenn, a Stanford University Ph.D. student involved in designing the water sheet target and conducting data analysis and the second author on the paper. The multitude of variables in this experiment—including the detailed properties of the laser, water sheet, and the vacuum environment—made such predictions impossible.

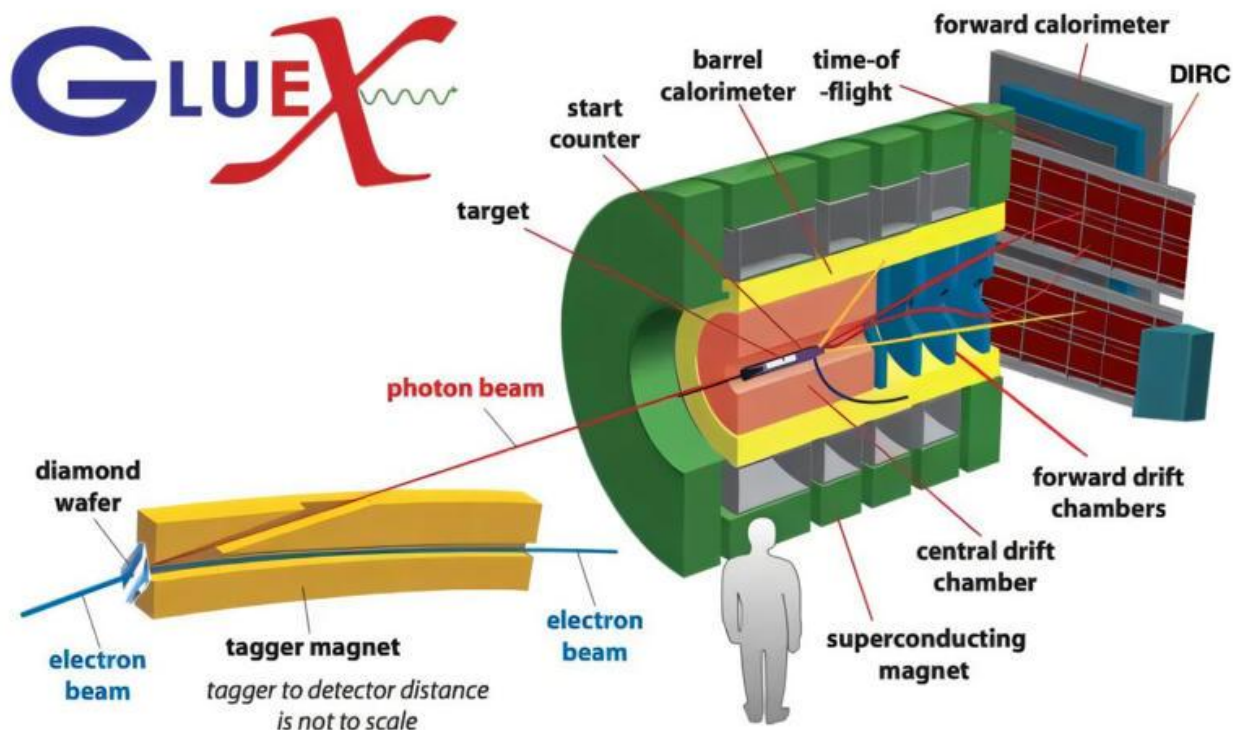
However, after observing the phenomenon, the team used experimental data to model and gain a deeper understanding of the underlying forces driving the effect. The team's findings suggest that this approach could be scaled to higher-energy systems, enabling even brighter and more energetic proton beams.

"This work has shifted the whole paradigm," Glenzer said. "Finally, we are no longer totally reliant on simulations. We can now drive the physics from an experimental point of view, testing different laser intensities, target densities, and environmental pressures. The entire physics regime is in front of us."

Notably, the proton beam consistently delivered the equivalent of 40 Gray with each shot, a standard radiation dosage used in proton therapies never before achieved with LPAs operating at this repetition rate. Furthermore, the results were achieved using an easily accessible low-energy laser system, marking a major advance toward preparing LPAs for practical applications in medicine and industry.

More information: M. J. V. Streeter et al, Stable laser-acceleration of high-flux proton beams with plasma collimation, *Nature Communications* (2025). DOI: [10.1038/s41467-025-56248-4](https://doi.org/10.1038/s41467-025-56248-4)

In a first, physicists set an upper limit in the search for hybrid mesons



Credit: Carnegie Mellon University

Carnegie Mellon University's Professor Curtis Meyer and his research colleagues explore an uncharted world inside protons and neutrons. For the first time, researchers have provided measurements describing a maximum boundary for a subatomic particle known as a hybrid meson in a journal paper [published](#) in *Physical Review Letters*. The measurements show scientists a path forward in a search for these elusive particles that provide a new look at the force that holds all matter together.

"The stage is set for future discoveries," said Meyer, senior associate dean for CMU's Mellon College of Science and the Otto Stern Professor of Physics. "We're at an exciting phase where we're able to analyze a great deal of data. This paper is the first to address one of the experiment's foundational questions."

Applying a symmetry property of the strong force, the team set the upper limit on the photoproduction cross sections of a hybrid meson known as the spin-exotic $\pi_1(1600)$.

Exotic-hybrid mesons are subatomic particles that have been theorized, but definitive experimental confirmation is still pending. By producing an exotic-hybrid meson, researchers aim to tease apart information about gluons—the carrier of the strong force, or the "glue," that binds a quark and antiquark together within mesons and all matter.

Meyer's work is with the Gluonic Excitation (GlueX) Experiment at Thomas Jefferson National Accelerator Facility in Newport News, Virginia. Using Jefferson Lab's Continuous Electron Beam Accelerator Facility, he is searching for new forms of matter, specifically the particles that hold quarks together in hybrid mesons.

Exotic-hybrid mesons are of particular interest to the research group because the gluons could potentially exist in an excited state. Understanding this state could reveal information about how subatomic particles are built and why quarks are never found alone in the universe.

Co-author Will Imoehl, a postdoctoral research associate in Carnegie Mellon's Department of Physics since 2022, conducted data analysis for the project. He described the measurements as important groundwork for future analysis.

"We showed that one type of reaction is more promising to look for the $\pi_1(1600)$ than the other ones," Imoehl said. "It set a road map of how we will search for hybrid mesons."

CMU's Reinhard A. Schumacher, faculty emeritus in physics, also contributes to the GlueX Experiment. Nine CMU graduate students have participated in the GlueX Experiment as well. Worldwide, the GlueX team is made up of approximately 150 physicists from 13 countries, with many other past contributors.

"One of my favorite parts of this project is how collaborative all of it is," Imoehl said. "It takes hundreds of people to make any of these experiments work."

Meyer led the \$60 million effort to design, build and commission the GlueX Experiment, and served as the project's elected spokesperson from 2007–2020. A fellow of the American Physical Society since 2004, Meyer has conducted research at national and international labs, including CERN and the U.S. Department of Energy's Brookhaven National Lab and Jefferson Lab.

From 2010 to 2013, a Carnegie Mellon team, led by Meyer, built a particle detector in Wean Hall and transported it to Jefferson Lab for use in the experiment. In 2016, the GlueX Experiment received its first data for analysis.

"It was terra incognita when we started, but now we have a better understanding of the accelerator and the reactions of the experiments," Meyer said. "We are continually churning out data."

More information: F. Afzal et al, Upper Limit on the Photoproduction Cross Section of the Spin-Exotic $\pi_1(1600)$, *Physical Review Letters* (2024). DOI: [10.1103/PhysRevLett.133.261903](https://doi.org/10.1103/PhysRevLett.133.261903). On *arXiv*: DOI: [10.48550/arxiv.2407.03316](https://doi.org/10.48550/arxiv.2407.03316)

Provided by Carnegie Mellon University

Genetics and Evolution

Quantum computing represents a monumental leap in computational power, with the potential to revolutionize fields as diverse as cryptography, medicine, and artificial intelligence. One especially promising area for its application is the study of animal genetics and evolution. The complex interplay of DNA that determines traits, adaptations, and evolutionary progressions of species is a challenge that demands immense computational resources. As researchers delve deeper into the mysteries of genetics, the emergence of quantum computing offers a powerful new tool to uncover the hidden mechanics of life on Earth.



The Intersection of Quantum Computing and Genetics

In genetics, researchers deal with vast datasets that detail the structure, function, and evolution of DNA. Understanding how genes influence traits or drive evolution often requires solving optimization problems and performing extensive simulations. Traditional computing methods are limited by their sequential processing capabilities. Quantum computing, on the other hand,

offers a paradigm shift by enabling faster processing of these datasets and more efficient modeling of genetic interactions.

Potential Applications in Animal Genetics

Quantum computing could revolutionize several aspects of animal genetics research. For instance, it might enable more efficient genome sequencing, allowing scientists to sequence and analyze the DNA of various species rapidly and more accurately. Another application could be in simulating genetic variations across populations to study how environmental pressures influence evolutionary changes. Furthermore, quantum computing could facilitate a deeper understanding of epigenetic factors, which play a crucial role in gene expression and adaptation.

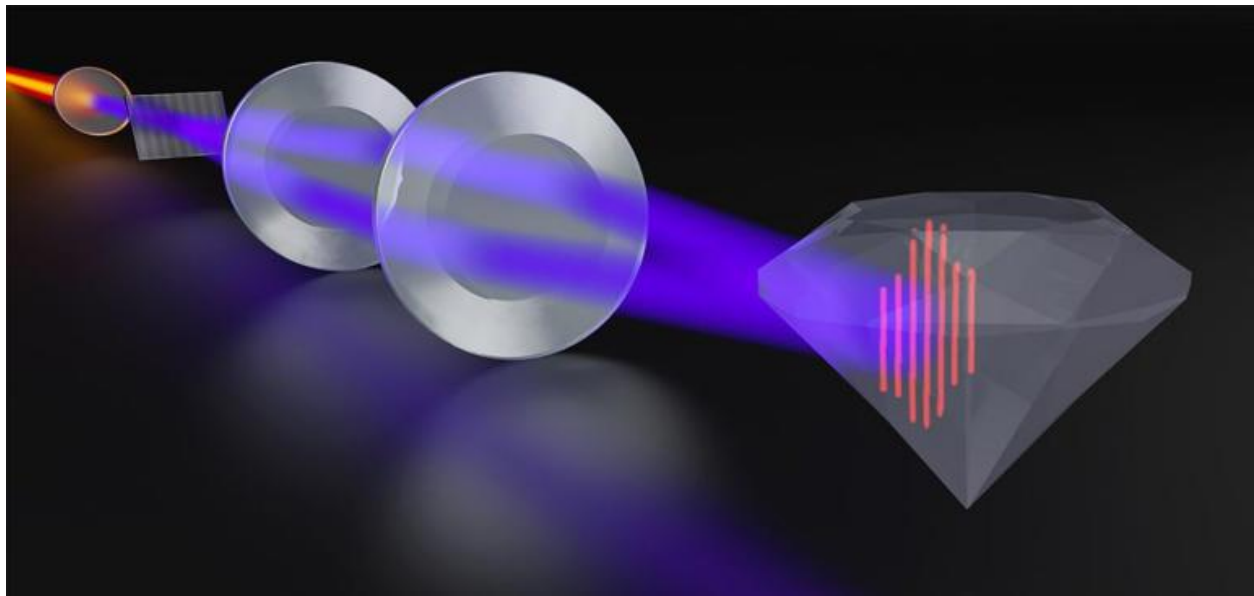
Decoding Evolutionary Mysteries Quantum computing may also unlock new avenues in phylogenetics, the study of evolutionary relationships among species. By analyzing genetic data from diverse species, quantum systems could model evolutionary pathways more efficiently than classical systems. This capability could help researchers trace how species diverged from common ancestors, providing a more comprehensive understanding of life's evolutionary tapestry.

Additionally, quantum algorithms could explore how environmental changes, such as climate shifts or habitat destruction, have influenced genetic evolution, enabling more accurate predictions about the future of species under changing conditions.

The integration of quantum computing into animal genetics represents an exciting and transformative frontier. As quantum technologies mature, interdisciplinary collaboration between quantum physicists, geneticists, computer scientists, and ecologists will be critical to harnessing this

technology's full potential. By applying quantum computing to genetics, researchers could develop new tools and methodologies for studying biodiversity, conserving endangered species, and understanding the forces shaping the natural world.

Powerful Ultraviolet Laser Reveals How Particles Move Through Diamonds



Schematic of how infrared light was turned into an ultraviolet laser to study diamonds. - Image Credit: Steven Burrows/Murnane and Kapteyn groups© IFL Science

Diamonds are forever and they are a girl's best friend. They are also among a class of materials known as ultrawide-bandgap semiconductors. These are seen as a key component of next-generation electronics as they can handle higher voltages, operate at higher frequencies, and are more efficient than traditional silicon designs. One issue, however, is that how electric charges and heat move in diamonds is poorly understood. Now, scientists have developed a laser-based microscope that allowed them to study this at an unprecedented scale.

[Diamonds](#) and similar materials have the quality to be transparent in visible and infrared light. To study the motion of particles in them, a more energetic form of light was required: ultraviolet light. The team had to devise a way to build a tabletop deep ultraviolet laser that would deliver the required energy and

precision. It needed to generate nanoscale heat patterns on a material surface without altering the material itself.

To do so, the team started with a near-infrared [laser](#) with a light wavelength of 800 nanometers (just at the edge of our vision). They shined it through non-linear crystals and changed its energy so that it reached shorter and shorter wavelengths, eventually getting to the deep ultraviolet (200 nanometers). The team had to go through a trial-and-error process of aligning light through three successive crystals, to achieve the hoped results.

"We brainstormed a new experiment to expand what our lab could study," lead author Emma Nelson, from the University of Colorado Boulder, said in a [statement](#). "It took a few years to get the experiment working during the pandemic, but once we had the setup, we could create patterns on a scale never before achieved on a tabletop."

The team used two beams to create a diffraction grating on the surface of the material. The wavelength is so small that it gives the nanoscale precision needed for the observations. They were indeed able to measure how heat, electrons, and mechanical waves move through materials like gold and diamonds, verifying the observations with computer simulations.

"Seeing the experiment work and align with the models we created was a relief and an exciting milestone," Nelson added.

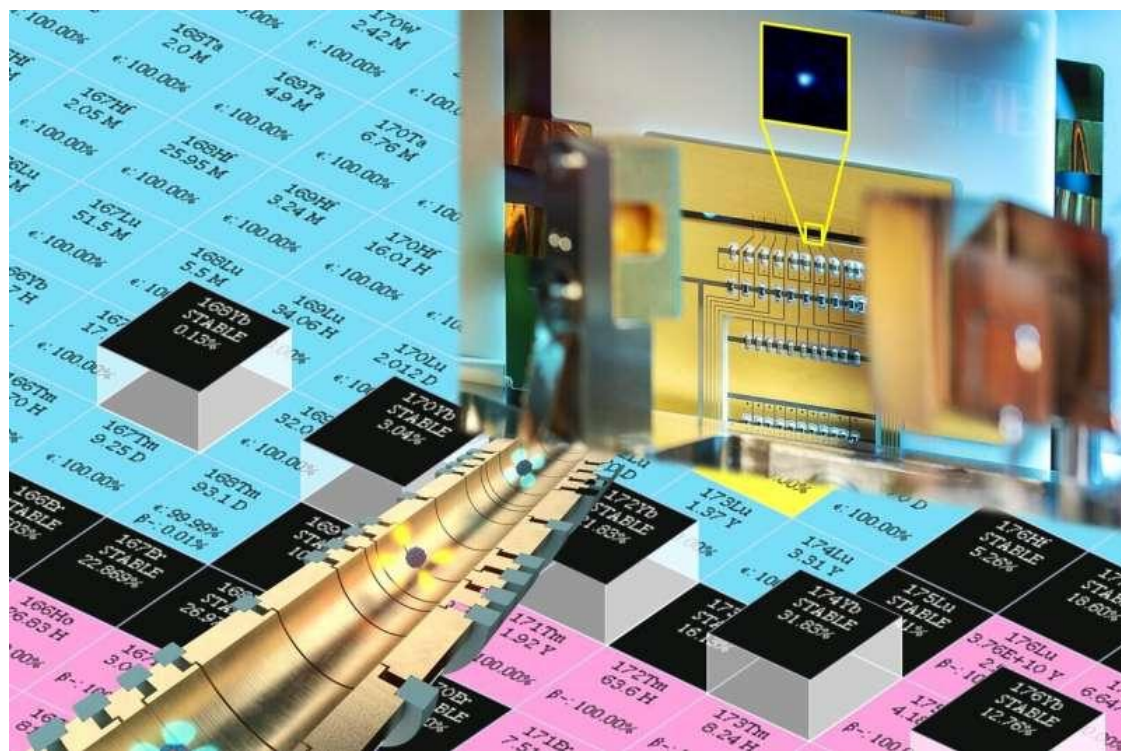
The team discovered that at the nanoscale heat transportation is not a smooth continuous flow, but it can be ballistic behavior or have some hydrodynamic effects. This means that it can move in a straight line without scattering or spreading like water flowing through channels.

The team is now planning to improve the laser microscope further and study even more material that might feature in the next-generation electronics.

The study is published in [Physical Review Applied](#).

FEBRUARY 12, 2025

Physicists find deformed nuclei when searching for 'dark forces'



PTB's ion traps (top right) and the PENTATRAP Penning trap mass spectrometer at MPIK in Heidelberg (bottom left) were used to obtain a new insight into the differences between isotopes and new limits for a "dark force". Credit: MPIK / PTB / Brookhaven National Laboratory

When world-leading teams join forces, new findings are bound to be made. This is what happened when quantum physicists from the Physikalisch-Technische Bundesanstalt (PTB) and the Max Planck Institute for Nuclear Physics (MPIK) in Heidelberg combined atomic and nuclear physics with unprecedented accuracy using two different methods of measurement.

Together with new calculations of the structure of atomic nuclei, theoretical physicists from the Technical University of Darmstadt and Leibniz University Hannover were able to show that measurements on the electron shell of an atom can provide information about the deformation of the atomic nucleus. At the same time, the precision measurements have set new limits regarding the strength of a potential dark force between neutrons and electrons.

The results have been [published](#) in the current issue of the journal *Physical Review Letters*.

For almost a century, measurements have indicated that a significant proportion of matter in the universe consists of unknown dark matter, which interacts with visible matter through gravitation. It is unclear whether there are also new, so-called "dark forces" that can "communicate" with the visible and the dark matter.

Such forces should also act on atoms, which can be analyzed with high precision nowadays. "Measuring the shift in electronic resonances in isotopes is a particularly powerful method for shedding light on the interaction between nuclear and electron structure," Tanja Mehlstäubler explains. Isotopes are different variants of an atomic element that differ only in the number of neutrons in the nucleus.

In 2020, a team at the Massachusetts Institute of Technology (MIT) discovered a deviation from the expected result—a nonlinearity—while examining such isotope shifts in the element ytterbium. This sent the world of atomic physicists into a spin: Could this anomaly be the first evidence of a new "dark force" or is it due to properties of the atomic nucleus? Did atomic physicists enter [nuclear physics](#) through the back door by comparing the transition frequencies of electrons measured in different isotopes?

Driven by this question, Tanja Mehlstäubler from PTB in Braunschweig and Klaus Blaum from MPIK in Heidelberg set out to investigate the ytterbium isotope shifts. Their research teams carried out high-precision measurements of atomic transition frequencies and isotope mass ratios of ytterbium isotopes. Linear high-frequency ion traps and ultra-stable laser systems were used for optical spectroscopy at PTB.

At MPIK, the isotope mass ratios were determined in the PENTATRAP Penning trap mass spectrometer. Both measurements were up to a hundred times more accurate than previous measurements of this kind.

The researchers confirmed the anomaly, and the team was able to provide an explanation with the help of new nuclear theory calculations by Achim Schwenk's group at TU Darmstadt. In collaboration with theoretical atomic physicists from MPIK in Heidelberg and the University of New South Wales in Sydney as well as particle physicists from Leibniz University Hannover, they were able to establish a new limit for the existence of dark forces.

The international collaboration team was even able to use this data to obtain direct information about the deformation of the atomic nucleus along the ytterbium isotope chain. This can provide new insights into the structure of heavy atomic nuclei and into the physics of neutron-rich matter, which forms the basis for understanding neutron stars.

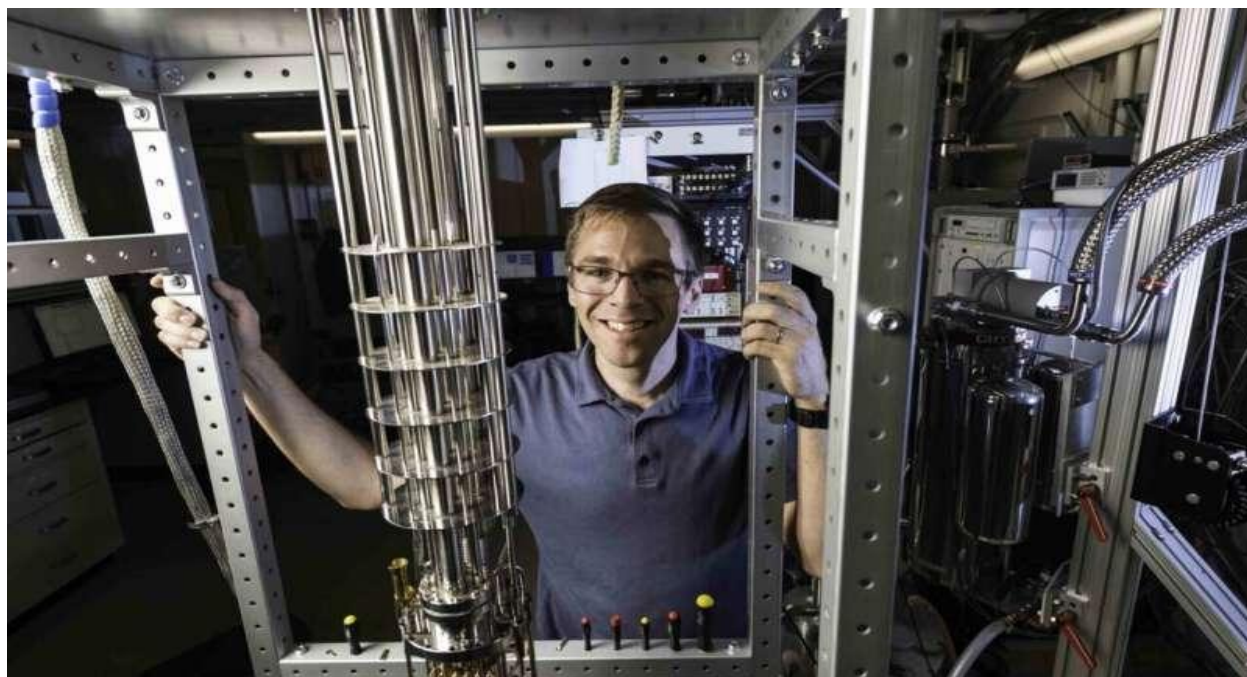
This research opens up new opportunities for atomic, nuclear and [particle physics](#) to collaborate in the search for new physics and to obtain a better understanding of the complex phenomena that determine the structure of matter.

More information: Menno Door et al, Probing New Bosons and Nuclear Structure with Ytterbium Isotope Shifts, *Physical Review Letters* (2025). DOI: [10.1103/PhysRevLett.134.063002](https://doi.org/10.1103/PhysRevLett.134.063002)

FEBRUARY 12, 2025

Scientists directly prove the existence of a nuclear-spin dark state

[University of Rochester](#)



Physicist John Nichol uses equipment such as a dilution refrigerator to study quantum systems. He recently provided the first direct evidence of a quantum state called the nuclear-spin dark state, a discovery that could lead to more efficient quantum computers and technologies. Credit: University of Rochester / J. Adam Fenster

Quantum computers have the potential to revolutionize technology by solving complex calculations and computations that are difficult, if not impossible, for traditional computers. One major roadblock, however, is instability—quantum states can be easily disrupted by "noise" from their surrounding environments, causing errors in the systems. Overcoming instability is important in creating effective and reliable quantum computers and other quantum technologies.

Researchers at the University of Rochester—including John Nichol, an associate professor in the Department of Physics and Astronomy—have taken a key step toward reducing instability in [quantum systems](#), by focusing on an elusive state called a nuclear-spin [dark state](#). Although scientists have long suspected that the nuclear-spin dark state could exist, they haven't been able to provide direct evidence of it—until now.

"By directly confirming the existence of the dark state and its properties, the findings not only validate decades of theoretical predictions but also open the door to developing more advanced quantum systems," Nichol says.

The research, [published](#) in *Nature Physics*, focuses on using [quantum dots](#)—tiny semiconductor particles that trap single electrons and use their "spin" to store information—to create a nuclear-spin dark state.

What is nuclear-spin dark state?

A nuclear-spin dark state is a special quantum state where the nucleus of an atom becomes, in essence, "hidden" from the outside world. In a nuclear-spin dark state, the tiny magnetic properties—known as spins—of atomic nuclei line up and synchronize in a way that stops them from disturbing an electron's spin. This helps to keep the electron spin stable.

Imagine an electron's spin is a soloist trying to perform, while the surrounding [atomic nuclei](#) are like an orchestra. If the musicians in the orchestra are out of sync, playing at different speeds and volumes, it can throw off the soloist. But if the orchestra members align their timing and play perfectly in sync, their sound can blend into the background, and the soloist's music will be clear and undisturbed.

Harnessing dark states for quantum technologies

Nichol and his colleagues used a technique called dynamic nuclear polarization to align the nuclear spins, creating conditions for the nuclear-spin dark state to form. They directly measured its effects and found that the dark state significantly reduced interactions between the spins of electrons and nuclei.

The research has many potential applications in quantum sensing and quantum memory technologies.

"By reducing the noise, this breakthrough will allow quantum devices to store information longer and perform calculations with great accuracy," Nichol says.

Because nuclear-spin dark states are very stable, they could be used in quantum computers and other technologies to store long-term information. They could also be used to make incredibly exact measurements by detecting tiny changes in magnetic fields, temperature, or pressure, improving medical imaging and navigation.

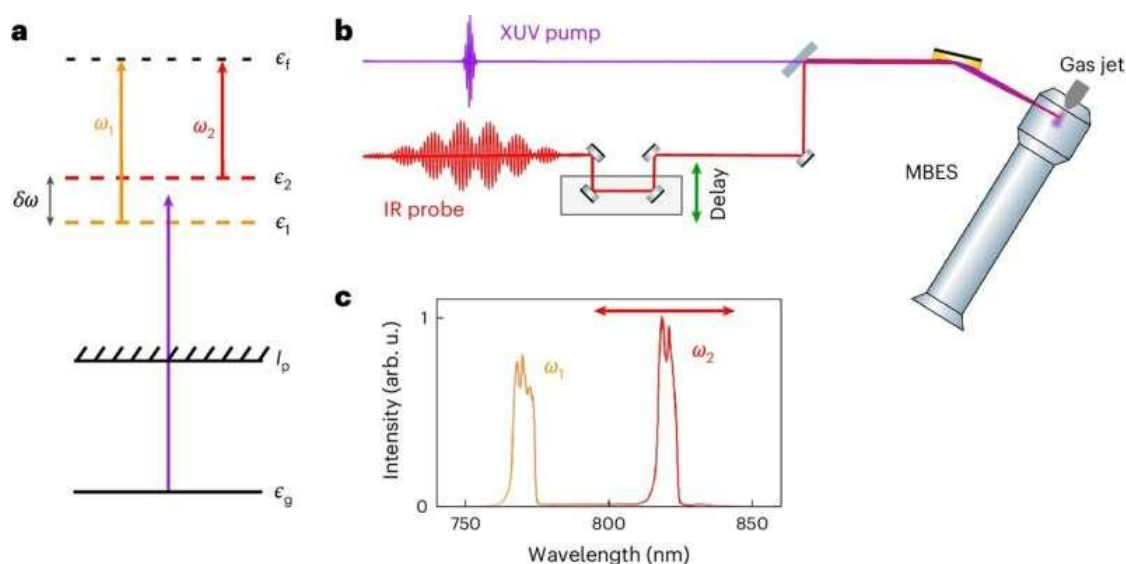
The fact that the nuclear-spin dark state was discovered in silicon makes the discovery even more exciting for possible future applications. Nichol says, "Silicon is already widely used in today's technology, which means it may someday be possible to integrate nuclear-spin dark states into future quantum devices."

More information: Xinxin Cai et al, The formation of a nuclear-spin dark state in silicon, *Nature Physics* (2025). DOI: [10.1038/s41567-024-02773-w](https://doi.org/10.1038/s41567-024-02773-w)

FEBRUARY 12, 2025

Q&A: Quantum state of photoelectrons measured for the first time

by [Lund University](#)



Principle of the KRAKEN technique. Credit: *Nature Photonics* (2025). DOI: 10.1038/s41566-024-01607-8

For the first time, researchers have been able to measure the quantum state of electrons ejected from atoms that have absorbed high-energy light pulses. This is thanks to a new measurement technique developed by researchers at Lund University in Sweden. The results can provide a better understanding of the interaction between light and matter.

When high-energy light with a very short frequency in the extreme ultraviolet or X-ray range interacts with atoms or molecules, it can cause an electron to be "detached" from the atom and ejected in a process called the [photoelectric effect](#). By measuring the emitted electron and its kinetic energy, a lot of information can be obtained about the atom being irradiated. This is the basic principle of photoelectron spectroscopy.

The electron that is emitted, known as the photoelectron, is often treated as a classical particle. In reality, the photoelectron is a quantum object that must be described quantum mechanically, as it is so small that at that scale the world is described in terms of quantum mechanics. This means that special rules applied in quantum mechanics have to be used to

describe the photoelectron, because it is not just an ordinary small particle but also behaves like a wave.

"By measuring the quantum state of the photoelectron, our technique can precisely address the question of 'how quantum is the electron.' It is the same idea used in CT scans used in medicine to image the brain: We reconstruct a complex 3D object by taking several 2D pictures of that object from many different angles," says David Busto, associate senior lecturer in atomic physics and one of the authors of the study now [published](#) in *Nature Photonics*.

This is done by producing the photoelectron quantum state, which is the equivalent of the 3D object to be measured, by ionizing atoms with ultrashort, high-energy [light pulses](#), and then using a pair of laser pulses with different colors to take the 2D pictures and reconstructing the quantum state slice by slice.

"The technique allows us to measure for the first time the quantum state of electrons emitted from helium and argon atoms, demonstrating that the photoelectron quantum state depends on the type of material from which it is emitted," says Busto.

In this interview, Busto discusses the findings.

Why are these results so interesting?

The photoelectric effect was explained over a century ago by Einstein, laying the foundations for the development of quantum mechanics. This same phenomenon was then exploited by Kai Siegbahn to study how electrons are arranged inside atoms, molecules and solids.

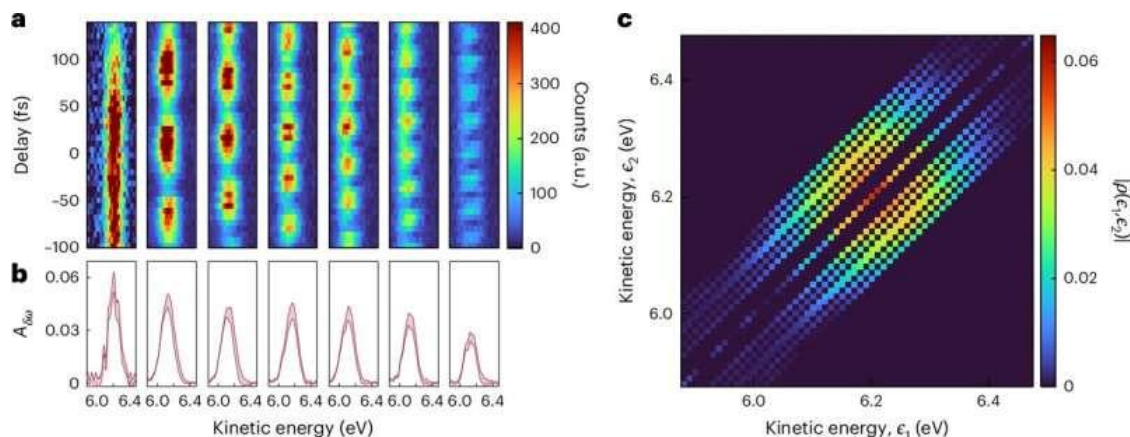
Paradoxically, this technique relies solely on measuring the classical properties of the photoelectron, such as its speed. Now, more than 40 years after Kai Siegbahn was awarded the Nobel Prize for photoelectron spectroscopy in 1981, there is finally a method that allows full characterization of the quantum properties of the emitted photoelectrons, expanding the potential of photoelectron spectroscopy. In particular, the new measurement technique provides access to [quantum information](#) that would otherwise not be available.

How can these results be useful?

We applied our technique to simple atoms, helium and argon, which are relatively well known. In the future, it could be used to study molecular gases, liquids and solids, where the quantum properties of the photoelectrons can provide a lot of information about how the ionized target reacts after the sudden loss of an electron. Understanding this process at the fundamental level could have a long-term impact on various fields of research. Examples include atmospheric photochemistry or the study of light-harvesting systems, which are systems that collect and utilize light energy, such as solar cells or photosynthesis in plants.

Another interesting aspect of this work is that it bridges two different areas of science: attosecond science and spectroscopy (the kind of research that Nobel Prize laureate Anne

L'Huillier is conducting) on the one hand, and quantum information and quantum technology on the other hand.



Experimental results obtained with the KRAKEN protocol in the case of photoionization of helium atoms. Credit: *Nature Photonics* (2025). DOI: 10.1038/s41566-024-01607-8
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How might this study be important to the public?

This work is connected to the ongoing second quantum revolution, which aims to manipulate individual quantum objects (in this case photoelectrons) to harness the full potential of their quantum properties for various applications. Our quantum state tomography technique will not lead to the construction of new quantum computers, but by providing access to knowledge about the quantum state of the photoelectrons, it will allow physicists to fully exploit their quantum properties for future applications.

What can the discovery be used for?

By measuring the speed and emission direction of the photoelectron, we can learn a lot about the structure of the material. This is essential, for example, to study the properties of new materials. Our technique allows us to go beyond previous methods by measuring the complete quantum state of the photoelectron. This means that we can gather more information about the target than is possible with traditional photoelectron spectroscopy. It is hoped that our technique can help unravel the processes that occur in the material after the electron has been ejected.

Was there anything in the results that surprised you?

The most surprising aspect is that our technique worked so well. Physicists had already tried to measure the quantum state of photoelectrons using a different method, and those experiments showed that it is very difficult. Everything has to be very stable over a long period of time, but we finally managed to achieve these very stable conditions.

When do you choose to describe/study things quantum mechanically and not according to classical physics?

At the microscopic scale, electrons, atoms and molecules are described quantum mechanically, while on a macroscopic scale, the objects we experience in everyday life follow the laws of classical physics. Atoms and other microsystems do not behave like everyday objects.

With a deliberate exaggeration, it could be said that they do not exist in the usual sense, with a well-defined point and with well-defined speed. The only thing that is known is the output of the laboratories' instruments. Since all macroscopic objects are made up of atoms and molecules that obey the laws of [quantum mechanics](#), we might ask why we do not see quantum effects at the macroscopic scale.

In short, the reason is that when we put many quantum objects close to each other, they start to affect each other in an uncontrolled way, effectively canceling out their individual quantum properties. This process is referred to as decoherence and is one of the key challenges that must be overcome to develop quantum technologies, such as quantum computers.

The electrons emitted during the photoelectric effect contain a lot of information about the irradiated material. By measuring the quantum state of the photoelectron, our technique can precisely address the question of "how quantum is the electron." In the future, we hope that our technique will allow us to follow how the quantum properties of electrons evolve over time from quantum to classical.

The new experimental measurement technique is called KRAKEN.

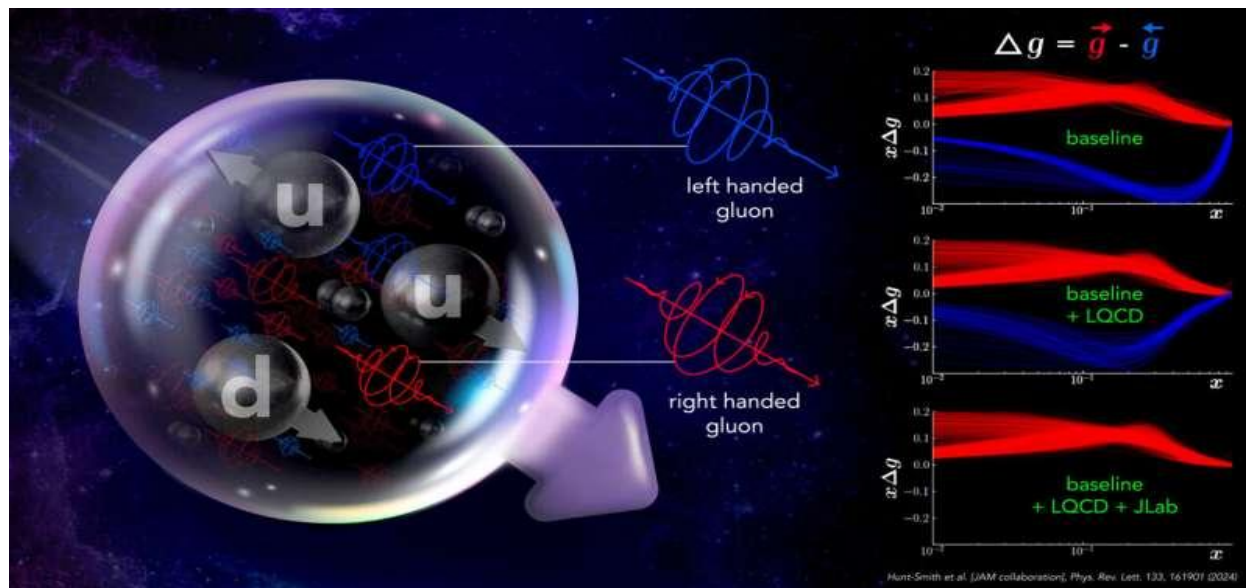
More information: Hugo Laurell et al, Measuring the quantum state of photoelectrons, *Nature Photonics* (2025). DOI: [10.1038/s41566-024-01607-8](https://doi.org/10.1038/s41566-024-01607-8)

Journal information: [Nature Photonics](#)

Provided by [Lund University](#)

Homing in on Δg : Study nearly nixes negative gluon spin

Thomas Jefferson National Accelerator Facility



Polarized proton containing spinning quarks and gluons (represented by right-handed and left-handed spirals). The negative Δg solutions (blue) are disfavored relative to the positive Δg solutions (red) after the addition of lattice QCD and Jefferson Lab data. Credit: DOE's Jefferson Lab

Researchers have been working for decades to understand the architecture of the subatomic world. One of the knottier questions has been where the proton gets its intrinsic angular momentum, otherwise referred to as its spin.

Nuclear physicists surmise that the proton's spin most likely comes from its constituents: quarks bound together by gluons carrying the strong force. But the details of the quark and gluon contributions have remained elusive.

Now, a new investigation from an international collaboration of physicists compiles evidence from observational results and analysis using lattice quantum chromodynamics (QCD) to present a compelling argument regarding how much of the proton's spin comes from its gluons.

A new paper featuring the results of the investigation, "New Data-Driven Constraints on the Sign of Gluon Polarization in the Proton," [appears](#) in the journal *Physical Review Letters*, authored by members of the Jefferson Lab Angular Momentum (JAM) collaboration. The collaboration includes theorists, experimentalists and computer scientists who investigate

subatomic particles' internal structure through QCD. QCD is a theory that describes how quarks and gluons interact via the strong force.

The authors, members of the JAM collaboration's Spin PDF Analysis Group, are Wally Melnitchouk and Nobuo Sato of the U.S. Department of Energy's Thomas Jefferson National Accelerator Facility; Nicholas Hunt-Smith, Anthony Thomas and Martin White, of the Centre for the Subatomic Structure of Matter (CSSM) and the ARC Centre of Excellence for Dark Matter Particle Physics in the Department of Physics at the University of Adelaide, Australia; and Christopher Cocuzza of the William & Mary Department of Physics.

Thomas noted that Jefferson Lab's fruitful connection with the University of Adelaide goes back decades, with the physicists working together in spite of a time difference of 14.5 hours.

"Many years ago, Wally held a joint position between Adelaide and Jefferson Lab when Nathan Isgur was chief scientist," Thomas said. "And I was at Jefferson Lab for six years as chief scientist, from 2004 to 2009. The physics collaboration has been ongoing."

The group's latest work addresses a knotty question that must first be resolved in order to make progress on the understanding of the origin of the proton's spin: What's the sign of Δg ? In other words, is the gluons' spin negative or positive?

The proton's intrinsic spin

When physicists discuss the spin of a proton—or any particle—they're referring to its [intrinsic angular momentum](#). As physicists' concept of subatomic spin is a quantum mechanical idea, explanations from our visible world only go so far; it carries this angular momentum even when it is at rest. Spin can be negative or positive—think clockwise and counterclockwise.

"Spin is a peculiar characteristic of the quantum world," Sato explained, "and the proton has spin of one-half. It's not .51, it's not .501. It's not .50001. It's .5. And that number is made of the components inside the proton, each of which has its own spin."

Melnitchouk said the value of the spin of the proton has been known since the 1920s. He added that it makes sense that the spin of the proton comes from the aggregate spins of the constituents making up the protons.

"What we don't know is: What portion of the proton's spin is carried by the three valence quarks in the proton? What portion is carried by gluons?" he said. "What portion is maybe due to the rotation, the orbital angular momentum, of the quarks and gluons in the proton?"

Nailing down the sign of Δg is vital to figuring out how the proton gets its spin, and years of observational work as well as theory have not delivered a conclusive answer.

Most physicists thought a positive Δg seemed more likely, but "these negative Δg solutions have always been sticking around," Hunt-Smith said. "There's no reason why we can't have a negative Δg , just from a purely physics perspective."

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A new analysis with world-first data

The JAM collaborators built their findings from previous analytical work as well as older and newer observational data from a number of experiments, including programs at Jefferson Lab's Continuous Electron Beam Accelerator Facility (CEBAF) and at the Relativistic Heavy Ion Collider (RHIC) at DOE's Brookhaven National Lab. Both of these particle accelerators are DOE Office of Science user facilities, which are used by [nuclear physicists](#) from around the world to conduct their research.

"Our analysis was different from other groups, in that we really tried as much as possible to remove theoretical assumptions about how things should behave," Melnitchouk said.

One such assumption was that unpolarized parton distributions have to have a probabilistic interpretation. Melnitchouk acknowledged that this assumption regarding partons (the collective term for gluons, quarks and other constituent particles inside the proton) is a "technicality."

"But it's something that has been assumed in previous analyses by other groups around the world," he added. "And we now believe that's not really something that is fundamental."

Melnitchouk said that originally, observational data from RHIC created a global consensus leading in the direction of a positive Δg .

"But further analysis made things less clear," he noted, "because there was a corner of parameter space that allowed for both positive and negative gluon spin."

He said the JAM collaborators published a paper a couple years ago that pointed out that negative Δg was still a viable possibility. That paper was controversial, as it bucked the common wisdom of the global nuclear physics community at the time, which leaned heavily in the direction of a positive gluon spin.

Meanwhile, the HadStruc collaboration had been addressing the same question in a different way. They were using supercomputers and the lattice QCD formulation to calculate the underlying QCD theory that describes the interactions among quarks and gluons in the proton.

"You basically discretize space-time," Hunt-Smith explained. "You cut space-time into a series of slices, and it makes it possible to calculate a lot of physical properties."

A subsequent joint JAM and HadStruc collaboration analysis, led by Joe Karpie, the Nathan Isgur Fellow in the Theory Center, combined the new lattice QCD results with the experimental data, noting that while this narrowed the room, it still admitted a negative Δg .

"There was a slight preference for the positive solution, but still not statistically significant," Hunt-Smith said. "This is where our new research comes in."

Energetic particles add new data for analysis

He went on to explain how the collaborators included data from deep-inelastic scattering experiments, including those using CEBAF at Jefferson Lab.

"You take an electron and fire it at a proton, and the idea is that you're able to probe what's inside the proton—the various quarks and gluons that are inside it—and you can understand more of the structure of the proton in that way," he said.

Hunt-Smith said the JAM group particularly focused on the high- x data from the deep-inelastic scattering experiments, the particularly significant bits of the results. This data refers to particles that have been detected with particularly high momentum—or very high energy—resulting from the electron's collision with the constituents of the proton. He noted that incorporation of the high- x data required some additional theoretical considerations.

"So, we added that theory in," he said. "We added more parameters into the analysis to account for that additional high- x data, and then we reran the analysis. And we found that with the inclusion of the high- x data, there was a statistically significant difference between the positive and negative Δg replicas, the key finding being that the negative ones were heavily disfavored."

Hunt-Smith went on to add that the JAM analysis showed that the Δg was constrained by not just the high- x data from deep-inelastic scattering, but also by the results of polarized-jets experiments from a different set of proton-collision studies at RHIC, as well as the recent HadStruc lattice QCD data.

The results are not completely definitive, but the analysis makes a negative Δg gluon far less likely than ever.

"I don't think anybody else has included this Jefferson Lab data in any analysis. I think it's a very important feature of this analysis," Thomas said. "This is a very comprehensive dataset of regions that nobody else has been able to get to, and it's the first time it's been included in a comprehensive global analysis."

Sato said that while the JAM paper makes negative Δg less likely, it doesn't completely close the door to the possibility. He added that additional observational data from instruments such as Jefferson Lab's ongoing CEBAF 12 GeV research program or the future Electron-Ion Collider would likely be capable of replacing remaining theoretical assumptions. Jefferson Lab is a partner with Brookhaven National Laboratory in designing and establishing the Electron-Ion Collider at Brookhaven.

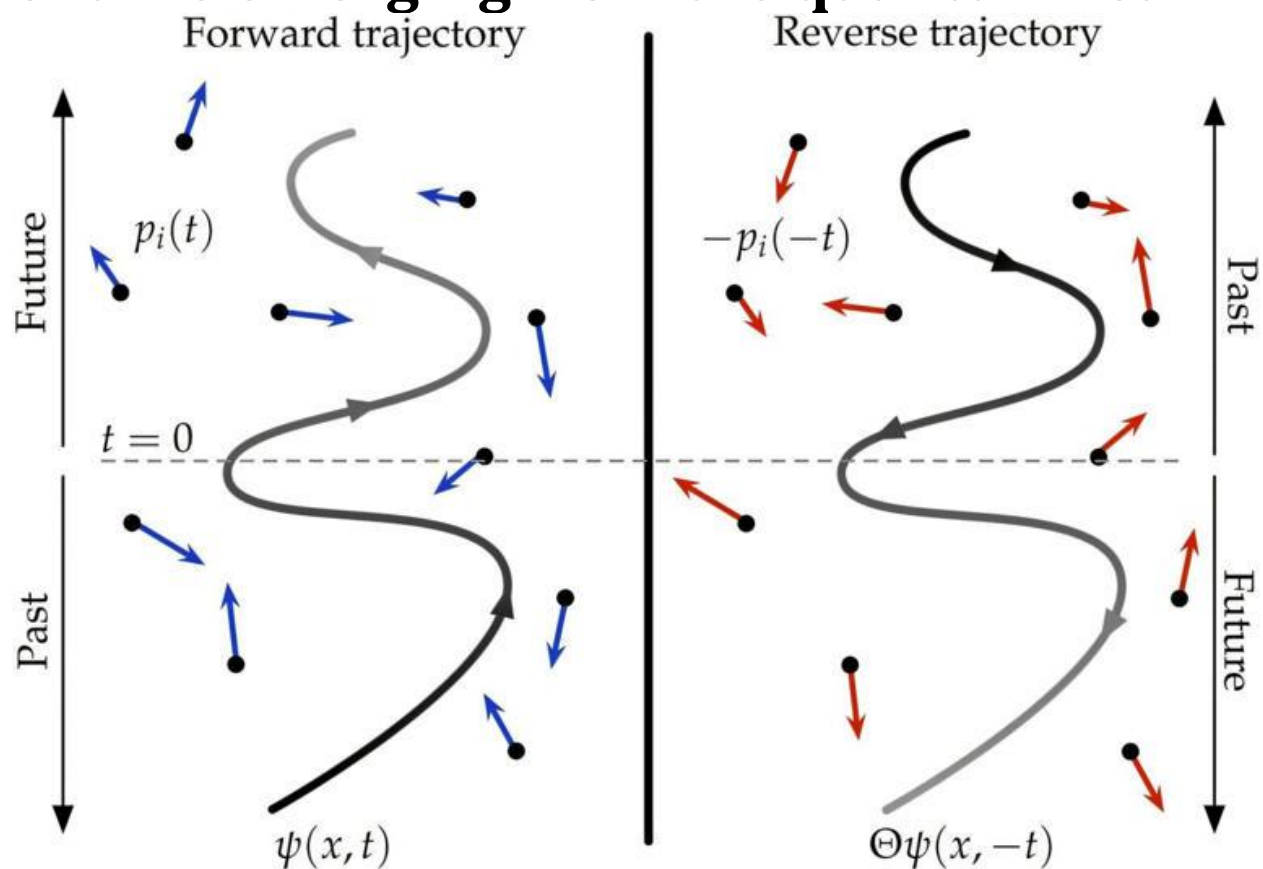
"Then it is possible that the door will be 100% closed," he said. "But now we are basically closing that gap."

More information: N. T. Hunt-Smith et al, New Data-Driven Constraints on the Sign of Gluon Polarization in the Proton, *Physical Review Letters* (2024). DOI: [10.1103/PhysRevLett.133.161901](https://doi.org/10.1103/PhysRevLett.133.161901)

Journal information: [Physical Review Letters](#)

Provided by [Thomas Jefferson National Accelerator Facility](#)

Physicists uncover evidence of two arrows of time emerging from the quantum realm



Schematic showing the concept behind the time-reversal transformation. The system and environment move backward in time. Credit: Scientific Reports (2025). DOI: 10.1038/s41598-025-87323-x

What if time is not as fixed as we thought? Imagine that instead of flowing in one direction—from past to future—time could flow forward or backwards due to processes taking place at the quantum level. This is the thought-provoking discovery made by researchers at the University of Surrey, as a new study reveals that opposing arrows of time can theoretically emerge from certain quantum systems.

For centuries, scientists have puzzled over the arrow of time—the idea that time flows irreversibly from past to future. While this seems obvious in our experienced reality, the underlying laws of physics do not inherently favor a single direction. Whether time moves forward or backwards, the equations remain the same.

Dr. Andrea Rocco, Associate Professor in Physics and Mathematical Biology at the University of Surrey and lead author of the study, said, "One way to explain this is when you look at a process like spilled milk spreading across a table, it's clear that time is moving forward. But if you were to play that in reverse, like a movie, you'd immediately know something was wrong—it would be hard to believe milk could just gather back into a glass.

"However, there are processes, such as the motion of a pendulum, that look just as believable in reverse. The puzzle is that, at the most fundamental level, the laws of physics resemble the pendulum; they do not account for irreversible processes.

"Our findings suggest that while our common experience tells us that time only moves one way, we are just unaware that the opposite direction would have been equally possible."

The study, [published in *Scientific Reports*](#), explored how a quantum system—the world of the sub-atomic—interacts with its environment, known as an "open quantum system."

Researchers investigated why we perceive time as moving in one direction, and whether this perception emerges from open quantum mechanics.

To simplify the problem, the team made two key assumptions. First, they treated the vast environment surrounding the system in such a way that they could focus only on the quantum system itself. Second, they assumed that the environment—like the entire universe—is so large that energy and information dissipate into it, never returning.

This approach enabled them to examine how time emerges as a one-way phenomenon, even though, at the microscopic level, time could theoretically move in both directions.

Even after applying these assumptions, the system behaved the same way whether time moved forward or backwards. This discovery provided a mathematical foundation for the idea that time-reversal symmetry still holds in open quantum systems—suggesting that time's arrow may not be as fixed as we experience it.

Thomas Guff, postdoctoral researcher who led the calculations, said, "The surprising part of this project was that even after making the standard simplifying assumption to our equations describing open quantum systems, the equations still behaved the same way whether the system was moving forwards or backwards in time.

"When we carefully worked through the math, we found that this behavior had to be the case because a key part of the equation, the 'memory kernel,' is symmetrical in time.

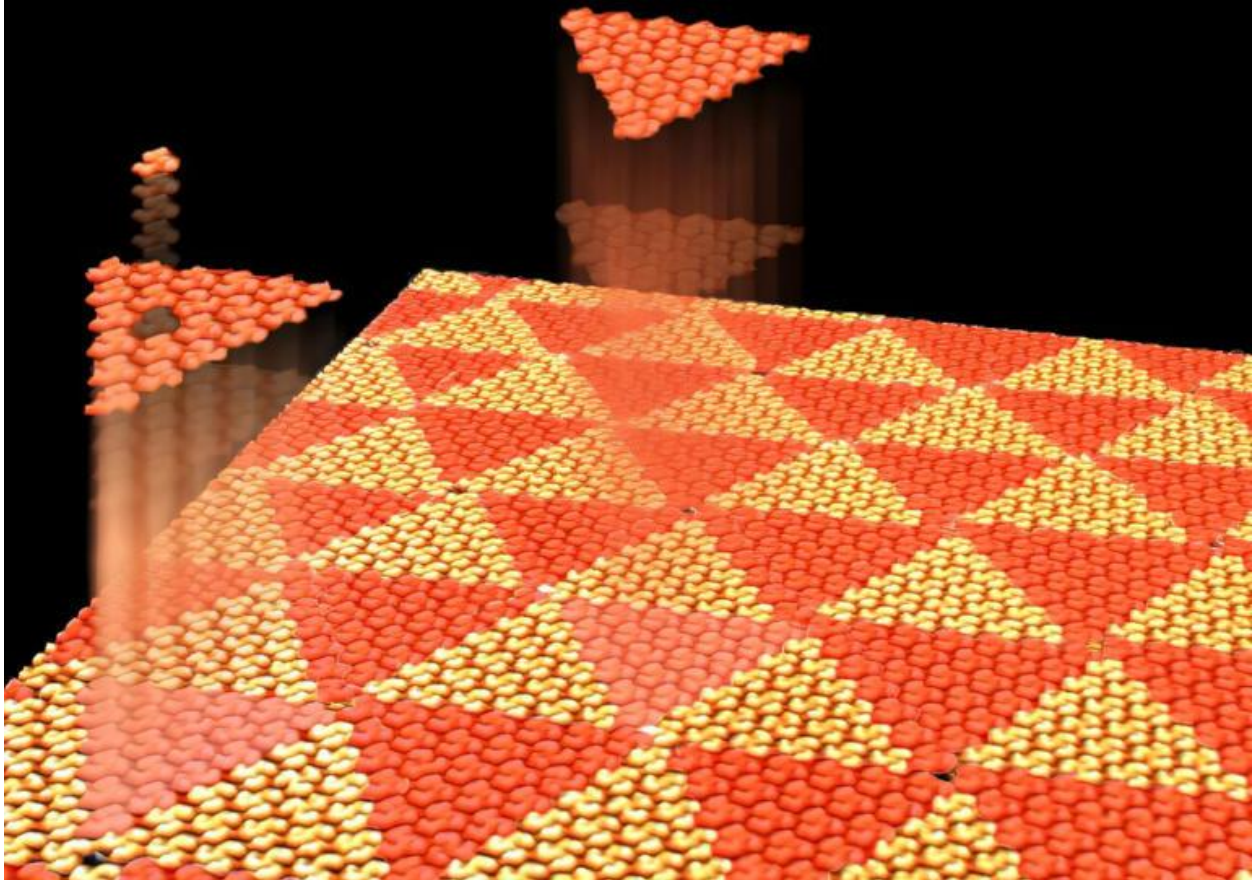
"We also found a small but important detail which is usually overlooked—a time discontinuous factor emerged that keeps the time-symmetry property intact. It's unusual to see such a mathematical mechanism in a physics equation because it's not continuous, and it was very surprising to see it pop up so naturally."

The research offers a fresh perspective on one of the biggest mysteries in physics. Understanding the true nature of time could have profound implications for quantum mechanics, cosmology and beyond.

More information: Thomas Guff et al, Emergence of opposing arrows of time in open quantum systems, *Scientific Reports* (2025). DOI: [10.1038/s41598-025-87323-x](https://doi.org/10.1038/s41598-025-87323-x)

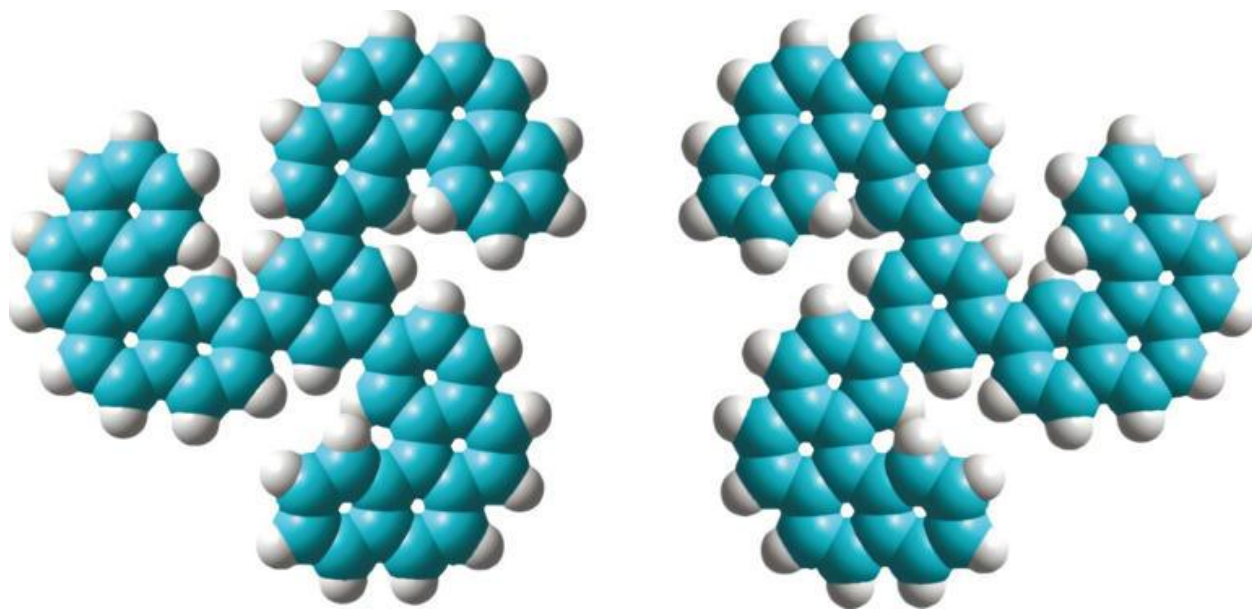
Provided by University of Surrey

The einstein problem: Molecular chirality leads to unexpected aperiodic patterns on metal surfaces



Triangles and defects: Due to the chirality – the handedness – of the molecules, the individual triangular tiles never fit together perfectly. Defects and offsets occur, which give the surface its aperiodicity. Credit: Swiss Federal Laboratories for Materials Science and Technology

Standing at the intersection between mathematics and the tiler's trade is the so-called einstein problem. Despite its name, this mathematical question has nothing to do with the Nobel Prize winner Albert Einstein. It asks: Can you seamlessly tile an endless surface with a single shape (an "einstein") in such a way that the resulting pattern is never repeated? Such a "proto-tile" was first discovered in 2022 by the English amateur mathematician David Smith.



The researchers used a molecule called tris(tetrahelicenebenzene) or t[4]HB, which can easily change its handedness. Credit: Swiss Federal Laboratories for Materials Science and Technology

Empa researcher Karl-Heinz Ernst is neither a mathematician nor a tiler. As a chemist, he researches the crystallization of molecules on metal surfaces. He never expected to deal with the einstein problem in his professional life—until his doctoral student Jan Voigt approached him with the unusual results of an experiment.

When a certain molecule crystallized on a silver surface, instead of the expected regular structure, irregular patterns were formed that never seemed to repeat themselves. Even more surprising: Each time he repeated the experiment, different aperiodic patterns emerged.

Like all good researchers, Ernst and Voigt initially suspected an experimental error. But it soon became clear that the strange finding was real. The next step was to find out why the molecules behaved in such a unique way. The researchers recently [published](#) the answer to this question in the journal *Nature Communications*.

Unexpected effects

Ernst and Voigt are interested in so-called chirality, the "handedness" that characterizes many organic molecules. Although chiral structures are chemically

identical, they cannot be rotated into one another—similar to our right and left hands. This property is particularly important in the pharmaceutical industry. More than half of all modern medicines are chiral.

Since biomolecules such as amino acids, sugars and proteins in our body all have the same handedness, active pharmaceutical ingredients must also be chiral. A drug with the wrong handedness is ineffective at best and at worst even harmful.

Controlling handedness during the synthesis of organic molecules is therefore of enormous interest in chemistry. One of the possibilities is the crystallization of chiral molecules. It is cheap, effective and widely used—and yet not fully understood.

The Empa researchers originally wanted to further this understanding with their experiment. To do this, they took a very special molecule, one that easily changes its handedness at room temperature—something that most chiral molecules practically never do.

"We expected the molecules to arrange themselves in the crystal according to their handedness," explains Karl-Heinz Ernst, "that is, either alternating or in groups with the same handedness." Instead, the molecules seemingly randomly arranged themselves into triangles of different sizes, which in turn formed irregular spirals on the surface—the non-repeating or aperiodic structure that the researchers initially thought was a mistake.

From puzzle pieces to physics

After a lot of puzzling, Voigt and Ernst finally managed to decipher the molecular patterns—not only through physics and mathematics, but also by trying them out with actual puzzle pieces on the computer or even at home at the kitchen table. The arrangement of the molecules is not completely random. They form triangles that measure between 2 and 15 molecules per side. In each experiment, one triangle size dominated. What's more, triangles one size larger and one size smaller were also represented—but no others.

"Under our experimental conditions, the molecules 'want' to cover the silver surface as densely as possible because this is the most energetically favorable

outcome," explains Ernst. "However, due to their chirality, the triangles they form do not fit together exactly at the edges and have to be slightly offset."

The smaller and larger triangles are needed to fill the surface as efficiently as possible. This arrangement also creates defects in some places—small inconsistencies or holes that can become the center of a spiral.

Entropy decides

"Defects are actually unfavorable in terms of energy," Ernst continues. "In this case, however, they enable a denser arrangement of the triangles, which compensates for the 'lost' energy." This balance also explains why the researchers never found the same pattern twice: If all patterns are the same in terms of their energy cost, entropy decides.

The mystery of the "molecular einstein" has been solved—but how does this insight benefit us? "Surfaces with defects at the atomic or molecular level can have unique properties," explains Ernst. "For an aperiodic surface like ours in particular, it has been predicted that the electrons in it would behave differently and that this could give rise to a new kind of physics."

To investigate this, however, the aperiodic molecule would have to be studied under the influence of magnetic fields on a different surface. Karl-Heinz Ernst, who has recently retired, is leaving this task to others. "I have a little too much respect for physics," smiles the chemist.

More information: Jan Voigt et al, An aperiodic chiral tiling by topological molecular self-assembly, *Nature Communications* (2025). DOI: [10.1038/s41467-024-55405-5](https://doi.org/10.1038/s41467-024-55405-5)

Provided by Swiss Federal Laboratories for Materials Science and Technology

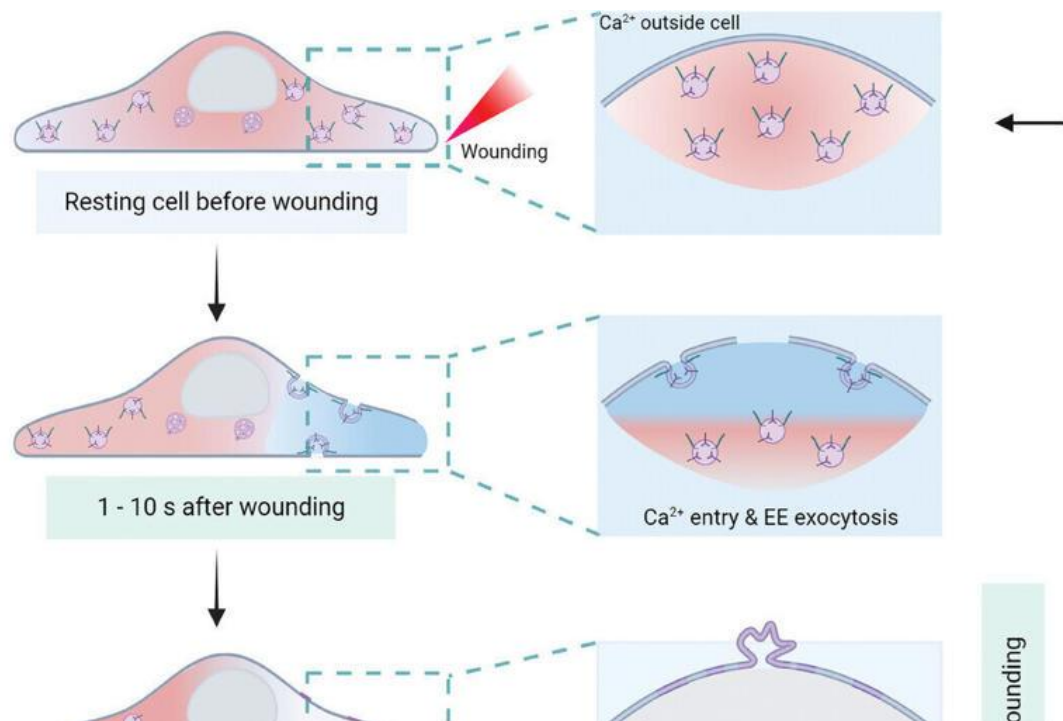
Wound healing at a smaller scale: Study reveals membrane tension regulates cellular repair

Dr. Nikita Raj, first and co-corresponding author of the study, working in the lab. Credit: Uni Münster/M. Ibrahim

Similar to a small cut that heals itself after a short time, individual cells in our body suffer "wounds" in their protective layer, the cell membrane, every day and have to repair them again.

Researchers at the University of Münster have now identified the processes that enable the precise closure of such membrane injuries. Their findings were recently [published](#) in the journal *Advanced Science*.

For their experiments, the team led by Prof. Volker Gerke from the Institute of Medical Biochemistry studied endothelial cells, which line the blood vessels. "We know that endothelial cells frequently experience membrane damage caused by changes in normal blood flow, and these cells must repair the damage to prevent cell death. To examine this process in detail, we used a laser to create controlled defects in the cells and observed their repair in real-time under the microscope," explains Dr. Nikita Raj, the study's first author.



Model highlighting the coordination of membrane tension changes, EE exocytosis, and CME for efficient plasma membrane repair. Credit: Advanced Science (2024). DOI: 10.1002/adv.202402317

In an earlier study, the researchers demonstrated that "early endosomes," which primarily function to transport substances into the cell, fuse with the cell membrane during wound closure to seal the damaged area. However, this fusion by itself is insufficient to complete repair, as the added material creates an uneven, scar-like surface on the membrane.

"At the site where early endosomes seal the wound, the membrane becomes loose, leading to a decrease in membrane tension. We were able to show for the first time that this change in tension serves as a signal, triggering the reuptake of excess membrane material into the cell," explains Prof. Volker Gerke. This reuptake restores the normal membrane tension which is necessary for maintaining cellular function.

These repair mechanisms are not limited to endothelial cells but are relevant to a wide range of cell types and have potential significant clinical implications.

"Impaired plasma membrane repair plays a crucial role in the development of neurodegenerative diseases, muscle degradation, and aging," says Dr. Raj.

Looking ahead, she adds, "Our fundamental insights into cellular repair processes are essential for understanding various diseases. In future studies, we aim to investigate how these mechanisms are disrupted in specific disease conditions, such as atherosclerosis."

More information: Nikita Raj et al, Membrane Tension Regulation is Required for Wound Repair, *Advanced Science* (2024). DOI: [10.1002/adv.202402317](https://doi.org/10.1002/adv.202402317)

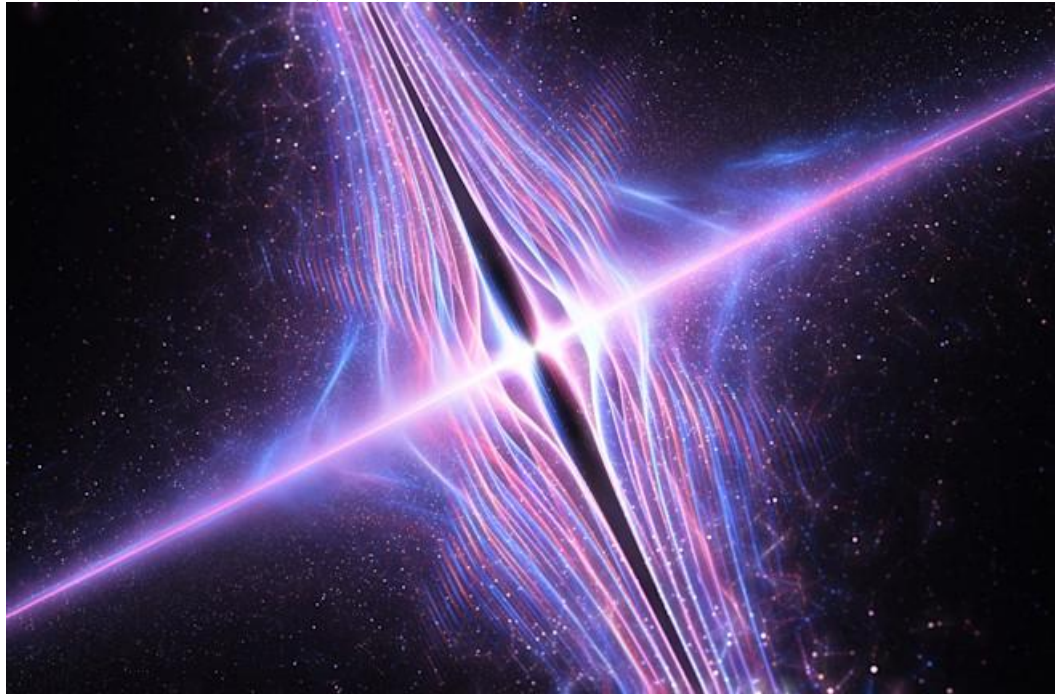
Provided by University of Münster

String Theory Is Not Dead

Out of the limelight, theoretical physicists seek the math that can explain the universe's particles and forces.

By [Tom Siegfried, Knowable Magazine](#)

Nov 29, 2024 12:00 AM Nov 29, 2024 1:00 PM



Scientists seeking the secrets of the universe would like to make a model that shows how all of nature's forces and particles fit together. It would be nice to do it with Legos. But perhaps a better bet would be connecting everything with strings.

Not literal strings, of course — but tiny loops or snippets of vibrating energy. And the “fit together” needs to be mathematical, not via properly shaped pieces of plastic. For decades now, many physicists have pursued the hope that equations involving an especially tiny “string” could provide the theory that solves nature's ultimate subatomic mysteries.

String theory, as it's called, has acquired a sort of fuzzy cultural acclaim, showing up in popular TV shows like *The Big Bang Theory* and *NCIS*. Among physicists, reaction to the theory has been mixed. After several promising bursts of discovery in the 1980s and '90s, strings fell somewhat out of favor for not delivering on their promises.

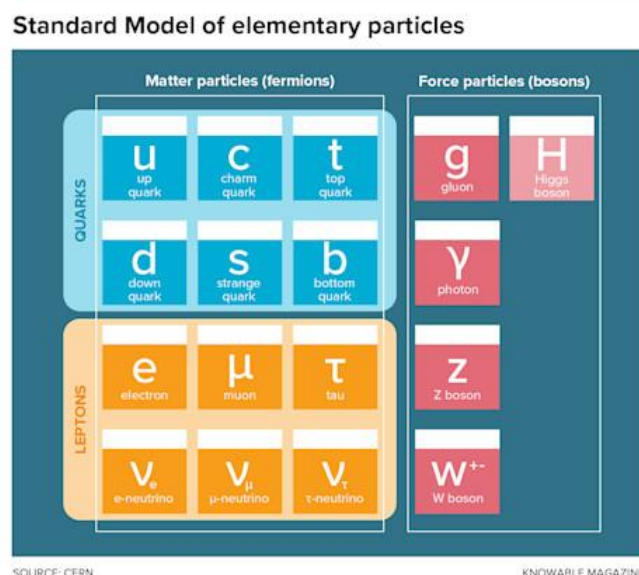
Among those was providing the proper way to include gravity in the quantum theory of subatomic particles. Another was revealing the math that would show nature's multiple fundamental forces to be just different offspring of one unified force. Still promises unkept.

Yet during the time since string theory's retreat from the limelight, a considerable cadre of string devotees have labored to tie all the loose ends together. Success remains elusive, but real progress has been made. Questions plaguing physicists about not only the smallest bits of matter but also the properties of the entire universe may yet yield to string theorists' efforts.

"Many of the unsolved problems in particle physics and cosmology are deeply intertwined," write physicists [Fernando Marchesano](#), [Gary Shiu](#) and [Timo Weigand](#) in the 2024 [Annual Review of Nuclear and Particle Science](#). String theory may provide the path to solving those problems.

Reality's Equations

One major approach in this quest is figuring out whether string theory can explain what is known as the Standard Model of particle physics. Developed in the last part of the 20th century, the Standard Model provides a sort of roster listing all of nature's basic particles. Some provide the building blocks of matter; others transmit forces between the matter particles, governing how they behave.



The Standard Model of particle physics describes nature's known forces and subatomic particles. They include quarks, leptons and bosons. Protons and neutrons are

composed of up and down quarks. Leptons include electrons and neutrinos. Photons transmit the electromagnetic force; gluons hold particles together in the atomic nucleus; and W and Z particles transmit the weak nuclear force, important for some forms of radioactivity. The Higgs boson is involved in conferring some particles with mass.

It's pretty simple to draw a chart displaying those particles. You need 12 spots for matter particles — six quarks and six leptons. You need four spots for force particles (collectively known as bosons) plus a spot for the Higgs boson, a particle needed to explain why some particles have mass. But the mathematics underlying the chart is unfathomably complex, a combination of equations that make hieroglyphics seem self-explanatory.

Those equations work superbly for explaining the results of virtually all particle physics behavior. But the Standard Model cannot be the whole story of the universe. "Despite the incredible success of the Standard Model in describing the observed particle physics up to the currently accessible energy scales, there are compelling arguments for why it is incomplete," Marchesano and collaborators write.

For one thing, its equations do not encompass gravity, which has no spot on the Standard Model chart. And Standard Model math leaves many questions unanswered, such as why some of the particles have the precise masses that they do. Standard Model math also does not include the mysterious dark matter that lurks within and between galaxies, nor does it explain why empty space is infused with **a form of energy that causes the universe to expand** at an accelerating rate.

Some physicists investigating these problems believe that string theory can help, since a string version of the Standard Model will contain additional math that could account for its shortcomings. In other words, if string theory is correct, the Standard Model would be just one segment of string theory's full mathematical description of reality. The problem is that string theory describes many different versions of reality. That's because the strings exist in a realm with multiple dimensions of space beyond the ordinary three. Kind of like the Twilight Zone on steroids.

String theorists concede that daily life proceeds just fine in a three-dimensional world. Therefore, the extra dimensions of the string world must be too small to notice: They have to shrink, or "compactify," into submicroscopic size. It's like the way an ant living on a vast sheet of paper would perceive a two-dimensional surface without ever realizing the paper had a third, very small dimension.

Not only must string theory's extra dimensions shrink, but they also can shrink into innumerable different configurations, or geometries, of the vacuum of space. One of those possible geometries might be the right shape of the shrunk dimensions to explain the properties of the Standard Model.

"Standard Model ... features, questions, and puzzles can be reformulated in terms of the geometry of extra dimensions," Marchesano and collaborators write.

Because string theory math can be expressed in several different forms, theorists have to explore multiple possible avenues to find the most fruitful formulation. So far, string approaches have been found that describe many features of the Standard Model. But different compactification geometries of the vacuum are needed to explain each feature. The challenge, Marchesano and colleagues point out, is to find one geometry for the vacuum that combines all those features at once, while also incorporating features that describe the known universe.

A successful compactification of the extra dimensions, for instance, would produce a vacuum in space that contained the right amount of "dark energy," the source of the universe's accelerating expansion. And candidates for the cosmic dark matter should appear in the string math as well. In fact, a whole additional set of force and matter particles emerges from string equations involving a mathematical property called supersymmetry. "Almost all string theory models that resemble the Standard Model display supersymmetry at the compactification scale," write Marchesano and his coauthors.

Versions of string theory containing supersymmetric particles go by the moniker "superstring theory." Such "superparticles" have long been suspected of comprising the universe's dark matter. But attempts to detect them in space or create them in particle accelerators have so far been unsuccessful.

As for gravity, particles conveying the gravitational force appear naturally in string theory math — one of the theory's big attractions to begin with. But the fact that many formulations of string theory include gravity does not tell you which formulation provides the correct description of the real world.

Tests are Possible

If string theory is correct, **fundamental particles of nature** would not be the zero-dimensional pointlike objects of standard theory. Instead, different particles would result from different modes of vibration of a one-dimensional string, either a loop or a

snippet with ends attached to multidimensional spatial objects called branes. Such strings would roughly be smaller than an atom to the extent that an atom is smaller than the solar system. Very small, with no feasible way of detecting them directly. The amount of energy needed to probe scales so tiny is far beyond the reach of any practical technology.

But if string theory can account for the Standard Model, it would also contain other features of reality that would be accessible to experiments, such as types of particles not included on the Standard Model chart. “String constructions that realize the Standard Model always contain additional sectors ... at an energy scale that could be tested in the near future,” Marchesano and colleagues write.

Ultimately, string theory remains a hopeful candidate for putting all the pieces of the cosmic puzzle together. If it works out, scientists could finally unravel the mysteries about how quantum physics’ relation to gravity, and the properties of nature’s particles and forces, are all deeply linked. “String theory,” write Marchesano and colleagues, “has all the ingredients to help us understand this profound connection.”

10.1146/knowable-112124-2

Not Even Wrong

This Week’s Hype, etc.

Posted on [December 17, 2024](#)

NYU today put out a press release claiming that [Physicists ‘Bootstrap’ Validity of String Theory](#), telling us that

NYU and Caltech scientists develop innovative mathematical approach to back existence of long-held framework explaining all physical reality.

and

String theory, conceptualized more than 50 years ago as a framework to explain the formation of matter, remains elusive as a “provable” phenomenon. But a team of physicists has now taken a significant step forward in validating string theory by using an innovative mathematical method that points to its “inevitability.”

It's the usual outrageous string theory hype machine in action, with a university press release promoting a [PRL paper](#) (this [preprint](#)) with hype and misinformation. This has now been going on for decades, clearly is never going to stop, no matter what.

Years ago I used to comment about this kind of thing that it wasn't helpful for the credibility of physics in particular, but also science in general. Why should you "trust science" when this is what scientists do? At this point though, the damage has now been done. All over social media you'll find negative attitudes towards science, with "string theory" given as a prime example for why you shouldn't trust science or scientists.

I took a look at Twitter (which now seems to come up by default featuring lots and lots of Elon Musk) for the first time in a while yesterday. The consensus on Twitter the past few years has been that string theory is an obviously failed research program, and that the failure to acknowledge this is prime evidence that one should not "trust science". Doing a search on "string theory", the latest news is that many people are now asking how this could have happened, with the favored explanation: "string theory is a psyop by the deep state, part of a plot to sidetrack physics and keep us all from having free unlimited amounts of energy". This is quite a bit less compelling than the older explanation that Edward Witten is an alien sent by a more advanced civilization in order to sidetrack physics.

A few other things I learned from Twitter is that Sabine Hossenfelder has a recent Youtube video [String Theory Isn't Dead](#). This is about the article I discussed [here](#), and Hossenfelder reaches much the same conclusion I reached long ago about the dead/non-dead question

They say that science progresses one funeral at a time. But it's no longer true. Because the first generation of string theorists has raised their students who are now continuing the same stuff. And why would they not, these are cozy jobs, and there is nothing and no one that could stop them. So yeah, Siegfried is right. String theory is not dead. It's undead, and now walks around like a zombie eating people's brains.

If you look at the few string theorists on Twitter, you find that they are outraged about what is going on. Their outrage though is not about their fellow string theorists discrediting the subject and making science look bad, but at Hossenfelder for pointing to the problem. For a very good discussion with Hossenfelder about her views and all of this, see Curt Jaimungal's podcast [What's Wrong With \(Fundamental\) Physics?](#).

One young string theorist (grad student at SUNY Albany) is trying to fight the anti-stringers, in particular with a new podcast where he interviews [Zohar Komargodski](#). The podcast is well-worth listening to, since Komargodski is a good example of the career path of quite a few prominent hep-th theorists these days and he does a good job of explaining the point of view of current leaders of the subject. While he started out as a grad student doing string theory, he soon turned to other topics, and has done excellent work in non-perturbative QFT of various sorts, very little of it involving strings. Despite this, he would often be described as “a string theorist.” The words “string theory” and “string theorist” now have no fixed meaning, making it very hard to have a serious discussion of the topic.

Komargodski does what he can to put a good face on the impact of string theory, but in some ways is not helpful to the anti-anti-string case the podcaster would like to make:

I'm sure that you know people before my time, way before my time in the 80s, people were claiming that soon enough they will find the standard model in some compactification of the heterotic string and this will explain the electron mass everything else and we'll be done. There were such claims in the 80s, of course that was premature it turned out to be completely false and as far as we understand it's not the right direction. So of course making preposterous claims is irresponsible and should be avoided by scientists at all costs because we're supposed to be responsible for what we're saying and we're supposed to be rigorous and careful.

Where I strongly disagree with Komargodski is in his argument that all is well, that we're just in a typical slow period of progress, that the only problem is that “the theory has yet attained its goal”. This is both bad history and an inaccurate characterization of the situation. String theory is not a research program that is slowly advancing towards its goal of a unified theory (or at least a successful theory of 4d quantum gravity). There has been progress, but it has been consistent progress towards understanding that this can't possibly work. Komargodski sees no particular problem with the job market: 3-5% of theory PhDs may get permanent jobs, the good ones don't fall through the cracks but do fine.

While both he and the podcaster have a lot of complaints about the critics and their “bad faith”, they don't seem interested in doing anything at all about the outrageous hype from their own kind that has done such huge damage to the field already, with more to come.

Update:

The absurd hype is just endless.

Update:

John Baez is both more of an optimist and more of a poet than I am:

And yet, despite having installed string theorists in top positions worldwide, string theory is gradually fading. Physics departments are less likely to hire string theorists than they were 10 years ago – and that was also true 10 years ago. So it seems the tree branch is slowly breaking off the tree, and will eventually crash onto the forest floor, opening up a bit more light for new plants to grow.

Update: *Even more egregious version of the “string theory shown to be only possibility” hype, from [Physics World](#).*

Mathematical physics

- **RESEARCH UPDATE**

String theory may be inevitable as a unified theory of physics, calculations suggest

16 Jan 2025



Bootstrapping strings *Evidence that string theory could be the sole viable*

“theory of everything” has emerged in a new theoretical study of particle scattering. (Courtesy: iStock/Anadmist)

Striking evidence that string theory could be the sole viable “theory of everything” has emerged in a new theoretical study of particle scattering that was done by a trio of physicists in the US. By unifying all fundamental forces of nature, including gravity, string theory could provide the long-sought quantum description of gravity that has eluded scientists for decades.

The research was done by Caltech’s [Clifford Cheung](#) and [Aaron Hillman](#) along with [Grant Remmen](#) at New York University. They have delved into the intricate mathematics of scattering amplitudes, which are quantities that encapsulate the probabilities of particles interacting when they collide.

Through a novel application of the bootstrap approach, the trio demonstrated that imposing general principles of quantum mechanics uniquely determines the scattering amplitudes of particles at the smallest scales. Remarkably, the results match the string scattering amplitudes derived in earlier works. This suggests that string theory may indeed be an inevitable description of the universe, even as direct experimental verification remains out of reach.

“A bootstrap is a mathematical construction in which insight into the physical properties of a system can be obtained without having to know its underlying fundamental dynamics,” explains Remmen. “Instead, the bootstrap uses properties like symmetries or other mathematical criteria to construct the physics from the bottom up, ‘effectively pulling itself up by its bootstraps’. In our study, we bootstrapped scattering amplitudes, which describe the quantum probabilities for the interactions of particles or strings.”

Why strings?

String theory posits that the elementary building blocks of the universe are not point-like particles but instead tiny, vibrating strings. The different vibrational modes of these strings give rise to the various particles observed in nature, such as electrons and quarks. This elegant framework resolves many of the mathematical inconsistencies that plague attempts to formulate a quantum description of gravity. Moreover, it unifies gravity with the other fundamental forces: electromagnetic, weak, and strong interactions.

However, a major hurdle remains. The characteristic size of these strings is estimated to be around 10^{-35} m, which is roughly 15 orders of magnitude smaller than the resolution of today's particle accelerators, including the Large Hadron Collider. This makes experimental verification of string theory extraordinarily challenging, if not impossible, for the foreseeable future.

Faced with the experimental inaccessibility of strings, physicists have turned to theoretical methods like the bootstrap to test whether string theory aligns with fundamental principles. By focusing on the mathematical consistency of scattering amplitudes, the researchers imposed constraints based on basic quantum mechanical requirements on the scattering amplitudes such as locality and unitarity.

“Locality means that forces take time to propagate: particles and fields in one place don't instantaneously affect another location, since that would violate the rules of cause-and-effect,” says Remmen. “Unitarity is conservation of probability in quantum mechanics: the probability for all possible outcomes must always add up to 100%, and all probabilities are positive. This basic requirement also constrains scattering amplitudes in important ways.”

In addition to these principles, the team introduced further general conditions, such as the existence of an infinite spectrum of fundamental particles and specific high-energy behaviour of the amplitudes. These criteria have long been considered essential for any theory that incorporates quantum gravity.

Unique solution

Their result is a unique solution to the bootstrap equations, which turned out to be the Veneziano amplitude — a formula originally derived to describe string scattering. This discovery strongly indicates that string theory meets the most essential criteria for a quantum theory of gravity. However, the definitive answer to whether string theory is truly the “theory of everything” must ultimately come from experimental evidence.

Cheung explains, “Our work asks: what is the precise math problem whose solution is the scattering amplitude of strings? And is it the unique solution?”. He adds, “This work can't verify the validity of string theory, which like all questions about nature is a question for experiment to resolve. But it can help illuminate whether the hypothesis that

the world is described by vibrating strings is actually logically equivalent to a smaller, perhaps more conservative set of bottom up assumptions that define this math problem.”

The trio’s study opens up several avenues for further exploration. One immediate goal for the researchers is to generalize their analysis to more complex scenarios. For instance, the current work focuses on the scattering of two particles into two others. Future studies will aim to extend the bootstrap approach to processes involving multiple incoming and outgoing particles.

Another direction involves incorporating closed strings, which are loops that are distinct from the open strings analysed in this study. Closed strings are particularly important in string theory because they naturally describe gravitons, the hypothetical particles responsible for mediating gravity. While closed string amplitudes are more mathematically intricate, demonstrating that they too arise uniquely from the bootstrap equations would further bolster the case for string theory.

The research is described in [Physical Review Letters](#).

[Physical Review Letters](#)

Bootstrap Principle for the Spectrum and Scattering of Strings

[Clifford Cheung](#)¹, [Aaron Hillman](#)¹, and [Grant N. Remmen](#)²

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Abstract

We show that the Veneziano amplitude of string theory is the unique solution to an analytically solvable bootstrap problem. Uniqueness follows from two assumptions: faster than power-law falloff in high-energy scattering and the existence of some infinite sequence in momentum transfer at which higher-spin exchanges cancel. The string amplitude—including the mass spectrum—is an output of this bootstrap. If the amplitude merely vanishes at high energies, the

solution is a three-parameter family containing the Veneziano, Coon, and hypergeometric amplitudes, and more.

Introduction—

String theory is a rare working prototype for how to consistently reconcile quantum mechanics and gravity at arbitrarily short distances. To do so, it asserts that the most basic building blocks of nature are vibrating strings rather than point particles. But is this assumption in any sense unique or inevitable?

Naively, the only way to assess the uniqueness of string theory is to compare and contrast it against its alternatives, but these are few and far between. A more systematic path is to apply the bootstrap principle, which aims to sculpt the observables of a theory directly from a set of conservative, bottom-up assumptions. A particularly fruitful version of this idea is the scattering amplitudes bootstrap, which utilizes basic principles like Lorentz invariance, locality, and unitarity to construct the space of all possible scattering amplitudes, which in turn dictates the space of all possible theories [1–4]. In this approach, theories like quantum chromodynamics and general relativity are not derived from textbook gauge invariance and general covariance, but rather as the unique theories of the interactions of massless spin one and spin two particles that are Lorentz invariant, local, and unitary.

Assumptions:

What are the bottom-up assumptions that fix the scattering amplitudes of string theory? That is, without any preconceived notions about the string, like its detailed spectrum or dynamics, how would we arrive at those elements from a systematic bootstrap?

We can look for hints to this question within the string amplitudes themselves, which famously exhibit a number of extraordinary properties. Chief among these is their high-energy behavior, which does not diverge with center-of-mass energy but rather attenuates, and at a rate that is impossible in a quantum theory of point particles. This falloff is encoded in the Regge limit,

$$\lim_{|s| \rightarrow \infty} \mathcal{A}_{f_0}(s, t) \sim s^{\alpha_{f_0}(t)},$$

(1)

where $\alpha_{f_0}(t)$ is the Regge trajectory. When there exists some range of t for which $\alpha_{f_0}(t) < 0$, as is the case for tree-level string amplitudes, an unsubtracted dispersion relation then implies that [5]

$$\mathcal{A}_{f_0}(s, t) = \oint_{s' = s - i\epsilon} \mathcal{A}_{f_0}(s', t) s' - s = \int_{-\infty - i\epsilon}^{\infty - i\epsilon} ds' \pi \text{Im} \mathcal{A}_{f_0}(s', t) s' - s.$$

(2)

A priori, the amplitude can have discontinuities in both the s and t channels. Nevertheless, it has been recast as a sum over solely s channel contributions. This property of dual resonance—that the amplitude can be expressed either as a sum over s or t channel exchanges—is implied by vanishing Regge behavior [6–10].

Throughout this Letter, we will posit a weakly coupled tree-level amplitude, so the right-hand side of the dispersion relation is a sum over simple poles,

$$\mathcal{A}_{f_0}(s, t) = \sum_{n=0}^{\infty} R_{f_0}(n, t) \mu_{f_0}(n) - s,$$

(3)

where the sequence $\mu_{f_0}(n)$ parametrizes an a priori arbitrary spectrum indexed by a level number n , which runs over the non-negative integers.

By definition, the pole in Eq. (3) at level n comprises a set of exactly degenerate exchanged states of different spins. The degree of each residue $R_{f_0}(n, t)$ with respect to t dictates the maximal spin exchanged at level n . If $R_{f_0}(n, t)$ is nonpolynomial, then the exchanged state is of finite energy but infinite spin. Any such mode has infinite extent, thus running afoul of locality [11,12]. Notably, unphysical amplitudes of this type—for example, $A \propto 1/(s-m_2)(t-m_2)(u-m_2)$ —appear as “extremal” amplitudes that are formally unitary but are nonlocal and frequently contaminate numerical bootstrap analyses [12–14]. In order to prune away these pathological amplitudes, we impose the additional assumption of locality, so any exchanged state has finite spin and $R_{f_0}(n, t)$ is a polynomial. Crossing symmetry then implies that Eq. (3) must have poles in s at arbitrarily high level n in order to account for expansion of the poles in the t channel. Assuming for simplicity that there are no distinct resonances with the same maximal spin, then without further loss of generality we can define the ordering of n such that n is the degree of $R_{f_0}(n, t)$, so $\mu_{f_0}(n)$ is a nonrepeating sequence and the sum in Eq. (3) runs over spin.

The amplitudes of confining gauge theories and fundamental strings both have vanishing Regge behavior, but it is the strength of this falloff that distinguishes them. For confining gauge theories, $f_{f_0}(t)$ asymptotes to a constant for negative t , corresponding to the impossibility of arbitrarily soft high-energy behavior in quantum field theory [15,16]. For fundamental strings, however, $f_{f_0}(t)$ decreases unboundedly for negative t . In the parlance of Ref. [17], such amplitudes are “superpolynomially soft,” which means that for any positive integer k there exists some range of t for which $A_{f_0}(s, t)$ is bounded by s^{-k} . This implies that there exist some tk for which $A_{f_0}(s, tk) \sim s^{-k}$ in the Regge limit [18]. This scaling implies that the Regge trajectory $f_{f_0}(t)$ crosses all negative integers, so $f_{f_0}(tk) = -k$. Since $A_{f_0}(s, tk) \sim s^{-k}$, it is then natural to wonder if the amplitude is actually a rational function of s at these points. Indeed, this is precisely the case for the Veneziano amplitude [19],

$$AV_{f_0}(s, t) = \Gamma_{f_0}(-s) \Gamma_{f_0}(-t) \Gamma_{f_0}(-s-t),$$

(4)

which degenerates to a rational polynomial of degree $-k$ precisely when $t = -k$. In particular, at these special values of the momentum transfer, the Veneziano amplitude exhibits a finite number of poles in the s channel,

$$AV_{f_0}(s, -k) = k - 1 \sum_{n=0}^{\infty} (1-k) n n! 1 n - s,$$

(5)

where we have defined the Pochhammer symbol $(a)_n = \prod_{k=0}^{n-1} (a+k) = \Gamma_{f_0}(a+n)/\Gamma_{f_0}(a)$. Setting $t = -k$, the partial waves at each level $n \geq k$ destructively interfere, leaving no sign of those exchanged states in the amplitude. We dub this phenomenon “level truncation,” where all terms at level $n \geq k$ in the dual resonant sum in Eq. (3) vanish at some sequence of values of t that we call $\xi_{f_0}(k)$, leaving a finite sum over poles. By definition, an amplitude that satisfies level truncation will be a rational polynomial at $t = \xi_{f_0}(k)$, with Regge behavior going at most like s^{-1} ; while the tree-level string itself has softer Regge scaling $\sim s^{-k}$, we will not enforce this improvement for now.

Approach and results:

In this Letter, we take this curious property of the Veneziano amplitude and elevate it the status of an input assumption of a bootstrap calculation. Concretely, we present an analytic bootstrap for tree-level, crossing symmetric amplitudes $A_{f_0}(s, t)$ describing a tower of finite-spin modes whose spectrum is an unspecified sequence $\mu_{f_0}(n)$. At the heart of our construction lie two nontrivial assumptions. The first is that the amplitude has vanishing Regge behavior, so it can be expressed as a sum over poles in just the s channel, as in Eq. (3). The second is level truncation, which states that this sum only receives contributions from a finite set of levels with $n < k$ when $t = \xi_{f_0}(k)$, where $\xi_{f_0}(k)$ is yet another unspecified sequence.

This bootstrap problem can be solved analytically and exactly. Our construction imposes nonlinear constraints on the sequences $\xi_{f_0}(n)$ and $a_{f_0}(n)$ and on the spectrum $\mu_{f_0}(n)$. Consequently, unlike all prior analyses in this subject, the spectrum $\mu_{f_0}(n)$ is an output of our bootstrap rather than an input. The general solution of this bootstrap problem is a three-parameter (q, r, w) family of amplitudes. The spectrum is

$$\mu_{f_0}(n) = [n]_q = 1 - qn - q, \quad (6)$$

which is the q -integer spectrum of the Coon amplitude [21]. As we will find, $q \geq 1$ is mandated by convergence of the dual resonant sum, but unitarity is violated for $q > 1$. Hence, we are left with $q = 1$, corresponding to the linear spectrum of the string. Meanwhile, r describes the parameter of the hypergeometric amplitudes proposed in Ref. [6], and the remaining parameter w characterizes a new class of amplitudes. By construction, all of these amplitudes have vanishing Regge behavior but only for $r = w = 0$ is the amplitude superpolynomially soft. As a result, the unique object satisfying this last condition is precisely the Veneziano amplitude.

Analytic bootstrap—

Vanishing Regge behavior implies that the amplitude admits the dual resonant representation in Eq. (3). We now show how level truncation constrains the residue and impose crossing symmetry.

Residue structure:

At $t = \xi_{f_0}(1)$, the amplitude only receives contributions from level $n = 0$. Consequently, all the other residues must vanish and are hence proportional to $t - \xi_{f_0}(1)$. On the other hand, at $t = \xi_{f_0}(2)$ the only exchanges are from levels $n = 0, 1$, so the remaining residues are proportional to $t - \xi_{f_0}(2)$, and so forth. Iterating this logic, we learn that the residues are

$$R_{f_0}(n, t) = a_{f_0}(n) \times [n]! [t - \xi_{f_0}(k)], \quad (7)$$

where $a_{f_0}(n)$ is an unspecified sequence.

Together, Eqs. (3) and (7) describe an amplitude parametrized by three infinite sequences: the spectrum $\mu_{f_0}(n)$, the residue normalization $a_{f_0}(n)$, and the loci of level truncation $\xi_{f_0}(k)$. The resulting amplitude has the same structure of coincident residue zeros as the Veneziano amplitude, but with the positions of all poles and zeroes in s and t transformed by the schematic replacement,

integer $\rightarrow$ arbitrary sequence.

(8)

Said another way, our bootstrap automatically sculpts out a putative space of scattering amplitudes whose poles and residue zeros have the same overall structure as Veneziano, but at a priori different locations.

Without loss of generality, let us consider all amplitudes with fixed overall normalization and modulo arbitrary transformations of s and t under shifts and rescaling. We can eliminate these degrees of freedom by fixing $\mu_{f_0}(0) = 0$, $\mu_{f_0}(1) = 1$, and $\alpha_{f_0}(0) = 1$, which will reduce the complexity of our formulas.

A common obstacle in attempting to bootstrap string amplitudes from first principles is that most starting assumptions allow for the possibility of sums of Veneziano satellites [17,22], which are simply Veneziano amplitudes evaluated at shifted or rescaled values of s and t . Hence, one typically anticipates an infinite space of viable solutions to any given bootstrap. However, in our case Eq. (7) shows that the residues that are implied by our assumptions are very constrained. A sum of Veneziano satellites will in general fail the condition required by Eq. (7). This is a victory because it means that the solution space of our bootstrap problem will not be diluted by these infinite classes of amplitudes.

Crossing symmetry:

The requirement of crossing symmetry has yet to be imposed. In general this is a formidable but in some cases achievable task [23] because the amplitude is an infinite sum of terms, as described in Eq. (3). Hence, crossing symmetry places an infinite number of constraints on an infinite number of parameters. However, due to level truncation we know that the amplitude reduces to a finite collection of terms at certain kinematic points, in which case the conditions of crossing symmetry are similarly finite.

Consider the amplitude at $s = \xi_{f_0}(i)$ and $t = \xi_{f_0}(j)$ for some positive integers i and j ,

$$A_{f_0}(\xi_{f_0}(i), \xi_{f_0}(j)) = j - 1 \sum_{n=0}^{\infty} \alpha_{f_0}(n) \times \prod_{k=1}^n (\xi_{f_0}(j) - \xi_{f_0}(k)) \mu_{f_0}(n) - \xi_{f_0}(i).$$

(9)

Imposing crossing symmetry, and assuming that $\xi_{f_0}(i)$ and $\xi_{f_0}(j)$ have real parts in the regime of convergence of the dual resonant sum, we have

$$A_{f_0}(\xi_{f_0}(i), \xi_{f_0}(j)) = A_{f_0}(\xi_{f_0}(j), \xi_{f_0}(i)),$$

(10)

mandating nonlinear constraints on the sequences $\alpha_{f_0}(n)$, $\xi_{f_0}(n)$, and $\mu_{f_0}(n)$. While these constraints are complicated, they only involve a finite number of sequence variables, and it turns out that we can solve them analytically.

Without prior knowledge of the existence of string amplitudes, it would be surprising that these equations admit any solutions at all. In particular, the constraint of crossing symmetry in Eq. (10) at large i and j involves a maximal level $n_{\max} \sim \max_{f_0}(i, j)$. The number of unknowns in the sequences $\alpha_{f_0}(n)$, $\xi_{f_0}(n)$, and $\mu_{f_0}(n)$ up to this maximal level scales as $3 \times n_{\max}$, while the number of equations in Eq. (10) scales as $n_{\max}^2$. Hence, this system of nonlinear equations is exceedingly overconstrained.

While Eq. (10) is a system of nonlinear equations, we can actually solve them sequentially as linear equations. First, we determine the normalization sequence $\hat{c}_{f_0}^{(i)}(n)$ by solving Eq. (10) in the case of $i=1$ and $j \geq 2$, yielding

$$\hat{c}_{f_0}^{(1)}(n) = (-1)^n \times (\xi_{f_0}^{(1)}(1) - \mu_{f_0}^{(1)}(n)) \prod_{n+1 \leq k=1}^{\infty} \xi_{f_0}^{(1)}(k).$$

(11)

Second, Eq. (10) for $i=2$ and $j \geq 3$ uniquely fixes the spectrum $\mu_{f_0}^{(2)}(n)$, whose solutions are defined by the recursion relation,

$$\mu_{f_0}^{(2)}(n) = \mu_{f_0}^{(2)}(n-1) \times [\xi_{f_0}^{(2)}(n+1) - 1] + \xi_{f_0}^{(2)}(2) \xi_{f_0}^{(2)}(n+1).$$

(12)

Last, Eq. (10) for $i=3$ and $j \geq 4$ determines the loci of level truncation, which are recursively defined by

$$\xi_{f_0}^{(3)}(n) = \xi_{f_0}^{(3)}(3) \times [\xi_{f_0}^{(3)}(n-1) - 1] \xi_{f_0}^{(3)}(2) - 1.$$

(13)

Note that the above manipulations assume that the sequence $\xi_{f_0}^{(i)}(n)$ is nonrepeating, which is equivalent to requiring that under level truncation the dual resonant sum at $t = \xi_{f_0}^{(i)}(k)$ receives contributions at and only at each pole $n < k$. The resulting space of solutions depends solely on three remaining variables, $\xi_{f_0}^{(1)}(1)$, $\xi_{f_0}^{(2)}(2)$, and $\xi_{f_0}^{(3)}(3)$, which we remap to new parameters (q, r, w) via

$$\xi_{f_0}^{(1)}(1) = [-1 - r - w]q, \quad \xi_{f_0}^{(2)}(2) = [-2 - r]q, \quad \xi_{f_0}^{(3)}(3) = [-3 - r]q.$$

(14)

The sequences are then

$$\mu_{f_0}^{(1)}(n) = [n]q, \quad \xi_{f_0}^{(1)}(n) = [-n - r - \delta 1 \times n \times w]q, \quad \hat{c}_{f_0}^{(1)}(n) = (1 - q)^n \times q^n \times (n + 3 + 2 \times r)/2 \times [1 + n + r + w]q(q^2 + r; q)_n \times [1 + r + w]q,$$

(15)

where $(a; q)_n = \prod_{k=0}^{n-1} (1 - a \times q^k)$ is the q -Pochhammer symbol. Thus, we arrive at a three-parameter (q, r, w) space of amplitudes. Note that Eq. (10) is necessary but not sufficient for crossing symmetry, and one must still check that the amplitudes corresponding to Eq. (15) are crossing symmetric at generic s and t for consistency.

Solution space—

The solutions in Eq. (15) encode the full space of scattering amplitudes that satisfy our bootstrap. Let us now present explicit expressions for these amplitudes and study their high-energy behavior.

Amplitudes:

For notational ease, let us first define convenient kinematic variables $\sigma = \log_{f_0}[1 - (1 - q) \times s] / \log_{f_0} q$ and $\tau = \log_{f_0}[1 - (1 - q) \times t] / \log_{f_0} q$, which are constructed so that $[\sigma]q = s$ and $[\tau]q = t$. Plugging Eq. (15) into Eq. (7), we have the residues

$$\hat{R}_{f_0}^{(1)}(n, t) = q^n \times (q^1 + r + \tau, q)_n \times [1 + r + \tau + w]q \times [1 + n + r + w]q q w \times (q^2 + r; q)_n \times [1 + r + \tau]q \times [1 + r + w]q,$$

(16)

for $n > 0$, while the $n=0$ residue is $\hat{R}_{f_0}^{(1)}(0, t) = 1$.

We then insert the residue in Eq. (16) into the dual resonant form of the amplitude in Eq. (3). From the definition of the q -deformed generalized hypergeometric functions [24] and their various identities, we obtain the amplitude in manifestly crossing symmetric form,

$$A_{f_0}(s,t)=[1+r]q[1+r+w]q\sigma\tau-w\Gamma q_{f_0}(-\sigma)\Gamma q_{f_0}(-\tau)\Gamma q_{f_0}(-\sigma-\tau)3\phi_2^{f_0}[q-\sigma,q-\tau,qr-q-\sigma-\tau,q1+r;q;q]+q-w[w]q([1+r+w]q+[1+r]q)[1+r+w]q\sigma\tau-q\sigma\tau-w[w]q([1+r+w]q+[1+r]q-q[-\sigma]q[-\tau]q)[1+r+w]q\sigma\tau\Gamma q_{f_0}(-\sigma)\Gamma q_{f_0}(-\tau)\Gamma q_{f_0}(1-\sigma-\tau)3\phi_2^{f_0}[q-\sigma,q-\tau,q1+r,q1-\sigma-\tau,q2+r;q;q].$$

(17)

Independently of r and w , Eq. (17) scales as $A \sim q\sigma\tau$ in the Regge limit, which vanishes when $\text{Re}_{f_0}(\tau) < 0$ [25]. For $q \geq 1$, this corresponds to a window $|1/(q-1)+t| < 1/(q-1)$, within which the amplitude indeed obeys the unsubtracted dispersion relation in Eq. (2). In this case, the amplitude can be expressed in the dual resonant form in Eq. (3), as advertised. For $q < 1$ the dual resonant sum in Eq. (3) does not even converge in general, so we restrict to $q \geq 1$ throughout [30].

Our solution (17) unifies many amplitudes previously discussed in the literature. For $w=0$, it is the q -hypergeometric amplitude of Ref. [6], while further setting $r=0$ yields the Coon amplitude [21]. For $r=w=0$ and $q=1$, it becomes the Veneziano amplitude (4).

While $q \geq 1$ is permitted by crossing symmetry, we find that unitarity excludes $q > 1$. See the Appendix for a detailed analysis. Consequently, we henceforth consider $q=1$, corresponding to the linear string spectrum. In this case, the amplitude in Eq. (17) can be written as

$$A_{f_0}(s,t)=1+r1+r+w\Gamma_{f_0}(-s)\Gamma_{f_0}(-t)\Gamma_{f_0}(-s-t)(3F_2^{f_0}[-s,-t,r-s-t,1+r;1]+w(2+2r+w+s+t)(1+r)(s+t)3F_2^{f_0}[-s,-t,1+r1-s-t,2+r;1]+w(2+2r+w)(1+r+w)s$$

(18)

which is dual resonant for $\text{Re}_{f_0}(t) < 0$.

High-energy behavior:

Let us consider the behavior of the amplitude in Eq. (18) for high-energy scattering in the Regge limit, and for fixed angle, respectively.

In the Regge limit, the amplitude in Eq. (18) scales as

$$A \sim s_{f_0}(s,t) + \mathcal{C}_{f_0}(r,w)s(1+t) + ws(1+t) + \dots,$$

(19)

where $\mathcal{C}_{f_0}(r,w) = 1 + r + w - (1+r)/(1+r+w)$ and $s_{f_0}(s,t) = t + \dots$, with ellipses denoting subleading terms. For $t > -1$, the amplitude exhibits the st scaling reminiscent of string theory, while for $t < -1$ it falls off as a power law. The apparent t channel pole is spurious, and simply indicates the transition between these two behaviors.

Crucially, we observe that superpolynomial softness for a range of holds if the terms in Eq. (19) vanish, which requires . Hence, the unique amplitude that exhibits superpolynomial softness and level truncation is the Veneziano amplitude.

On the other hand, for hard fixed-angle scattering, where at fixed , Eq. (18) scales

(20)

where . For , the amplitude diverges as in the Veneziano case, while for there is power-law scaling.

Discussion—

We have presented a bootstrap problem that is analytically solvable and whose complete solution space spans the Veneziano amplitude and its cousins. Our starting point is an arbitrary crossing symmetric amplitude with an unknown spectrum $\mu_{f_0}(n)$. We then assume vanishing Regge behavior and level truncation, which mandates that at $t = \xi_{f_0}(k)$ the amplitude only receives contributions from levels $n < k$. These conditions sculpt out a three-parameter (q, r, w) space of solutions. Only $q = 1$ is consistent with positivity, and within this space only $r = w = 0$ exhibits superpolynomial softness. Thus, the unique object satisfying our most stringent conditions is the Veneziano amplitude.

Since our bootstrap conditions are very constraining, it is natural to relax our assumptions to accommodate more solutions. A natural deformation that weakens our criteria is to instead assume partial level truncation, which zeros out all exchanges at level $n \geq k + \lambda$, where λ is a nonnegative integer and $\lambda = 0$ corresponds to our original analysis. Partial level truncation requires a more flexible form for the residue than Eq. (7). For example, it is possible to consider the residue ansatz

$$R_{f_0}(n, t) = a_{f_0}(n) \times [n - \lambda]! k = 1(t - \xi_{f_0}(k)) \times [n]! / [n - \lambda + 1]! \chi_{f_0}(n, j),$$

(21)

where $\chi_{f_0}(n, j)$ are unknowns. Plugging Eq. (21) into Eq. (3) and enforcing the crossing symmetry conditions of Eq. (10), we obtain a system of nonlinear equations for the sequences of variables $a_{f_0}(n)$, $\xi_{f_0}(n)$, $\mu_{f_0}(n)$, and $\chi_{f_0}(n, j)$.

This system of equations is finite but not solvable using the straightforward analytic methods that were sufficient for the $\lambda = 0$ case. Indeed, the algebraic variety defined by these equations is sufficiently complicated that it approaches the limits of existing numerical techniques. It would be interesting to explore the varieties defined by our problem more systematically using the modern tools of algebraic geometry.

Nonetheless, since the Veneziano amplitude is a known solution of these nonlinear equations in the space of sequence variables, we can consider linear perturbations about it. Expanding to linear order in perturbations of the sequence variables and finding the solutions that exhibit superpolynomial falloff—so $A_{f_0}(s, \xi_{f_0}(k)) \sim s^{-k}$ for all k —we find for $\lambda = 0, 1, 2, 3, 4$ that there are 1, 5, 11, 18, 27 such solutions, with spectra more general than the (q -deformed) integers. While some or even all of these solutions may be spurious and could violate crossing symmetry at higher order in perturbations, it is enticing to imagine that these could be bona fide scattering amplitudes. We leave a full analysis of these other putative solutions of the bootstrap to future work.

Another possible direction for future work is the generalization to higher-point scattering. As noted in Eq. (8), the constraint of level truncation yields amplitudes that are structurally similar to the Veneziano amplitude but with kinematic poles and zeros shifted from integers to arbitrary sequences. This observation immediately suggests a natural higher-point generalization. For example, higher-point string amplitudes have well known integer-spaced poles, and their residues have numerous zeros and conform to stringent factorization constraints [31–33]. It would be interesting to relocate these poles and zeroes to arbitrary locations to evaluate the

uniqueness of higher-point string amplitudes. Of course, the physical motivation for level truncation itself remains a compelling open question.

Last but not least is the question of extending our setup to include gravity. Here, the natural object of study is the Virasoro-Shapiro amplitude of string theory, which describes scattering gravitons. Notably, the residues of the Virasoro-Shapiro amplitude exhibit double zeroes, in contrast with the single zeros that appear in Eq. (7). For this reason it would be natural to explore whether gravitational amplitudes are uniquely specified by their Regge behavior and some version of enhanced level truncation.

FEBRUARY 14, 2025

Quantum-inspired advancement turns crystal gaps into terabyte storage for classical memory

by Paul Dailing, [University of Chicago](#)



A crystal used in the study charges under UV light. The process created by the University of Chicago Pritzker School of Molecular Engineering Zhong Lab could be used with a variety

of materials, taking advantage of rare earths' powerful, flexible optical properties. Credit: UChicago Pritzker School of Molecular Engineering / Zhong Lab
From punch card-operated looms in the 1800s to modern cellphones, if an object has an "on" and an "off" state, it can be used to store information.

In a computer laptop, the binary ones and zeroes are transistors either running at low or high voltage. On a compact disc, the one is a spot where a tiny indented "pit" turns to a flat "land" or vice versa, while a zero is when there's no change.

Historically, the size of the object making the "ones" and "zeroes" has put a limit on the size of the storage device. But now, University of Chicago Pritzker School of Molecular Engineering (UChicago PME) researchers have explored a technique to make ones and zeroes out of crystal defects, each the size of an individual atom for classical computer memory applications.

Their research [was published](#) today in Nanophotonics.

"Each memory cell is a single missing atom—a single defect," said UChicago PME Asst. Prof. Tian Zhong. "Now you can pack terabytes of bits within a small cube of material that's only a millimeter in size."

The innovation is a true example of UChicago PME's [interdisciplinary research](#), using quantum techniques to revolutionize classical, non-quantum computers and turning research on [radiation](#) dosimeters—most commonly known as the devices that store how much radiation hospital workers absorb from X-ray machines—into groundbreaking microelectronic memory storage.

"We found a way to integrate solid-state physics applied to radiation dosimetry with a research group that works strongly in quantum, although our work is not exactly quantum," said first author Leonardo França, a postdoctoral researcher in Zhong's lab. "There is a demand for people who are doing research on [quantum systems](#), but at the same time, there is a demand for improving the storage capacity of classical non-volatile memories. And it's on this interface between quantum and [optical data storage](#) where our work is grounded."

From radiation dosimetry to optical storage

The research got its start during França's Ph.D. research at the University of São Paulo in Brazil. He was studying radiation dosimeters, the devices that passively monitor how much radiation workers in hospitals, synchrotrons and other radiation facilities receive on the job..

"In the hospitals and in [particle accelerators](#), for instance, it's needed to monitor how much of a radiation dose people are exposed to," said França. "There are some materials that have this ability to absorb radiation and store that information for a certain amount of time."

He soon became fascinated about how through optical techniques—shining a light—he could manipulate and "read" that information.



Researchers in the lab of Asst. Prof. Tian Zhong of the UChicago Pritzker School of Molecular Engineering, including postdoctoral researcher and first author Leonardo França (pictured), have explored a technique to store memory out of crystal defects. Credit: UChicago Pritzker School of Molecular Engineering / Zhong Lab

"When the crystal absorbs sufficient energy, it releases electrons and holes. And these charges are captured by the defects," França said. "We can read that information. You can release the electrons, and we can read the information by optical means."

França soon saw the potential for memory storage. He brought this non-quantum work into Zhong's quantum laboratory to create an interdisciplinary innovation using quantum techniques to build classical memories.

"We're creating a new type of microelectronic device, a quantum-inspired technology," Zhong said.

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Rare earth

To create the new memory storage technique, the team added ions of "rare earth," a group of elements also known as lanthanides, to a crystal.

Specifically, they used a rare-earth element called Praseodymium and an Yttrium oxide crystal, but the process they reported could be used with a variety of materials, taking advantage of rare earths' powerful, flexible optical properties.

"It's well known that rare earths present specific electronic transitions that allows you to choose specific laser excitation wavelengths for optical control, from UV up to near-infrared regimes," França said.

Unlike with dosimeters, which are typically activated by X-rays or gamma rays, here the storage device is activated by a simple ultraviolet laser. The laser stimulates the lanthanides, which in turn release electrons. The electrons are trapped by some of the oxide crystal's defects, for instance the individual gaps in the structure where a single oxygen atom should be, but isn't.

"It's impossible to find crystals—in nature or artificial crystals—that don't have defects," França said. "So what we are doing is we are taking advantage of these defects."

While these [crystal defects](#) are often used in quantum research, entangled to create "qubits" in gems from [stretched diamond](#) to [spinel](#), the UChicago PME team found another use. They were able to guide when defects were charged and which weren't. By designating a charged gap as "one" and an uncharged gap as "zero," they were able to turn the crystal into a powerful memory storage device on a scale unseen in classical computing.

"Within that millimeter cube, we demonstrated there are about at least a billion of these memories—classical memories, traditional memories—based on atoms," Zhong said.

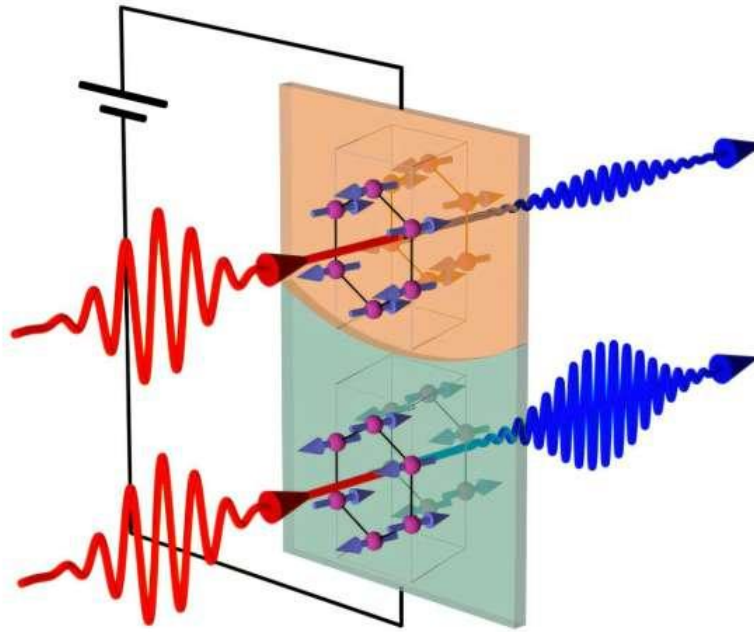
More information: Leonardo V. S. França et al, All-optical control of charge-trapping defects in rare-earth doped oxides, *Nanophotonics* (2025). DOI: [10.1515/nanoph-2024-0635](https://doi.org/10.1515/nanoph-2024-0635)

Provided by [University of Chicago](#)

FEBRUARY 14, 2025

A novel technique for identifying magnetic ordering in antiferromagnets

by [RIKEN](#)



Light waves (red arrows) passing through a crystal can reveal magnetic domains in certain 2D antiferromagnets. Credit: RIKEN Center for Emergent Matter Science

A new trick for illuminating the internal ordering within a special type of magnet could help engineers build better memory-storage devices. Developed by RIKEN physicists, [this technique](#) could make memory devices less corruptible.

The work is published in the journal *Nature Communications*.

Conventional hard disks are based on ferromagnets—materials in which the [magnetic dipoles](#), or spins, associated with each atom all point in the same direction. This alignment gives the material a net [magnetic field](#). Data is stored by creating different magnetization patterns across the material.

But physicists are looking to improve device performance by using antiferromagnets instead of ferromagnets. In antiferromagnets, neighboring spins are aligned in [opposite directions](#). This configuration ensures that the material has no net magnetic field since the opposing spins cancel each other out.

"In principle, antiferromagnetic memories should be much faster, smaller and more robust against errors than ferromagnetic ones," says Naoki Ogawa of the RIKEN Center for Emergent Matter Science (CEMS).

Ideally for applications, the antiferromagnet's spins should be ordered regularly, in an antiparallel fashion, across the whole material. However, "this doesn't happen in antiferromagnetic crystals naturally," notes Ogawa.

Instead, the material is split into [magnetic domains](#)—within each domain, adjacent spins are antiparallel, but in neighboring domains the alternation pattern is reversed.

The trouble is that before physicists can manipulate the domains to correct their orientations, they need to be able to find them, and that's not easy. "You can't just look and see them," says Ogawa. "You need a way to visualize them."

One strategy for identifying domains involves shining a light across the material in one direction and then again in the opposite way. Magnetic domains can be determined by examining the different ways in which the light's frequency is affected by the symmetry of the atoms and spins.

"The material responds differently when you reverse the direction of the light, allowing you to determine its structure," explains Ziqian Wang, also of CEMS.

This effect is tough to pick out. But in a proof-of-principle study, Wang, Ogawa and colleagues have found a way in a two-dimensional crystal containing manganese, phosphorus and sulfur.

They applied an [electric field](#) as an added source of interference, which enhanced the visibility of the domains by up to 90%. Previous attempts used a combination of magnetic and electric fields, notes Wang, but that required bulkier instruments and was much slower.

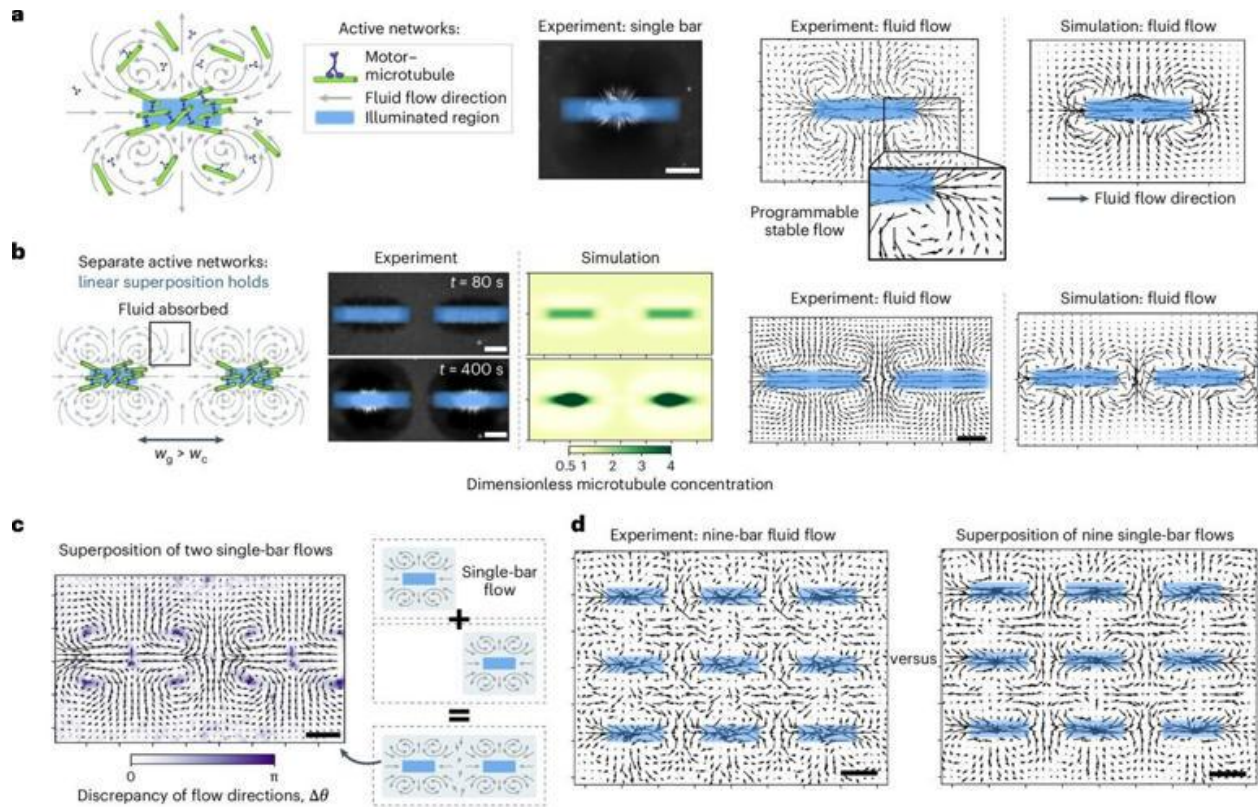
"Now we can visualize the domains, our next step is to develop an ultrafast technique to locally manipulate them," says Wang.

More information: Ziqian Wang et al, Electric-field-enhanced second-harmonic domain contrast and nonreciprocity in a van der Waals antiferromagnet, *Nature Communications* (2024). DOI: [10.1038/s41467-024-51943-0](https://doi.org/10.1038/s41467-024-51943-0)

Journal information: [Nature Communications](#)

Provided by [RIKEN](#)

First 'programming language' for active material enables precise control at cellular level



Linear superposition quantitatively predicts fluid flow fields induced by optically controlled active matter. Credit: Nature Materials (2025). DOI: 10.1038/s41563-024-02090-w

In 2019, Caltech researchers demonstrated a new method to use light to control active matter—a kind of material made up of individual energy-consuming pieces that act as a whole to create mechanical motion. The process works similarly to how many individual birds form a swarm that seems to move as a whole. In the research, the team focused on active matter in the form of millimeter-sized protein filaments that normally make up a cell's skeleton, or "cytoskeleton."

Now, powered by insights from computational theory, the team has developed the first "programming language" for active matter, enabling researchers to conduct precise operations in tiny volumes of fluid on the cellular level. The method has major applications in nanotechnology and for studying cell interactions.

The research was a collaboration between the laboratories of Matt Thomson, professor of computational biology and a Heritage Medical Research Institute Investigator, and Rob Phillips, the Fred and Nancy Morris Professor of Biophysics, Biology, and Physics. The work is described in a paper [appearing](#) in the journal Nature Materials. Postdoctoral scholar Fan Yang and graduate student Shichen Liu are the study's co-first authors.

Cellular skeletons, or cytoskeletons, are shapeshifting networks of tiny protein filaments that enable cells to propel themselves, carry cargo, and divide. The "bones" of the cytoskeleton are thin, tube-like filaments called microtubules that can form together into three-dimensional scaffolds.

Each microtubule is 1,000 times thinner than a human hair and only about 10 micrometers long (about 1,000 times smaller than a common black ant). Along with motor proteins that power movement, these incredibly small structures combine to propel the relatively large cell—analogous to ants steering and powering a car.

"Active matter has been a potential new material or resource for bioengineering but has, until this point, been impossible to control," Thomson says. "Using theoretical and computational modeling, Fan utilized principles of linear superposition—which only hold in specific size regimes—to develop the first programming language for active matter. Fan's theoretical insight enabled the development of the programming framework."

Cells naturally use gradients of chemicals to induce changes in the structure of their microtubule skeletons. In 2019, the team [engineered protein microtubules to respond instead to gradients of light](#), which allowed the researchers to shine specific patterns of light on a clump of microtubules and induce them to organize into a specific shape or pattern. But the system was not programmable because the team had not yet discovered how to design light patterns to generate fluid flow fields to accomplish tasks like moving cells or mixing fluids.

In the new work, Yang developed a programming language to design active matter fluid flows that can move, sort, and assemble cells; mix chemicals; and apply mechanical stresses to small objects like lipid vesicles in cells. Liu, an experimentalist, then conducted the lab work to verify that the microtubules did in fact assemble as predicted.

The work has major applications for how researchers manipulate cells for study. Usually, scientists need to use needle-like micropipettes to stretch and separate individual cells, risking damage to those cells. With active matter, researchers can add light-activated microtubules to a clump of cells and gently nudge them to desired positions using only light.

"We were inspired by Erik Winfree's work on DNA computing and programming strand displacement reactions," Thomson says. "Now, we are starting to work with people like Magdalena Zernicka-Goetz to apply light-controlled, active matter to control cells during the construction of synthetic embryos. We are also using the system to manipulate immune cells, and to apply mechanical forces to tissues in the lab to simulate mechanical stresses."

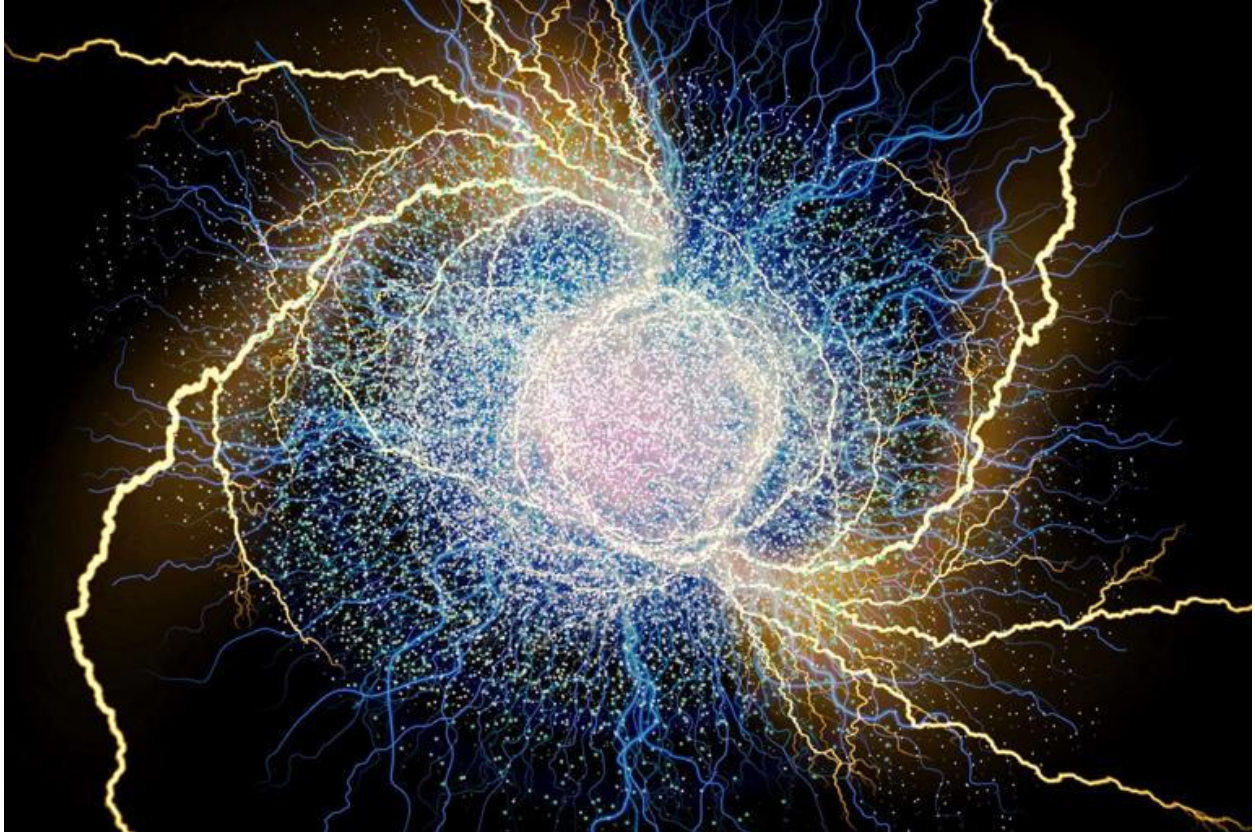
Winfree is a Caltech professor of computer science, computation and neural systems, and bioengineering; Zernicka-Goetz is Caltech's Bren Professor of Biology and Biological Engineering.

In addition to Yang, Liu, Phillips, and Thomson, Caltech staff scientist Heun Jin Lee is a co-author.

More information: Fan Yang et al, Dynamic flow control through active matter programming language, Nature Materials (2025). DOI: [10.1038/s41563-024-02090-w](https://doi.org/10.1038/s41563-024-02090-w)

Provided by California Institute of Technology

Scientists measure the quantum state of electrons for the first time



Researchers at Lund University have successfully measured the quantum state of photoelectrons, revealing new insights into light-matter interactions. (CREDIT: Christine Daniloff)© The Brighter Side of News

The photoelectric effect, first explained by Albert Einstein in 1905, laid the foundation for quantum mechanics. It occurs when high-energy light strikes atoms, releasing electrons. This phenomenon is crucial for technologies such as spectroscopy, holography, and electron microscopy. Yet, despite its widespread use, the true quantum nature of photoelectrons has remained elusive—until now.

For the first time, researchers at [Lund University](#) in Sweden have successfully measured the quantum state of electrons emitted from atoms after absorbing high-energy light pulses. This achievement, made possible through a novel measurement technique, provides an unprecedented view into the interaction between light and matter.

David Busto, an associate senior lecturer in atomic physics and one of the study's authors, explains, "By measuring the quantum state of the photoelectron, our technique can precisely address the question of 'how quantum is the electron.'"

Their findings, published in the journal [Nature Photonics](#), could revolutionize multiple scientific fields, from quantum mechanics to material science, shedding light on fundamental processes that govern electron behavior.



Image from the laser lab used in the research. (CREDIT: Charlotta Carlberg Bårg)© The Brighter Side of News

The Quantum Nature of Photoelectrons

In classical physics, an electron is often treated as a small particle with well-defined properties. However, at the quantum scale, electrons behave as both particles and waves, making their characterization far more complex. The new measurement technique developed by the researchers allows them to reconstruct the quantum state of photoelectrons with high precision.

When high-energy ultraviolet or [X-ray light](#) interacts with atoms or molecules, it causes an electron to detach in a process known as ionization. By measuring the kinetic energy and momentum of this ejected electron, scientists gain insight into

the atomic structure of the material. This principle is the basis of photoelectron spectroscopy, a technique pioneered by Nobel laureate Kai Siegbahn in the 1980s.

Until now, photoelectron spectroscopy focused on measuring classical properties like electron speed and direction. But the Lund researchers have developed a method that goes further—it captures the quantum state of the electron, revealing details that were previously inaccessible.

World's smallest particle accelerator could revolutionize medicine and physics

A microchip-sized particle accelerator has been successfully tested, marking a breakthrough in miniaturized high-energy physics.

JOSEPH SHAVIT

Published Feb 12, 2025

A microchip-sized particle accelerator has been successfully tested, marking a breakthrough in miniaturized high-energy physics. (CREDIT: FAU/Laser Physics, Stefanie Kraus, Julian Litzel)

Share this story

Scientists have successfully activated the world's smallest [particle accelerator](#), a device as compact as a coin. This breakthrough, which could transform fields ranging from medicine to physics, represents a significant step toward miniaturized particle acceleration technology.

The video player is currently playing an ad.

Traditional particle accelerators rely on radio-frequency waves and metallic structures to propel charged particles. These methods impose size and cost limitations due to the constraints of radio-frequency fields, which can only withstand acceleration gradients in the range of megavolts per meter.

In contrast, dielectric materials can tolerate optical fields exceeding 10 gigavolts per meter, enabling much stronger acceleration gradients.

The new approach, known as a dielectric laser accelerator (DLA), leverages nanophotonic structures to synchronize optical nearfields with moving [charged particles](#). This configuration achieves acceleration rates up to 100 times greater than conventional radio-frequency-based systems, drastically reducing both the size and cost of accelerators.

The nanophotonic accelerator measures just 500 micrometers in length, making it 54 million times smaller than the 27-kilometer-long Large Hadron Collider (LHC) at CERN.

Schematics of the experimental setup. Ultraviolet (UV) laser pulses of 257 nm wavelength (blue) and infrared (IR) laser pulses of 1.93 μm wavelength (red) are generated in an optical parametric amplifier (OPA) and fourth harmonic generation setup (two BBO crystals).

(CREDIT: Nature)

A key challenge in any accelerator is maintaining particle confinement to prevent energy loss. In the DLA, confinement occurs within a narrow, nanometer-wide channel, structured to keep electrons focused as they gain energy.

To overcome the focusing limitations posed by [Earnshaw's theorem](#), researchers employed an alternating phase focusing (APF) technique. This method alternates between focusing and defocusing forces to guide the electrons along their trajectory, ensuring consistent acceleration.

Historic First Test of a Chip-Based Accelerator

This device, called the nanophotonic electron accelerator (NEA), is a microchip containing a vacuum channel lined with thousands of tiny pillars. When laser beams strike these pillars, they generate the fields necessary to accelerate electrons through the structure.

Researchers at [Friedrich–Alexander University of Erlangen–Nuremberg](#) (FAU) in Germany successfully demonstrated the NEA's capabilities by accelerating electrons from 28.4 kiloelectron volts (keV) to 40.7 keV, a 43% energy increase.

Related Stories

This milestone, published in [Nature](#), marks the first successful demonstration of a nanophotonic electron accelerator—a concept first proposed in 2015.

"For the first time, we really can speak about a particle accelerator on a [micro]chip," said Roy Shiloh, a physicist and co-author of the study. A team at [Stanford University](#) has reportedly achieved similar results, though their findings are still under review.

Unlike the LHC, which uses more than 9,000 superconducting magnets to accelerate particles to nearly the speed of light, the NEA relies on laser beams to excite the tiny pillars inside its structure. While this method is far less powerful, it is significantly more compact and energy-efficient.

Potential for Medical and Scientific Applications

The electrons accelerated by the NEA carry only about a millionth of the energy produced by the [LHC](#). However, researchers believe they can enhance its power by incorporating new materials or stacking multiple acceleration structures. Even with improvements, the NEA will never rival large-scale colliders, but its strengths lie elsewhere.

Electron energy spectra showing coherent electron acceleration. (CREDIT: Nature)

The primary goal of developing miniaturized accelerators is not just high-energy physics but also practical applications in medicine. The high-energy electrons generated by the

NEA could be used in precise radiotherapy techniques, potentially reducing the harmful side effects associated with conventional [radiation treatments](#).

Tomáš Chlouba, the study's lead author, envisions a future where miniaturized accelerators could be integrated into endoscopes for targeted cancer treatment. "If we can make a particle accelerator small enough to fit inside a medical device, we could deliver highly localized radiation directly to tumors," Chlouba explained. However, he cautioned that such applications remain distant and will require further technological refinements.

A New Era of Miniature Accelerators

The successful operation of the NEA marks a turning point in accelerator physics. While large-scale particle colliders will continue to play a crucial role in fundamental research, miniaturized accelerators could revolutionize medicine, [materials science](#), and electronics. The ability to produce high-energy electrons within a microscopic device opens the door to portable diagnostic tools, advanced imaging systems, and new methods for studying matter at the nanoscale.

The LHC is 54 million times longer than the vacuum tube of the nanophotonic electron accelerator. (CREDIT: Getty Images)

As researchers refine the technology, the applications of nanophotonic accelerators will continue to expand, potentially reshaping multiple scientific and medical fields.

This tiny accelerator, no larger than a grain of rice, demonstrates that the future of [high-energy physics](#) is not just about building bigger machines—but also about making them smaller and more accessible.

Scientists discover new particle made entirely of nuclear force

For decades, scientists have pursued the elusive "glueballs," exotic particles composed entirely of gluons.

Published May 23, 2024

For decades, scientists have pursued the elusive "glueballs," exotic particles composed entirely of gluons. Gluons are the "sticky" particles responsible for holding nuclear particles together. Glueballs, however, are notoriously unstable and can only be detected indirectly through their decay, a process not yet fully understood. Now, it appears that this long-standing scientific quest has reached a significant milestone.

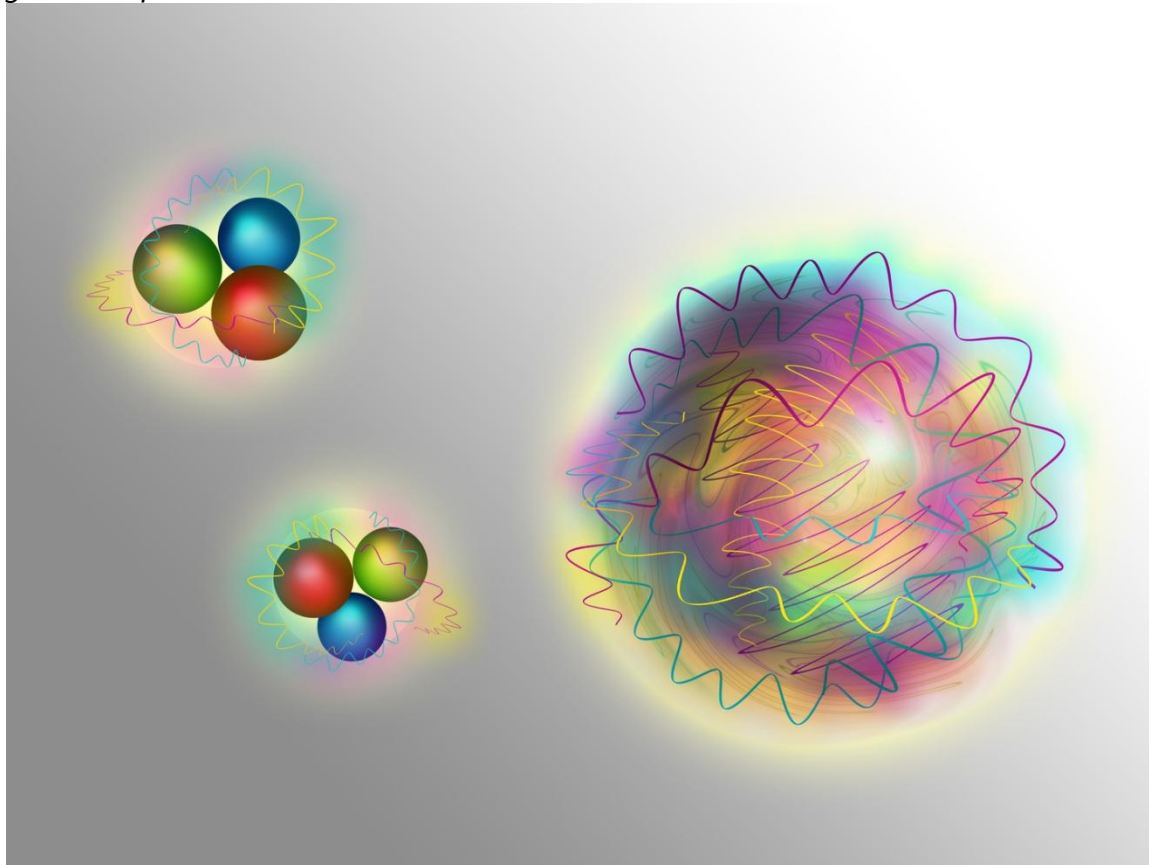
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Professor Anton Rebhan and Frederic Br  nner from [TU Wien](#) (Vienna) have made a breakthrough in calculating glueball decay using a novel theoretical approach. Their results align remarkably well with data from particle accelerator experiments, providing strong evidence that a resonance known as " $f_0(1710)$ " could indeed be the long-sought glueball.

Forces as Particles

Protons and neutrons are made of even smaller particles called quarks, which are bound together by the strong nuclear force. "In particle physics, every force is mediated by a special kind of force particle, and the force particle of the strong nuclear force is the gluon," explains Anton Rebhan.



Gluons are more complex than photons, which mediate electromagnetic forces. Unlike photons, which are massless and do not interact with each other, gluons do interact with themselves. This interaction allows for the possibility of particles composed entirely of gluons, known as glueballs.

The concept of glueballs was first proposed in 1972 by physicists Murray Gell-Mann and Harald Fritsch, shortly after the theory of quarks and gluons was established.

Several candidate particles have been observed in particle accelerator experiments, but there has been no consensus on whether any of these could be glueballs. The challenge

lies in the fact that glueballs are too short-lived to be detected directly and must be identified by studying their decay patterns.

"Unfortunately, the decay pattern of glueballs cannot be calculated rigorously," says Rebhan. Previous models suggested two candidates for glueballs: the mesons $f_0(1500)$ and $f_0(1710)$. While $f_0(1500)$ was initially considered the more likely candidate, $f_0(1710)$ has a higher mass, which aligns better with computer simulations.

However, $f_0(1710)$ decays into many heavy quarks, known as "strange quarks," which seemed improbable since gluon interactions typically do not distinguish between quark masses.

Rebhan and Br  nner have made significant progress by employing a different theoretical approach. They utilized the fundamental connections between quantum theories describing particle behavior in our three-dimensional world and certain gravitational theories in higher-dimensional spaces. This approach allows them to answer quantum physical questions using tools from gravitational physics.



"Our calculations show that it is indeed possible for glueballs to decay predominantly into strange quarks," says Rebhan. Surprisingly, their calculated decay pattern into two lighter particles matches the decay pattern measured for $f_0(1710)$. Additionally, other possible decays into more than two particles have also been calculated.

These alternative glueball decays have not yet been measured, but new data from upcoming experiments are expected to shed light on this theory. Two experiments at the Large Hadron Collider at CERN (TOTEM and LHCb) and one accelerator experiment in Beijing (BESIII) are expected to provide new insights within the next few months.

"These results will be crucial for our theory," says Rebhan. "For these multi-particle processes, our theory predicts decay rates that are quite different from the predictions of other, simpler models. If the measurements agree with our calculations, this will be a remarkable success for our approach."

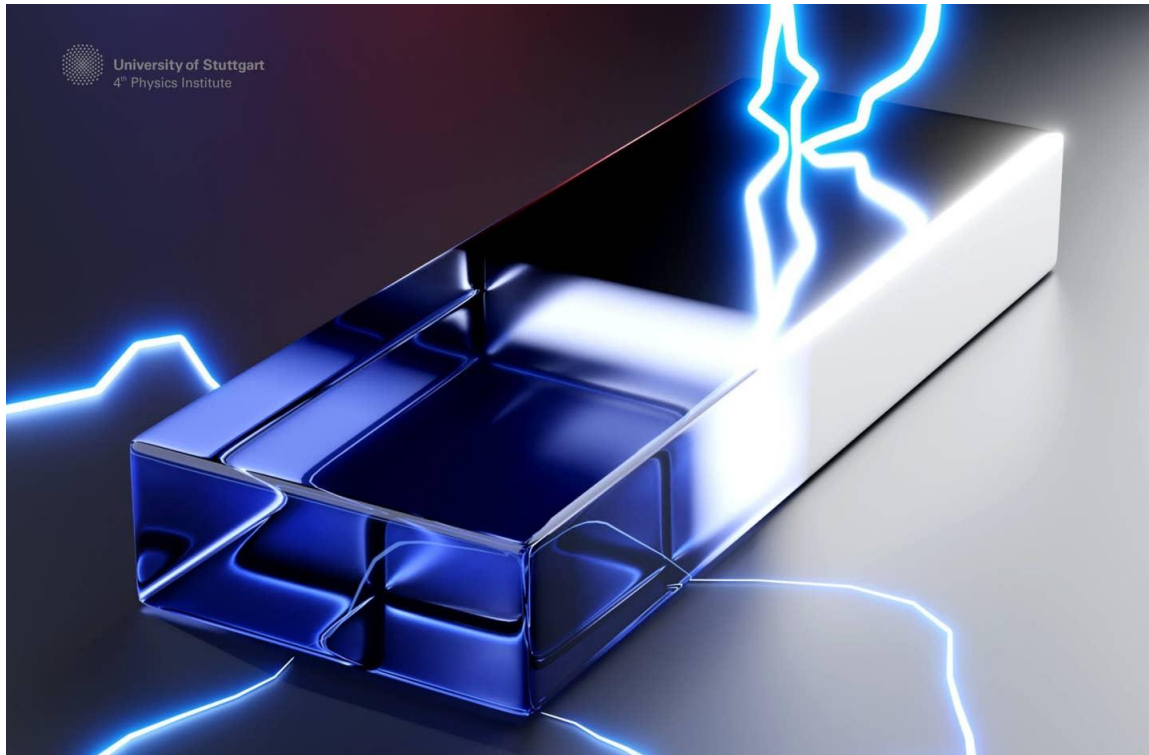
Confirming these predictions would provide overwhelming evidence that $f_0(1710)$ is indeed a glueball. Moreover, it would demonstrate the power of higher-dimensional gravitational theories to answer questions in particle physics. This would be another significant triumph for Einstein's theory of general relativity, which celebrates its 100th anniversary next month.

As the scientific community awaits further experimental results, the prospect of confirming the existence of glueballs offers a thrilling glimpse into the fundamental forces that govern our universe.

The study can be found at: Frederic Brünner et al. "[Nonchiral Enhancement of Scalar Glueball Decay in the Witten-Sakai-Sugimoto Model](#)," Physical Review Letters (2015).

Researchers make a breakthrough in 3D holographic displays

Researchers have now introduced a completely new approach to realize such dynamic holographic displays.



[University of Stuttgart]

a completely new approach to realize such dynamic holographic displays. (CREDIT: Julian Karst, University of Stuttgart)

Video conferencing played a key role during the COVID-19 pandemic and is set to dominate many meetings in the future. To realize the true feeling of a face-to-face dialog, three dimensional video is required and yet the holographic technology is still missing.

Researchers at the University of Stuttgart in Germany have now introduced a completely new approach to realize such dynamic holographic displays, based on electrically switchable plasmonic nanoantennas made from conductive metallic polymers.

This key element provides the missing technology to enable holographic displays at video rate, which would enable virtual conferences with a "real-life" feeling.

The paper detailing this work has been published in the journal Science on 29 October 2021.

Holograms creating impressive three-dimensional static images are well known. Dynamic holograms switchable at video rates using data from a high-speed internet connection are not possible until now.

Previously, the limiting factor was the display resolution. Holographic images require a resolution of 50 000 dpi (pixels per inch) which is 100x more than the best smartphone displays.

For such a resolution one has to reduce the pixel size to half a micrometer (one thousands of a millimeter). However, current liquid-crystal technology does not allow for such small pixels, being limited to a few micrometers pixel size.

Researchers at the University of Stuttgart have succeeded in breaking this fundamental barrier. In an interdisciplinary collaboration between Physics and Chemistry, they developed the idea to use electrically switchable plasmonic nanoantennas with dimensions of only a few hundred nanometers and made from conductive polymers. For several years, researchers had created metasurfaces that generate static 3-dimensional holograms. However, their components, or nanoantennas, consisted of metals such as gold or aluminum that could not be switched like common liquid crystal materials.

After searching for several years for the right material, Ph.D. student Julian Karst and nanophotonics expert Dr. Mario Hentschel from the group of Prof. Harald Giessen, together with polymer chemist Prof. Sabine Ludwigs and her team, identified electrically conducting polymers as possible candidates for switchable plasmonics.

Sabine Ludwigs contributed her expertise on electrochemical switching of such functional polymers, that were at the focus of the 2000 Chemistry Nobel Prize.

Until now such materials had mostly been used for current transport in flexible displays and solar cells. In collaboration with cleanroom head Monika Ubl, Karst and Hentschel developed a process to nanostructure the metallic polymers using a combination of electron beam lithography and etching, thereby creating the plasmonic nanoantennas. The team showed that the optical appearance of the nanoantennas could be switched between that of a shiny metal and a transparent material by applying a voltage between minus and plus one volt. This switching effect works even at video rates of 30 Hertz. Despite being only a few tens of nanometers thick and less than 400 nanometers in size, the nanoantennas do the same job as the much larger and thicker liquid crystals used in current state-of-the-art technology. These new devices reach the required pixel densities of about 50.000 dpi.

Karst created a simple hologram metasurface from the nanoantennas that could deflect an infrared laser beam 10 degrees onto one side by applying a voltage.

Currently, he is working on making this deflection available for many angles for applications in LIDAR devices in autonomous vehicles, of keen interest to the automotive industry. Additionally, Karst created a hologram that behaves like an optical lens, which can be turned on and off by simply applying ± 1 Volt.

This technology is crucial for future smartphone cameras or optical sensors that could be zoomed from wide angle to telephoto by switching the applied voltage. Currently, up to four lenses are required for this functionality.

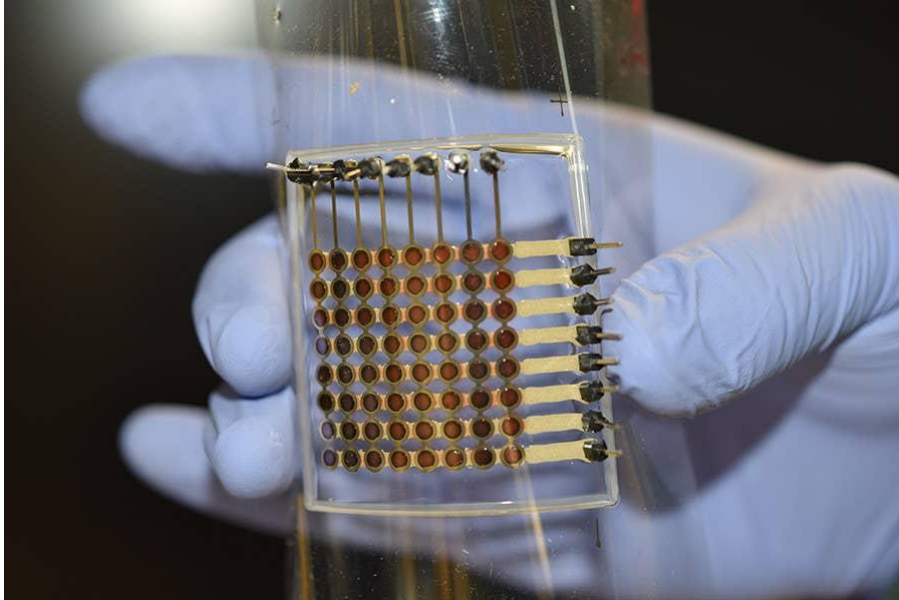
In the future, Prof. Harald Giessen and his team aim to address every single pixel individually, to dynamically change the holograms at will at video rates. Also, the optical properties of the polymer nanoantennas have to be shifted into the visible wavelength range, which requires collaborations with chemists and material scientists.

Together with engineers, integrated and dynamically switchable optical displays and the first moving holograms could be integrated into AR/VR goggles and eventually onto smartphone screens and even televisions.

Applying Moore's law to display technology, this advance by about a factor of 100 could happen commercially around the year 2035.

Researchers develop first fully 3D-printed, flexible OLED display

The fully 3D-printed flexible organic light-emitting diode (OLED) display prototype is about 1.5 inches on each side and has 64 pixels.



University of Minnesota

The fully 3D-printed flexible organic light-emitting diode (OLED) display prototype is about 1.5 inches on each side and has 64 pixels. Every pixel works and displays light. The 3D-printed display is also flexible, which could make it useful for a wide variety of applications, such as foldable smartphone displays. (CREDIT: McAlpine Group, University of Minnesota)

In a groundbreaking new study, researchers at the University of Minnesota Twin Cities used a customized printer to fully 3D print a flexible organic light-emitting diode (OLED) display. The discovery could result in low-cost OLED displays in the future that could be widely produced using 3D printers by anyone at home, instead of by technicians in expensive microfabrication facilities.

The research is published in Science Advances, a peer-reviewed scientific journal published by the American Association for the Advancement of Science (AAAS).

The OLED display technology is based on the conversion of electricity into light using an organic material layer. OLEDs function as high quality digital displays, which can be made flexible and used in both large-scale devices such as television screens and monitors as well as handheld electronics such as smartphones.

OLED displays have gained popularity because they are lightweight, power-efficient, thin and flexible, and offer a wide viewing angle and high contrast ratio.

"OLED displays are usually produced in big, expensive, ultra-clean fabrication facilities," said Michael McAlpine, a University of Minnesota Kuhrmeyer Family Chair Professor in the Department of Mechanical Engineering and the senior author of the study.

"We wanted to see if we could basically condense all of that down and print an OLED display on our table-top 3D printer, which was custom built and costs about the same as a Tesla Model S."

The group had previously tried 3D printing OLED displays, but they struggled with the uniformity of the light-emitting layers. Other groups partially printed displays but also relied on spin-coating or thermal evaporation to deposit certain components and create functional devices.

In this new study, the University of Minnesota research team combined two different modes of printing to print the six device layers that resulted in a fully 3D-printed, flexible organic light-emitting diode display. The electrodes, interconnects, insulation, and encapsulation were all extrusion printed, while the active layers were spray printed using the same 3D printer at room temperature. The display prototype was about 1.5 inches on each side and had 64 pixels. Every pixel worked and displayed light.

"I thought I would get something, but maybe not a fully working display," said Ruitao Su, the first author of the study and a 2020 University of Minnesota mechanical engineering Ph.D. graduate who is now a postdoctoral researcher at MIT. "But then it turns out all the pixels were working, and I can display the text I designed. My first reaction was 'It is real!' I was not able to sleep, the whole night."

Su said the 3D-printed display was also flexible and could be packaged in an encapsulating material, which could make it useful for a wide variety of applications.

"The device exhibited a relatively stable emission over the 2,000 bending cycles, suggesting that fully 3D printed OLEDs can potentially be used for important applications in soft electronics and wearable devices," Su said.

The researchers said the next steps are to 3D print OLED displays that are higher resolution with improved brightness.

"The nice part about our research is that the manufacturing is all built in, so we're not talking 20 years out with some 'pie in the sky' vision," McAlpine said. "This is something that we actually manufactured in the lab, and it is not hard to imagine that you could translate this to printing all kinds of displays ourselves at home or on the go within just a few years, on a small portable printer."

In addition to McAlpine and Su, the research team included University of Minnesota mechanical engineering researchers Xia Ouyang, a postdoctoral researcher; Sung Hyun Park, who is now a senior researcher at Korea Institute of Industrial Technology; and Song Ih Ahn, who is now an assistant professor of mechanical engineering at Pusan National University in Korea.

The research was funded primarily by the National Institute of Biomedical Imaging and Bioengineering of the National Institutes of Health (Award No. 1DP2EB020537) with additional support from The Boeing Company and the Minnesota Discovery, Research, and Innovation Economy (MnDRIVE) Initiative through the State of Minnesota. Portions of this study were conducted in the Minnesota Nano Center, which is supported by the National Science Foundation through the National Nano Coordinated Infrastructure Network (NNCI).

To read the entire research paper entitled “3D printed flexible organic light-emitting diode displays,” visit the [Science Advances website](#).

Stretchy, bendy, flexible PeLEDs may be the first step in an electronics revolution

Sure, you could attach two screens with a hinge and call a cell phone “foldable,” but what if you could roll it up and put it in your wallet

Sure, you could attach two screens with a hinge and call a cell phone “foldable,” but what if you could roll it up and put it in your wallet? Or stretch it around your wrist to wear it as a watch?

The next step in digital displays being developed at the McKelvey School of Engineering at Washington University in St. Louis could make that a reality.

First, there were light-emitting diodes, or LEDs. Then, organic LEDs, or OLEDs. Now, researchers in the lab of [Chuan Wang](#), assistant professor in the Preston M. Green Department of Electrical & Systems Engineering, have developed a new material that has the best of both technologies and a novel way to fabricate it — using an inkjet printer.

The research was published this month in the journal [Advanced Materials](#).

Organic LEDs, made with organic small molecules or polymer materials, are cheap and flexible. “You can bend or stretch them — but they have relatively low performance and short lifetime,” Wang said. “Inorganic LEDs such as microLEDs are high performing, super bright and very reliable, but not flexible and very expensive.”

"What we have made is an organic-inorganic compound," he said. "It has the best of both worlds."

They used a particular type of crystalline material called an organometal halide perovskite — though with a novel twist. The traditional way to create a thin layer of perovskite, which is in liquid form, is to drip it onto a flat, spinning substrate, like a spin art toy, in a process known as spin coating. As the substrate spins, the liquid spreads out, eventually covering it in a thin layer.

From there, it can be recovered and made into perovskite LEDs, or PeLEDs. Like spin art, however, a lot of material is wasted in that process — as the substrate spins at several thousand RPM, some of the dripping perovskite splatters and flies away, not sticking to the substrate.

"Because it comes in a liquid form," Wang said, "we imagined we could use an inkjet printer" in place of spin coating.

Inkjet fabrication saves materials, as the perovskite can be deposited only where it's needed, in a similar way to the precision with which letters and numbers are printed on a piece of paper; no splatter, less waste. The process is much faster as well, cutting fabrication time from more than five hours to less than 25 minutes.

Another benefit of using the inkjet printing method has the potential to reshape the future of electronics: perovskite can be printed onto a variety of unconventional substrates, including those that wouldn't lend themselves to stability while spinning — materials such as rubber.

"Imagine having a device that starts out the size of a cell phone but can be stretched to the size of a tablet," Wang said.

For a display to be flexible, however, printing stiff LEDs on rubber won't do the trick. The LEDs themselves need to be flexible. Perovskite is not.

First author Junyi Zhao, a PhD candidate in Wang's lab, was able to solve the problem by embedding the inorganic perovskite crystals into an organic, polymer matrix made of polymer binders. This made the perovskite and, by association, the PeLEDs, themselves, elastic and stretchable in nature.

The best of both worlds.

The process wasn't exactly straightforward. It took long days — and a few nights — in the lab before getting it right. Wang and Zhao agreed that the biggest roadblock was making sure the different layers of material didn't mix.

Because all parts of the PeLED were made from liquid — the perovskite layer as well as the two electrodes and a buffer layer — a major concern was keeping all of the layers from mixing.

LEDs are constructed in a sandwich-like configuration, with at least an emissive layer, an anode layer and a cathode layer. Additional layers such as electron and hole transporting layers may sometimes also be used. Zhao had to keep the perovskite layer safe from mixing with any of the others, the way running a highlighter over freshly written ink might smear it.

He needed to find a suitable polymer, one that could be inserted between the perovskite and the other layers, protecting it from them while not interfering too much with the PeLED's performance.

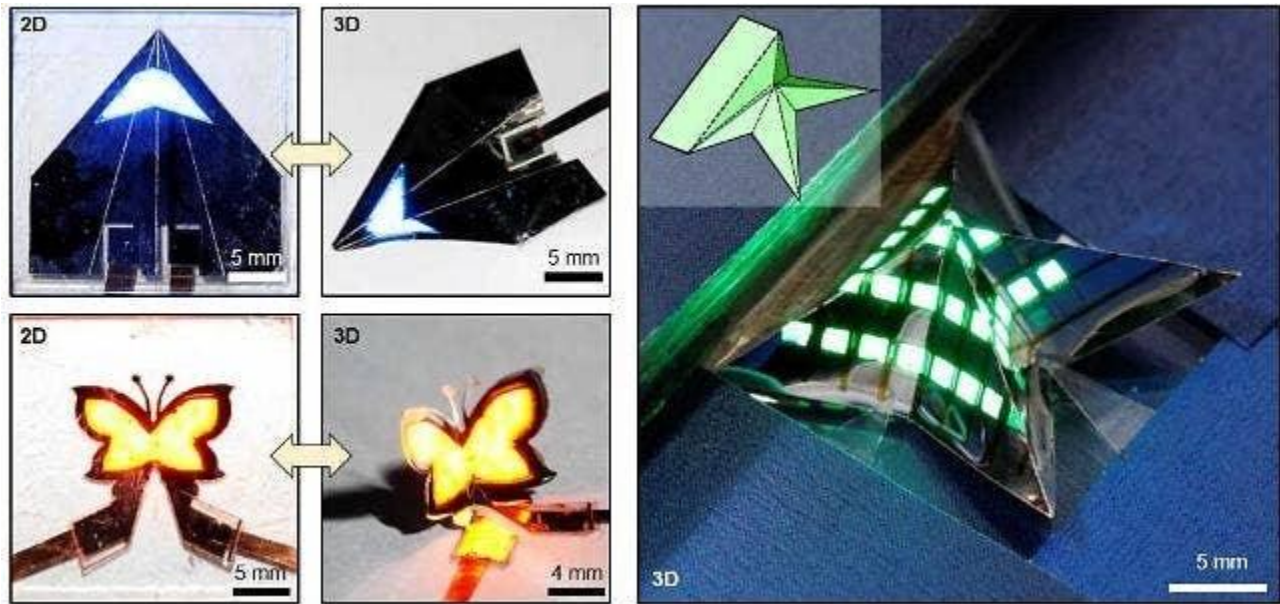
"We found the best material and best thickness to balance performance and protection of the device," Zhao said. After that, he went on to print the first stretchy PeLEDs. The university's Office of Technology Management has a pending patent on the technology and fabrication method.

These PeLEDs may be just the first step in an electronics revolution: Walls could provide lighting or even display the day's newspaper. They can be used to make wearable devices, even smart wearables, like a pulse oximeter to measure blood oxygen.

Most excitingly, being able to print stretchy, flexible PeLEDs cheaply and quickly may lead to new technologies yet to be dreamed up.

Revolutionary new quantum dot LED (QLED) is as flexible to fold as paper

The new 3 micrometer thick QLED paper can be folded into complex 3D structures such as butterflies, airplanes, and pyramids.



Quantum dot light-emitting diode (QLED), which employs quantum dots as a light-emitting material, has attracted significant attention as a promising alternative for next-generation display technologies, owing to its outstanding electroluminescence properties. Since it does not require any bulky components such as backlight units, QLED displays can potentially be manufactured into an ultrathin form factor.

A joint research team led by KIM Dae-Hyeong (Professor at Seoul National University) and HYEON Taeghwan (Distinguished professor at Seoul National University) from the Center for Nanoparticle Research within the Institute for Basic Science has previously unveiled a prototype QLED back in 2015. The device had a thickness of only 3 micrometers, which is only one-thirtieth of that of human hair. Due to such an extremely reduced thickness, the ultrathin QLED exhibited outstanding mechanical flexibility, which allowed it to be readily applicable in various wearable devices, such as electronic tattoos.

Recently, the team further advanced this technology and developed a foldable variant of the ultrathin QLED, inspired by the ancient art of paper folding known as origami. The IBS researchers reported three-dimensional foldable QLEDs, which can be freely transformed into various user-customized 3D structures, such as butterflies, airplanes, and pyramids. Considering the rising popularity of foldable smartphones, the advancement of foldable display technology is gaining greater importance. It is expected this technology can provide unprecedented opportunities for next-generation electronics with user-customized form factors with complex structures, as well as allowing for dynamic three-dimensional display of visual information.

The researchers endowed foldability to the conventional planar QLED via a new fabrication process that can partially etch the epoxy film deposited on the QLED surface

without damaging the underlying QLED. Using a power-controllable carbon dioxide pulsed laser and the silver-aluminum alloy-based etch-stop layers, the etching depth can be precisely controlled. As the laser-etched part of the device is relatively thinner than the surrounding region, it is possible to etch out deformation lines along which the device can be folded like origami paper.

Based on the selective laser-etching technique, researchers were able to precisely control the radius of curvature down to less than 50 micrometers. Under such a small curvature radius, the fold line resembles a sharp edge with no visible curvature. By using mechanical simulation to carefully engineer the device, researchers were able to minimize the strain loaded on the light-emitting components. The entire QLED including the crease region (a fold line) was able to maintain a stable light-emitting performance even when after it was repeatedly folded 500 times. The technology was applied to fabricate 3D foldable QLEDs with various complex shapes such as butterflies, airplanes, and pyramids.

"We were able to build a 3D foldable QLED that can be freely folded just like a paper artwork", said KIM Dae-Hyeong, the vice-director of the Center for Nanoparticle Research. He also said, "By fabricating the passively driven, 3D foldable QLED arrays composed of 64 individual pixels, we have shown the possibility of developing displays with greater complexity in the future." HYEON Taeghwan, the director of the Center for Nanoparticle Research, states that "Through the technology reported in this research, paper-like QLEDs that can be folded into various complex structures have been successfully fabricated. Who knows when the day will come when electronic paper with a display unit can replace real paper?"

Bioengineers develop new class of human-powered bioelectronics

The technology converts human body motions into electricity that could be used to power wearable and implantable diagnostic sensors.



UCLA-designed self-powered, stretchable, waterproof magnetoelastic generator for bioelectronics. (Credit: Jun Chen/UCLA)

A team of bioengineers at the UCLA Samueli School of Engineering has invented a novel soft and flexible self-powered bioelectronic device. The technology converts human body motions—from bending an elbow to subtle movements such as a pulse on one's wrist—into electricity that could be used to power wearable and implantable diagnostic sensors

The researchers discovered that the magnetoelastic effect, which is the change of how much a material is magnetized when tiny magnets are constantly pushed together and pulled apart by mechanical pressure, can exist in a soft and flexible system—not just one that is rigid. To prove their concept, the team used microscopic magnets dispersed in a paper-thin silicone matrix to generate a magnetic field that changes in strength as the matrix undulated. As the magnetic field's strength shifts, electricity is generated.

Nature Materials published today a research study detailing the discovery, the theoretical model behind the breakthrough and the demonstration.

"Our finding opens up a new avenue for practical energy, sensing and therapeutic technologies that are human-body-centric and can be connected to the Internet of Things," said study leader Jun Chen, an assistant professor of bioengineering at UCLA

Samueli. "What makes this technology unique is that it allows people to stretch and move with comfort when the device is pressed against human skin, and because it relies on magnetism rather than electricity, humidity and our own sweat do not compromise its effectiveness."

Chen and his team built a small, flexible magnetoelastic generator (about the size of a U.S. quarter) made of a platinum-catalyzed silicone polymer matrix and neodymium-iron-boron nanomagnets. They then affixed it to a subject's elbow with a soft, stretchy silicone band. The magnetoelastic effect they observed was four times greater than similarly sized setups with rigid metal alloys. As a result, the device generated electrical currents of 4.27 milliamperes per square centimeter, which is 10,000 times better than the next best comparable technology.

In fact, the flexible magnetoelastic generator is so sensitive that it could convert human pulse waves into electrical signals and act as a self-powered, waterproof heart-rate monitor. The electricity generated can also be used to sustainably power other wearable devices, such as a sweat sensor or a thermometer.

There have been ongoing efforts to make wearable generators that harvest energy from human body movements to power sensors and other devices, but the lack of practicality has hindered such progress. For example, rigid metal alloys with magnetoelastic effect do not bend sufficiently to compress against the skin and generate meaningful levels of power for viable applications.

Other devices that rely on static electricity tend not to generate enough energy. Their performance can also suffer in humid conditions, or when there is sweat on the skin. Some have tried to encapsulate such devices in order to keep water out, but that cuts down their effectiveness. The UCLA team's novel wearable magnetoelastic generators, however, tested well even after being soaked in artificial perspiration for a week. A patent on the technology has been filed by the UCLA Technology Development Group.

New LED material emits light without generating heat

The brighter these LED technologies shine, the more inefficient they become, releasing more energy as heat instead of light.



Applying mechanical strain on this atomically thin, transparent monolayer semiconductor results in a material with near 100% light-emission efficiency. (Credit: Ali Javey/Berkeley Lab)

Smartphones, laptops, and lighting applications rely on light-emitting diodes (LEDs) to shine bright. But the brighter these LED technologies shine, the more inefficient they become, releasing more energy as heat instead of light.

Now, as reported in the journal Science, a team led by researchers at Lawrence Berkeley National Laboratory (Berkeley Lab) and UC Berkeley has demonstrated an approach for achieving near 100% light-emission efficiency at all brightness levels. Their approach focuses on stretching or compressing a thin semiconductor film in a way that favorably changes its electronic structure.

The team identified just how the semiconductor's electronic structure dictated interaction among the energetic particles within the material. Those particles sometimes collide and annihilate each other, losing energy as heat instead of emitting light in the process. Changing the material's electronic structure reduced the likelihood for annihilation and led to a near-perfect conversion of energy to light, even at high brightness.

"It's always easier to emit heat than emit light, particularly at high brightness levels. In our work we have been able to reduce the loss process by one hundredfold," said Ali Javey, a faculty senior scientist at Berkeley Lab and professor of electrical engineering and computer sciences at UC Berkeley.

LED performance depends on excitons

The Berkeley team's discovery was made using a single, 3-atom-thick layer of a type of semiconductor material, called a transition metal dichalcogenide, that was subjected to mechanical strain. These thin materials have a unique crystal structure that gives rise to unique electronic and optical properties: When their atoms are excited either by passing an electric current or shining light, energetic particles called excitons are created.

Excitons can release their energy either by emitting light or heat. The efficiency with which excitons emit light as opposed to heat is an important metric that determines the ultimate performance of LEDs. But achieving high performance requires precisely the right conditions.

"When the exciton concentration is low, we had previously found how to achieve perfect light-emission efficiency," said Shiekh Zia Uddin, a UC Berkeley graduate student and co-lead author on the paper. He and his colleagues had shown that chemically or electrostatically charging single-layered materials could lead to high-efficiency conversion, but only for a low concentration of excitons.

For the high exciton concentration at which optical and electronic devices typically operate, though, too many excitons annihilate each other. The Berkeley team's new work suggests that the trick to achieve high performance for high concentrations lay in tweaking the material's band structure, an electronic property that controls how excitons interact with each other and could reduce the probability of exciton annihilation.

"When more excited particles are created, the balance tilts toward creating more heat instead of light. In our work, we first understood how this balance is controlled by the band structure," said Hyungjin Kim, a postdoctoral fellow and co-lead author on the work. That understanding led them to propose modifying the band structure in a controlled way using physical strain.

High-performance under strain

The researchers started by carefully placing a thin semiconductor (tungsten disulfide, or WS₂) film atop a flexible plastic substrate. By bending the plastic substrate, they applied a small amount of strain to the film. At the same time, the researchers focused a laser beam with different intensities on the film, with a more intense beam leading to a higher concentration of excitons—a high "brightness" setting in an electronic device.

Detailed optical microscope measurements allowed the researchers to observe the number of photons emitted by the material as a fraction of the photons it had absorbed from the laser. They found that the material emitted light at nearly perfect efficiency at all brightness levels through appropriate strain.

To further understand the material's behavior under strain, the team performed analytical modeling.

They found that the heat-losing collisions between excitons are enhanced due to "saddle points"—regions where an energy surface curves in a way that resembles a mountain pass between two peaks—found naturally in the single-layer semiconductor's band structure.

Applying the mechanical strain led the energy of that process to change slightly, drawing the excitons away from the saddle points. As a result, the particles' tendency to collide was reduced, and the reduction in efficiency at high concentrations of charged particles ceased to be a problem.

"These single-layer semiconductor materials are intriguing for optoelectronic applications as they uniquely provide high efficiency even at high brightness levels and despite the presence of large number of imperfections in their crystals," said Javey. Future work by the Berkeley Lab team will focus on using the material to fabricate actual LED devices for further testing of the technology's high efficiency under increasing brightness.

New LED innovation will enable refrigerators to identify food that is spoiling

Your smart device could soon be even smarter with a new infrared light emitting diode that is 'tuneable' to different wavelengths of light

Your smart device could soon be even smarter with a new infrared light emitting diode (LED) that is 'tuneable' to different wavelengths of light – it could enable your fridge to tell you when your food is going off and your phone to tell you if that Gucci purse is real.

The technology has been developed by the [University of Melbourne](#), the [Lawrence Berkeley National Laboratory](#), the [University of California, Berkeley](#), and the Australian Research Council Centre of Excellence for Transformative Meta-Optical Systems (TMOS). They have come up with a device that could identify a suite of gases, potentially including lethal ones, improving the safety of firefighters, miners, the military, and your local plumber. The work appeared in the journal, [Nature](#).

Infrared (IR) spectrometers are common laboratory equipment that can identify different materials by analysing their infrared signatures, which is invisible to the human eye. Just like an AM radio can be tuned to different frequencies of radio wave, IR spectrometers can be tuned to different wavelengths, giving a broad-spectrum analysis of a gas sample. However, these machines are bulky and expensive and not usually practical to take out of the laboratory and into the field.

"Our new technology bonds a thin layer of black phosphorus crystals to a flexible, plastic-like substrate, allowing it to be bent in ways that cause the black phosphorus to emit light of different wavelengths essentially creating a tuneable infrared LED that allows for the detection of multiple materials," University of Melbourne Professor Kenneth Crozier said. "This technology could fit inside smartphones and become part of everyday use."

For example, the bacteria found in meat release various gases as they multiply. The presence of these gases is a good indication that the meat is spoiling and is no longer fit for consumption.

"The device placed inside a fridge could send a notification that meat is going off. When pointed at a handbag, it could reveal whether the bag is made of real leather or a cheaper substitute," said Professor Crozier, who is also the Deputy Director of TMOS. Current materials that are used for IR photodetectors and light emitting devices can be difficult to manufacture, in large part due to the need for multiple layers of perfectly linked crystals. This new black phosphorus technology requires just one layer allowing the device to be flexible, giving it unique properties when bent.

"The shift in black phosphorus' emission wavelength with bending is really quite dramatic, enabling the LED to be tuned across the mid-infrared," said Professor Ali Javey, from the University of California at Berkeley, whose group led the work. Importantly, the device could make the work of firefighters, miners and military safer, allowing them to identify potentially lethal gases from safe distances as the ultra-thin, ultra-light devices can be placed on small drones. Flying such a drone over a building fire could tell firefighters what dangers they face and equipment they'll need.

The low-cost technology could also make its way into devices for use by plumbers and building managers.

"Our IR photo detectors could be integrated into a camera so that we could look at our phone screen and 'see' gas leaks or emissions and be able to determine what kind of gas it is," Professor Crozier said.

Researchers are developing interactive holograms you can touch and feel

Star Trek: The Next Generation introduced millions of people to the idea of a complete environment that you could interact with and touch.



The TV show "Star Trek: The Next Generation" introduced millions of people to the idea of a holodeck: an immersive, realistic 3D holographic projection of a complete environment that you could interact with and even touch.

In the 21st century, holograms are already being used in a variety of ways such as medical systems, education, art, security and defense. Scientists are still developing ways to use lasers, modern digital processors, and motion-sensing technologies to create several different types of holograms which could change the way we interact.

My colleagues and I working in the University of Glasgow's bendable electronics and sensing technologies research group have now developed a system of holograms of people using "aeroaptics," creating feelings of touch with jets of air. Those jets of air deliver a sensation of touch on people's fingers, hands and wrists.

In time, this could be developed to allow you to meet a virtual avatar of a colleague on the other side of the world and really feel their handshake. It could even be the first steps towards building something like a holodeck.

To create this feeling of touch we use affordable, commercially available parts to pair computer-generated graphics with carefully directed and controlled jets of air.

In some ways, it's a step beyond the current generation of virtual reality, which usually requires a headset to deliver 3D graphics and smart gloves or handheld controllers to provide haptic feedback, a stimulation that feels like touch. Most of the wearable gadgets-based approaches are limited to controlling [the virtual object](#) that is being displayed.

Controlling a virtual object doesn't give the feeling that you would experience when two people touch. The addition of an artificial touch sensation can deliver the additional dimension without having to wear gloves to feel objects, and so feels much more natural.

Using glass and mirrors

Our research uses graphics that provide the illusion of a 3D virtual image. It's a modern variation on a 19th-century illusion technique known as Pepper's Ghost, which thrilled Victorian theatergoers with visions of the supernatural onstage.

The systems uses glass and mirrors to make a two-dimensional image appear to hover in space without the need for any additional equipment. And our haptic feedback is created with nothing but air.

The mirrors making up our system are arranged in a pyramid shape with one open side. Users put their hands through the open side and interact with computer-generated objects which appear to be floating in free space inside the pyramid. The objects are graphics created and controlled by a software program called Unity Game Engine, which is often used to create 3D objects and worlds in videogames.

Located just below the pyramid is a sensor that tracks the movements of users' hands and fingers, and a single air nozzle, which directs jets of air towards them to create complex sensations of touch. The overall system is directed by electronic hardware programmed to control nozzle movements. We developed an algorithm which allowed the air nozzle to respond to the movements of users' hands with appropriate combinations of direction and force.

One of the ways we've demonstrated the capabilities of the "aerohaptic" system is with an interactive projection of a basketball, which can be convincingly touched, rolled and

bounced. The touch feedback from air jets from the system is also modulated based on the virtual surface of the basketball, allowing users to feel the rounded shape of the ball as it rolls from their fingertips when they bounce it and the slap in their palm when it returns.

Users can even push the virtual ball with varying force and sense the resulting difference in how a hard bounce or a soft bounce feels in their palm. Even something as apparently simple as bouncing a basketball required us to work hard to model the physics of the action and how we could replicate that familiar sensation with jets of air.

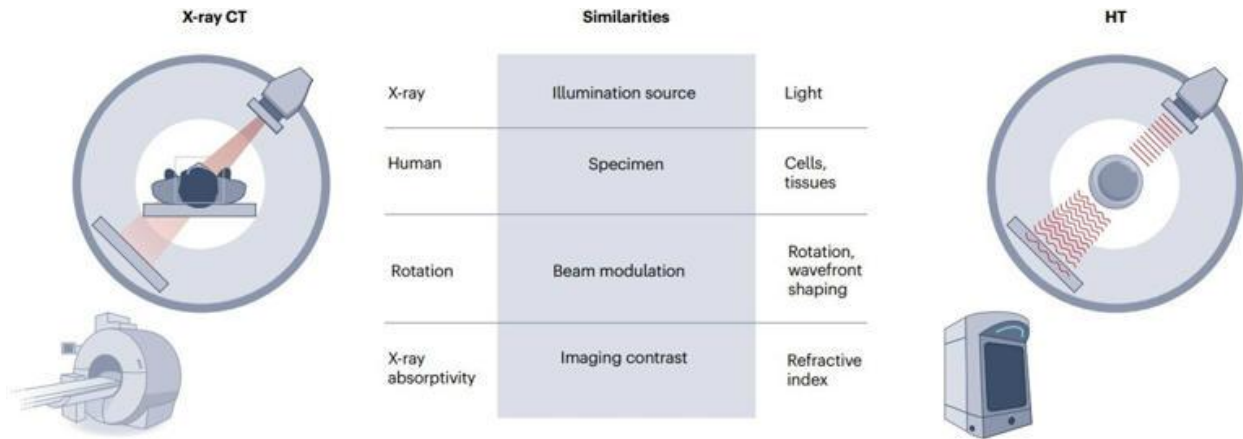
Smells of the future

While we don't expect to be delivering a full Star Trek holodeck experience in the near future, we're already boldly going in new directions to add additional functions to the system. Soon, we expect to be able to modify the temperature of the airflow to allow users to feel hot or cold surfaces. We're also exploring the possibility of adding scents to the airflow, deepening the illusion of virtual objects by allowing users to smell as well as touch them.

As the system expands and develops, we expect that it may find uses in a wide range of sectors. Delivering more absorbing video game experiences without having to wear cumbersome equipment is an obvious one, but it could also allow more convincing teleconferencing too. You could even take turns to add components to a virtual circuit board as you collaborate on a project.

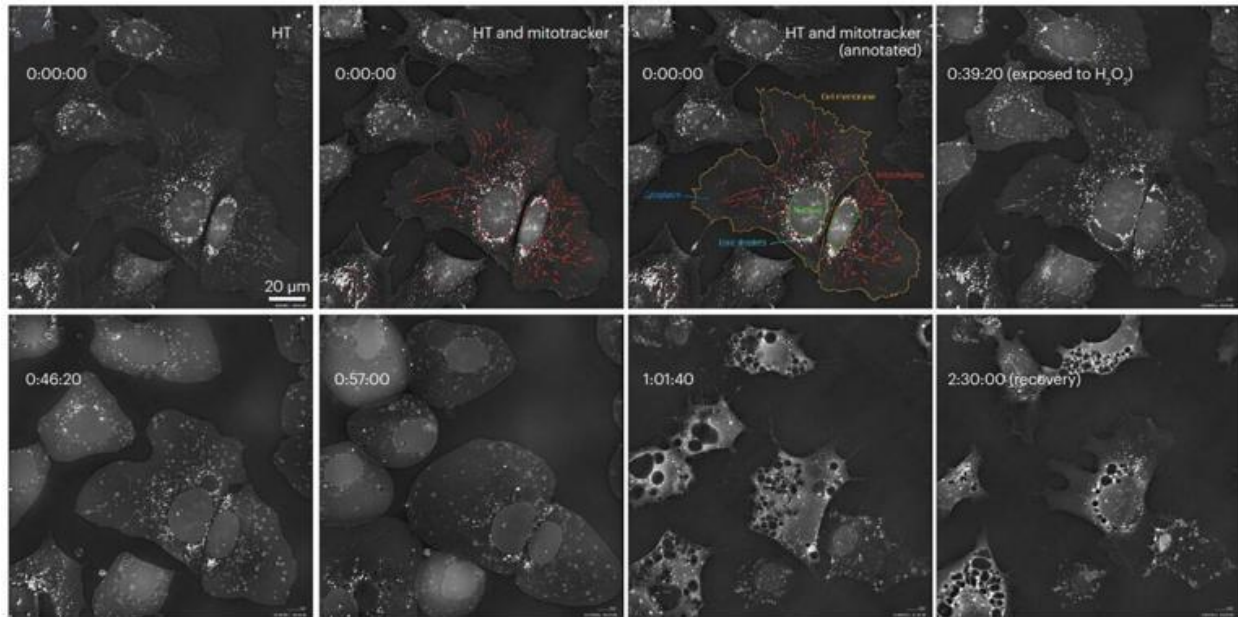
It could also help clinicians to collaborate on [treatments for patients](#), and make patients feel more involved and informed in the process. Doctors could view, feel and discuss the features of tumor cells, and show patients plans for a medical procedure.

Paper introduces strategies for holotomography in advanced bio research



Schematic illustration of holotomography compared to X-ray CT. Similar to CT, they share the commonality of measuring the optical properties of an unlabeled specimen in three dimensions. Instead of X-rays, holotomography irradiates light in the visible range, and provides refractive index measurements of transparent specimens rather than absorptivity. While CT obtains three-dimensional information only through mechanical rotation of the irradiating light, holotomography can replace this by applying wavefront control technology in the visible range. Credit: KAIST Biomedical Optics Laboratory

Measuring and analyzing three-dimensional (3D) images of live cells and tissues is considered crucial in advanced fields of biology and medicine. Organoids, which are 3D structures that mimic organs, are particular examples that significantly benefit 3D live imaging. Organoids provide effective alternatives to animal testing in the drug development processes, and can rapidly determine personalized medicine. On the other hand, active research is ongoing to utilize organoids for organ replacement.

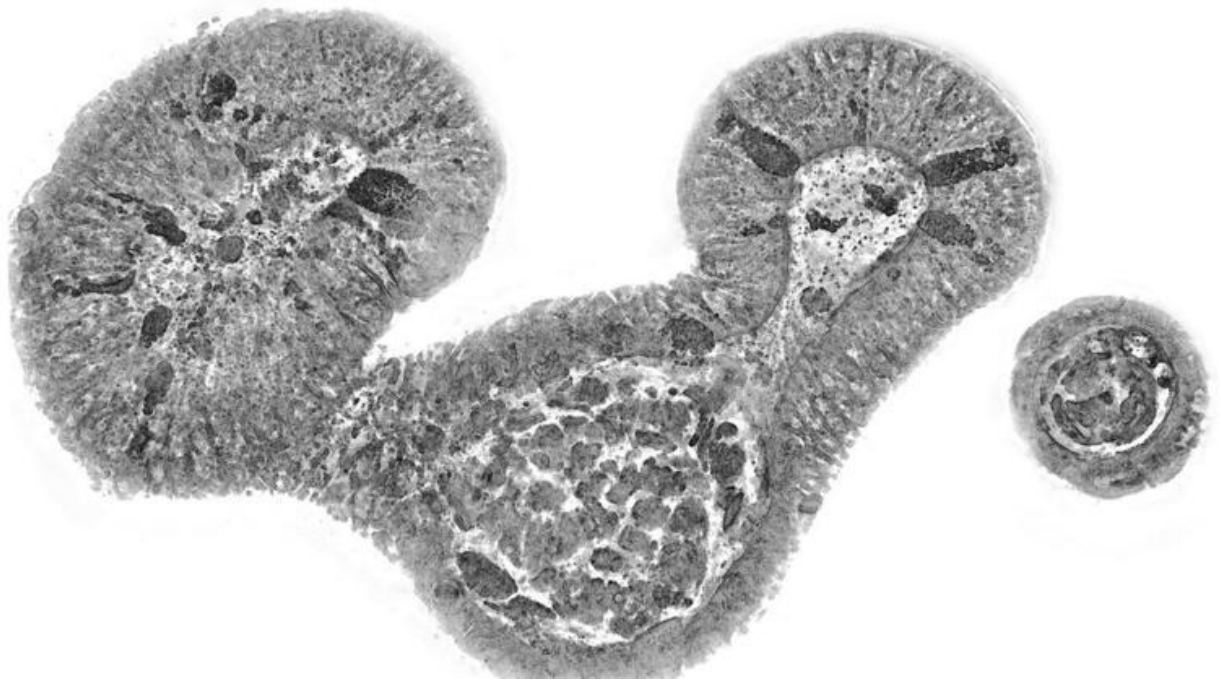


Label-free 3D imaging of diverse live cells. Time-lapse image of Hep3B cells illustrating subcellular morphology changes upon H₂O₂ treatment, followed by cellular recovery after returning to the regular cell culture medium. Credit: KAIST Biomedical Optics Laboratory

Organelle-level observation of 3D biological specimens such as organoids and stem cell colonies without staining or preprocessing holds significant implications for both innovating basic research and bioindustrial applications related to regenerative medicine and bioindustrial applications.

Holotomography (HT) is a 3D optical microscopy that implements 3D reconstruction analogous to that of X-ray computed tomography (CT). Although HT and CT share a similar theoretical background, HT facilitates high-resolution examination inside cells and tissues, instead of the human body.

HT obtains 3D images of cells and tissues at the organelle level without chemical or genetic labeling, thus overcoming various challenges of existing methods in bio research and industry. Its potential is highlighted in research fields where sample physiology must not be disrupted, such as regenerative medicine, personalized medicine, and infertility treatment.



Various types of cells and organelles that make up the imaging barrier of a living intestinal organoid can be observed using holotomography. Credit: KAIST Biomedical Optics Laboratory

This paper introduces the advantages and broad applicability of HT to biomedical researchers, while presenting an overview of principles and future technical challenges to optical researchers. It showcases various cases of applying HT in studies such as 3D biology, regenerative medicine, and cancer research, as well as suggesting future optical development.

*Also, it categorizes HT based on the light source, to describe the principles, limitations, and improvements of each category in detail. In particular, the paper addresses strategies for deepening cell and organoid studies by introducing artificial intelligence (AI) to HT. The research is [published](#) in the journal *Nature Reviews Methods Primers*.*

Due to its potential to drive advanced bioindustry, HT is attracting interest and investment from universities and corporates worldwide. The KAIST research team has been leading this international field by developing core technologies and carrying out key application research throughout the last decade.

This paper was co-authored by Dr. Geon Kim from KAIST Research Center for Natural Sciences, Professor Ki-Jun Yoon's team from the Department of Biological Sciences, Director Bon-Kyoung Koo's team from the Institute for Basic Science (IBS)

Center for Genome Engineering, and Dr. Seongsoo Lee's team from the Korea Basic Science Institute (KBSI).

More information: Geon Kim et al, Holotomography, Nature Reviews Methods Primers (2024). DOI: [10.1038/s43586-024-00327-1](https://doi.org/10.1038/s43586-024-00327-1)

Provided by The Korea Advanced Institute of Science and Technology (KAIST)

Scientists Replicated the Energy System That May Be the Secret of Life's Inception



How did life arise from lifeless molecules? Scientists recreated the mitochondria and biochemical nutrient transport throughout a synthetic cell. © Yuichiro Chino - Getty Images

- *Several Dutch institutions are working together to investigate how life arose from lifeless molecules.*
- *In two recently published papers, scientists successfully recreated the mitochondria (in a simple form) and biochemical nutrient transport throughout a synthetic cell.*

- While these are only two of a whole host of processes that need to be recreated to truly mimic a cell, these first creations show compelling evidence of how life first formed a toehold on Earth.

One of the greatest questions of science centers on how life seemingly formed from lifeless molecules. This has led researchers to do things like investigate how [rain might have helped form membranes](#) of protocells and search for life's [Last Universal Common Ancestor \(LUCA\)](#). In keeping with the tradition of this “where do we come from” scientific investigation, Dutch researchers are trying to synthetically reconstruct the basic building blocks of cells.

Now, the consortium of scientists, known as Building a Synthetic Cell (BaSys), has put out two papers. Published in [Nature Nanotechnology](#) and [Nature Communications](#), respectively, they detail methods for creating synthetic mitochondria and certain cellular processes. The hope is that if we can reconstruct these basic building blocks of life in a laboratory, it may shine light on how these components came together on [Earth](#) billions of years ago.

Bert Poolman, Professor of Biochemistry at the University of Groningen in the Netherlands, leads the team in investigating ways to artificially reconstruct energy conversion, and that necessarily centers on the [mitochondria](#)—often referred to as the “powerhouse of the cell.” At the heart of this process is the molecule ADP, which produces essentially a cell's fuel, ATP. However, Poolman's team didn't set out to create mitochondria exactly. They were after a simplified version.

“Instead of the hundreds of components of mitochondria, our system for energy conversion uses just five,” Poolman [said in a press statement](#). “[Evolution](#) is a one-way street, it builds on existing components and this often makes the outcome very complex.” However, when you're building from scratch, you can design the cell from the ground up with specific functions in mind.

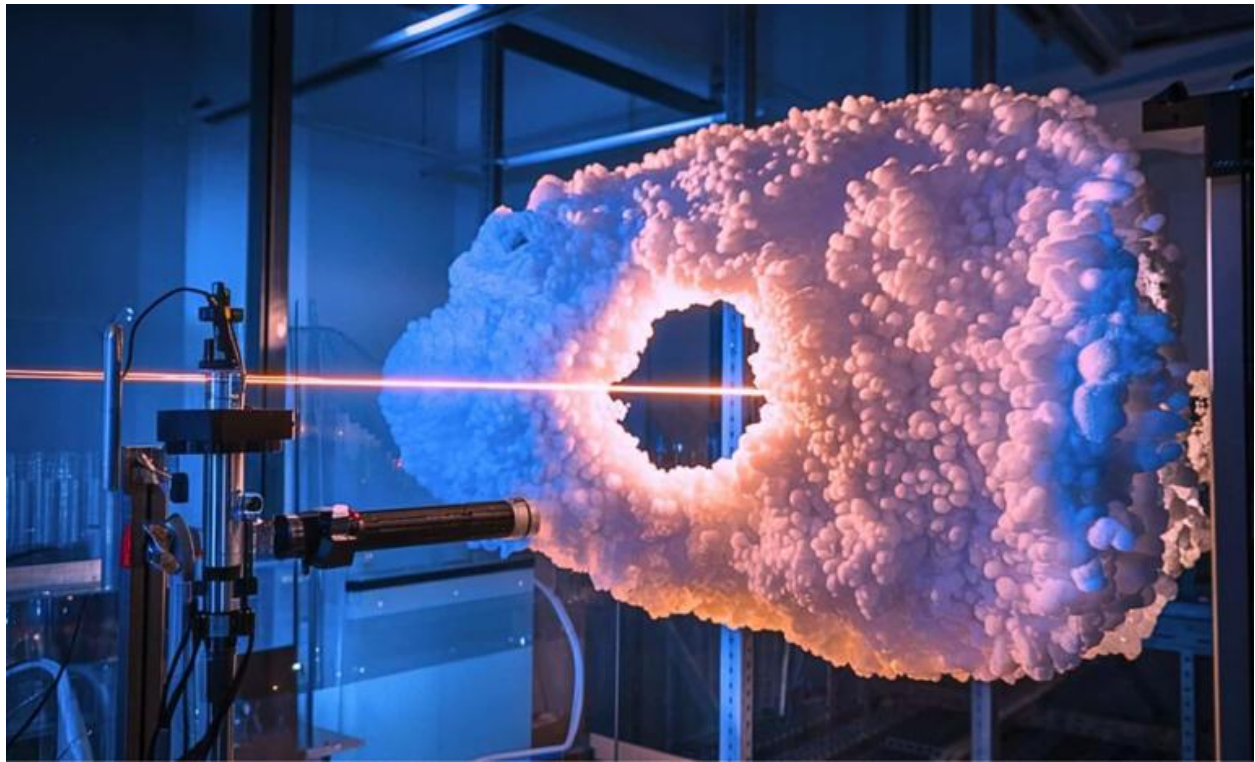
By creating tiny cell-like sacs known as vesicles, the team successfully created components capable of absorbing both ADP and the amino acid arginine. When the arginine deaminated, it created the necessary [energy](#) to produce ATP. A second vessel used this “fuel” to create an energy-consuming reaction, which then reverted back to ADP that was ready to be absorbed by the first vesicle, creating a kind of loop. While this mimics the power-making wonders of cells, it's not a one-to-one copy.

"Of course, the simplification comes at a price: we can only use arginine as the energy source, while cells use all kinds of different molecules, such as amino acids, fats, and sugars," Poolman said in a press statement.

Additionally, Poolman's team successfully recreated the nutrient transport process in a synthetic cell, which is crucial to the function of the cell and only required two components. And while these two synthetic cell components are a good start, the project still has a long way to go to simulate how life sprung up from lifeless molecules. Luckily, the BaSyc consortium is evolving into a new group called EVOLF (Evolving life from non-life) that's funded for another decade and is dedicated to this same mission.

"Ultimately, this would give us a blueprint for life, something that is currently lacking in biology," Poolman said in a press statement. "This may eventually have all kinds of applications, but will also help us to better understand what life is."

Physicists “Slow Down Light” to Just 61 Kilometers per Hour Using Ultracold Quantum Matter



Physicists “Slow Down Light” to Just 61 Kilometers per Hour Using Ultracold Quantum Matter | The Daily Galaxy --Great Discoveries Channel© Daily Galaxy UK

*The **speed of light** is often regarded as the ultimate cosmic speed limit, but researchers have now managed to slow it down dramatically—to just **61 kilometers per hour**. This was achieved by using a **Bose-Einstein condensate (BEC)**, a peculiar quantum state of matter that allows light to be slowed or even stopped entirely. This discovery, which builds on decades of research, has implications for **quantum physics, computing, and information storage**.*

The Quantum Jelly Effect

*In everyday conditions, light moves at **299,792,458 meters per second** in a vacuum, and its speed decreases slightly when passing through materials*

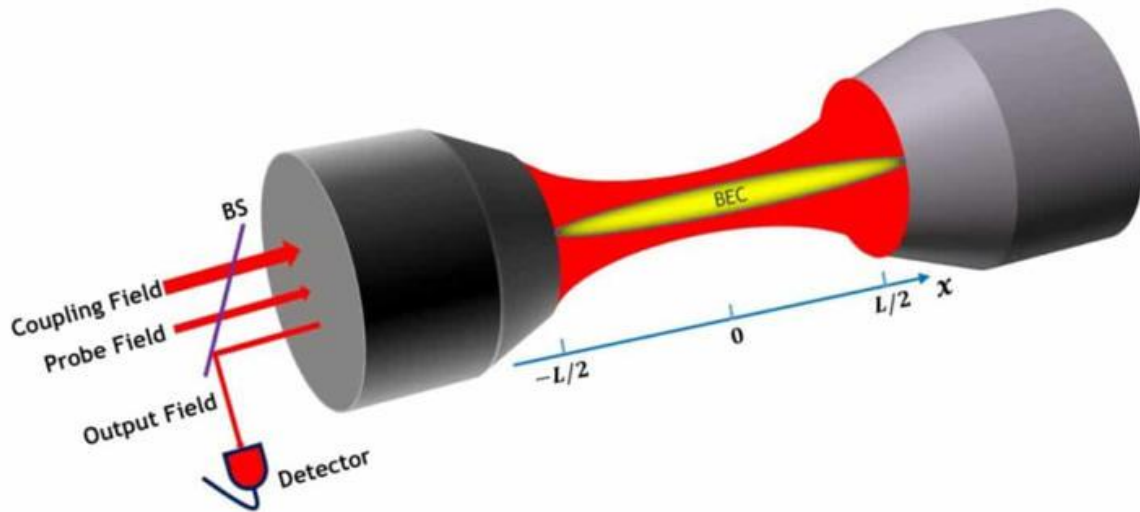
like **glass** or **water**. However, these reductions are relatively small. In contrast, when light travels through a **Bose-Einstein condensate**, it can be slowed to a near standstill.

A **Bose-Einstein condensate** is an exotic state of matter, first predicted by **Albert Einstein** and **Satyendra Nath Bose**, that occurs when a gas is cooled to [temperatures just above absolute zero](#). Under these conditions, the atoms behave as a **single quantum entity**, exhibiting **superfluidity** and interacting with light in ways not seen in ordinary materials.

A Breakthrough in Light Manipulation

Decades of research have led to a major breakthrough in controlling light. The ability to slow and manipulate it using BECs was first demonstrated in the late 1990s by **Lene Hau and her team at Harvard University** ([Harvard SEAS](#)). In their groundbreaking experiment, they cooled **sodium atoms** to an ultra-low temperature and directed **laser pulses** into the condensate. As the **photons** interacted with the ultracold atoms, the speed of light dropped dramatically to just **17 meters per second**—comparable to a person jogging.

Subsequent developments have shown that not only can light be slowed, but it can also be **completely halted** and stored within the condensate. An experiment published in *Nature* ([Nature](#)) demonstrated how researchers could stop light entirely for a brief period and then release it without losing information. This remarkable ability to trap and later retrieve light raises the possibility of **storing optical information in atomic systems**, a potential game-changer for quantum computing.



A Fabry-Perot cavity containing a BEC is simultaneously driven from the left mirror and along the cavity axis by a coupling field at rate ε_c and a weak probe field at rate ε_p . An ultraslow light can be detected on the left hand side of the cavity.

Physicists "Slow Down Light" to Just 61 Kilometers per Hour Using Ultracold Quantum Matter© Daily Galaxy UK

The Mechanics Behind Slow Light

The reason BECs can slow light lies in a phenomenon known as **electromagnetically induced transparency (EIT)**. This process manipulates how atoms in the condensate interact with light, creating a medium that dramatically alters the speed of photons passing through it. When a control laser is used, it effectively opens a **transparent window** in the normally opaque condensate, allowing the light pulse to travel through it at an extremely slow speed.

Experimental observations confirm the significance of this effect. Researchers have demonstrated that **slow light pulses can be compressed**, reducing their spatial size within the condensate while still maintaining their original information content ([Optica](#)). This compression could play a crucial role in future applications involving data storage and information processing.

From Quantum Memory to Computing

This discovery paves the way for groundbreaking applications.

• **Quantum computing** – The ability to **store and retrieve light-based information** could be used in **quantum memory**, allowing for the development of

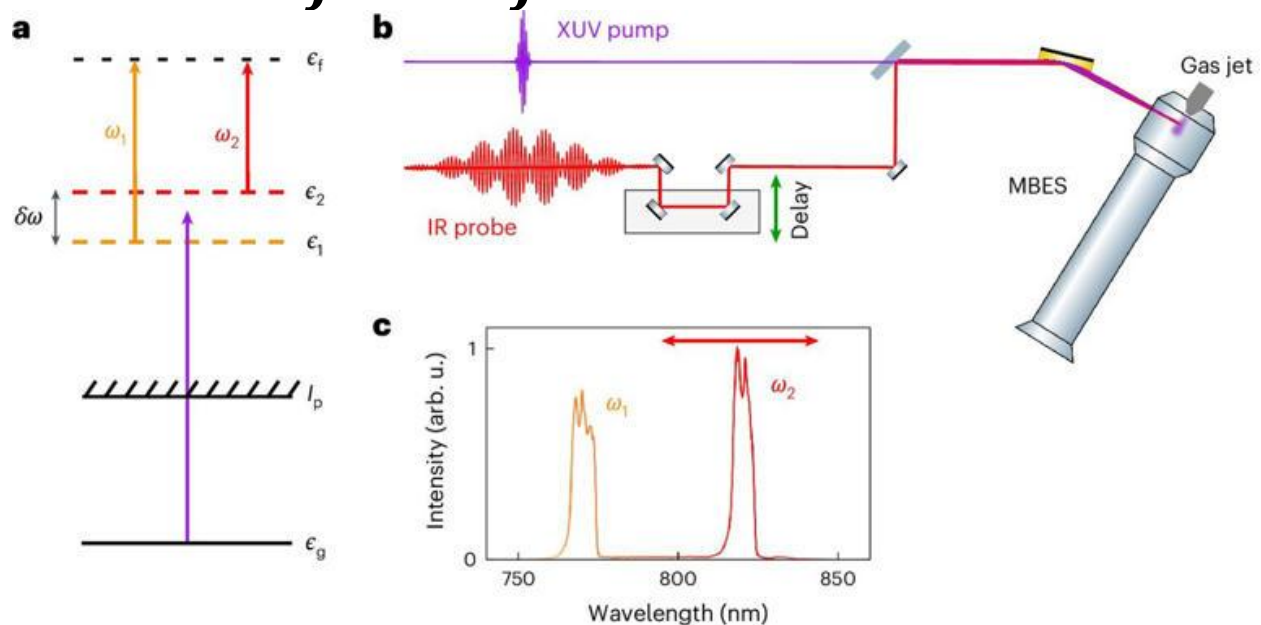
advanced **photon-based processors**. This could enable powerful quantum computers that operate on principles vastly different from today's electronics.

- **Optical data storage** – Since light can be trapped and later released, **BECs could function as optical memory units**, leading to the next generation of ultra-fast, energy-efficient data storage systems.

- **Precision sensors** – The sensitivity of light to changes in the environment when slowed could make BEC-based devices excellent **quantum sensors**, capable of detecting even the smallest changes in external conditions.

These advancements challenge the traditional understanding of **the nature of light and quantum mechanics**. Research in this field continues, as scientists seek new ways to manipulate **photonic information** and develop technologies that were once thought impossible.

Q&A: Quantum state of photoelectrons measured for the first time



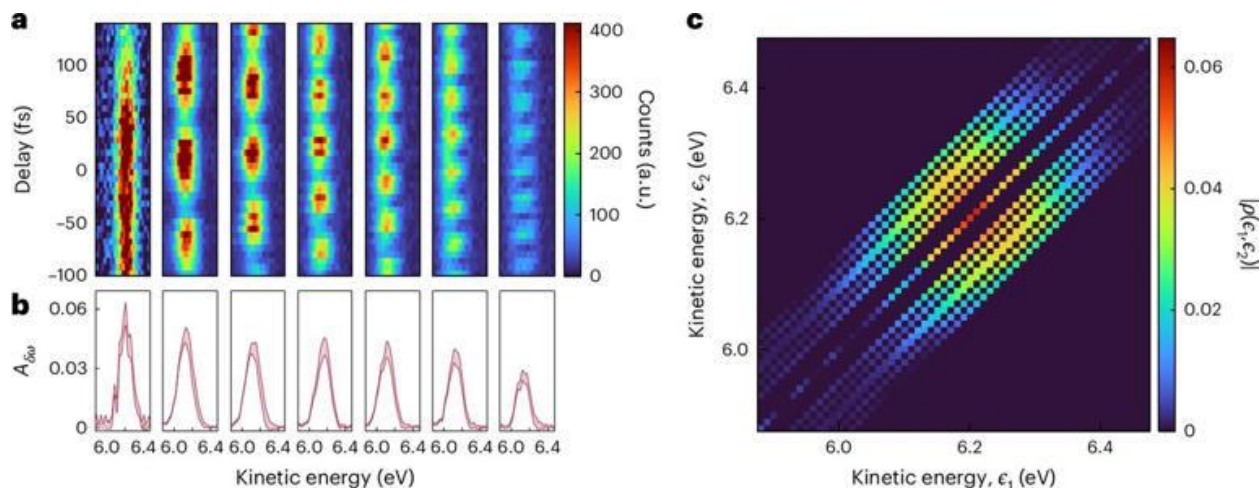
Principle of the KRAKEN technique. Credit: Nature Photonics (2025). DOI: 10.1038/s41566-024-01607-8

For the first time, researchers have been able to measure the quantum state of electrons ejected from atoms that have absorbed high-energy light pulses. This is thanks to a new measurement technique developed by researchers at Lund

University in Sweden. The results can provide a better understanding of the interaction between light and matter.

When high-energy light with a very short frequency in the extreme ultraviolet or X-ray range interacts with atoms or molecules, it can cause an electron to be "detached" from the atom and ejected in a process called the photoelectric effect. By measuring the emitted electron and its kinetic energy, a lot of information can be obtained about the atom being irradiated. This is the basic principle of photoelectron spectroscopy.

The electron that is emitted, known as the photoelectron, is often treated as a classical particle. In reality, the photoelectron is a quantum object that must be described quantum mechanically, as it is so small that at that scale the world is described in terms of quantum mechanics. This means that special rules applied in quantum mechanics have to be used to describe the photoelectron, because it is not just an ordinary small particle but also behaves like a wave.



Experimental results obtained with the KRAKEN protocol in the case of photoionization of helium atoms. Credit: Nature Photonics (2025). DOI: 10.1038/s41566-024-01607-8

"By measuring the quantum state of the photoelectron, our technique can precisely address the question of 'how quantum is the electron.' It is the same idea used in CT scans used in medicine to image the brain: We reconstruct a complex 3D object by taking several 2D pictures of that object from many different angles," says David Busto, associate senior lecturer in atomic physics and one of the authors of the study now [published](#) in Nature Photonics.

This is done by producing the photoelectron quantum state, which is the equivalent of the 3D object to be measured, by ionizing atoms with ultrashort, high-energy light pulses, and then using a pair of laser pulses with different colors to take the 2D pictures and reconstructing the quantum state slice by slice.

"The technique allows us to measure for the first time the quantum state of electrons emitted from helium and argon atoms, demonstrating that the photoelectron quantum state depends on the type of material from which it is emitted," says Busto.

In this interview, Busto discusses the findings.

Why are these results so interesting?

The photoelectric effect was explained over a century ago by Einstein, laying the foundations for the development of quantum mechanics. This same phenomenon was then exploited by Kai Siegbahn to study how electrons are arranged inside atoms, molecules and solids.

Paradoxically, this technique relies solely on measuring the classical properties of the photoelectron, such as its speed. Now, more than 40 years after Kai Siegbahn was awarded the Nobel Prize for photoelectron spectroscopy in 1981, there is finally a method that allows full characterization of the quantum properties of the emitted photoelectrons, expanding the potential of photoelectron spectroscopy. In particular, the new measurement technique provides access to quantum information that would otherwise not be available.

How can these results be useful?

We applied our technique to simple atoms, helium and argon, which are relatively well known. In the future, it could be used to study molecular gases, liquids and solids, where the quantum properties of the photoelectrons can provide a lot of information about how the ionized target reacts after the sudden loss of an electron. Understanding this process at the fundamental level could have a long-term impact on various fields of research. Examples include atmospheric

photochemistry or the study of light-harvesting systems, which are systems that collect and utilize light energy, such as solar cells or photosynthesis in plants.

Another interesting aspect of this work is that it bridges two different areas of science: attosecond science and spectroscopy (the kind of research that Nobel Prize laureate Anne L'Huillier is conducting) on the one hand, and quantum information and quantum technology on the other hand.

How might this study be important to the public?

This work is connected to the ongoing second quantum revolution, which aims to manipulate individual quantum objects (in this case photoelectrons) to harness the full potential of their quantum properties for various applications. Our quantum state tomography technique will not lead to the construction of new quantum computers, but by providing access to knowledge about the quantum state of the photoelectrons, it will allow physicists to fully exploit their quantum properties for future applications.

What can the discovery be used for?

By measuring the speed and emission direction of the photoelectron, we can learn a lot about the structure of the material. This is essential, for example, to study the properties of new materials. Our technique allows us to go beyond previous methods by measuring the complete quantum state of the photoelectron. This means that we can gather more information about the target than is possible with traditional photoelectron spectroscopy. It is hoped that our technique can help unravel the processes that occur in the material after the electron has been ejected.

Was there anything in the results that surprised you?

The most surprising aspect is that our technique worked so well. Physicists had already tried to measure the quantum state of photoelectrons using a different method, and those experiments showed that it is very difficult. Everything has to be very stable over a long period of time, but we finally managed to achieve these very stable conditions.

When do you choose to describe/study things quantum mechanically and not according to classical physics?

At the microscopic scale, electrons, atoms and molecules are described quantum mechanically, while on a macroscopic scale, the objects we experience in everyday life follow the laws of classical physics. Atoms and other microsystems do not behave like everyday objects.

With a deliberate exaggeration, it could be said that they do not exist in the usual sense, with a well-defined point and with well-defined speed. The only thing that is known is the output of the laboratories' instruments. Since all macroscopic objects are made up of atoms and molecules that obey the laws of quantum mechanics, we might ask why we do not see quantum effects at the macroscopic scale.

In short, the reason is that when we put many quantum objects close to each other, they start to affect each other in an uncontrolled way, effectively canceling out their individual quantum properties. This process is referred to as decoherence and is one of the key challenges that must be overcome to develop quantum technologies, such as quantum computers.

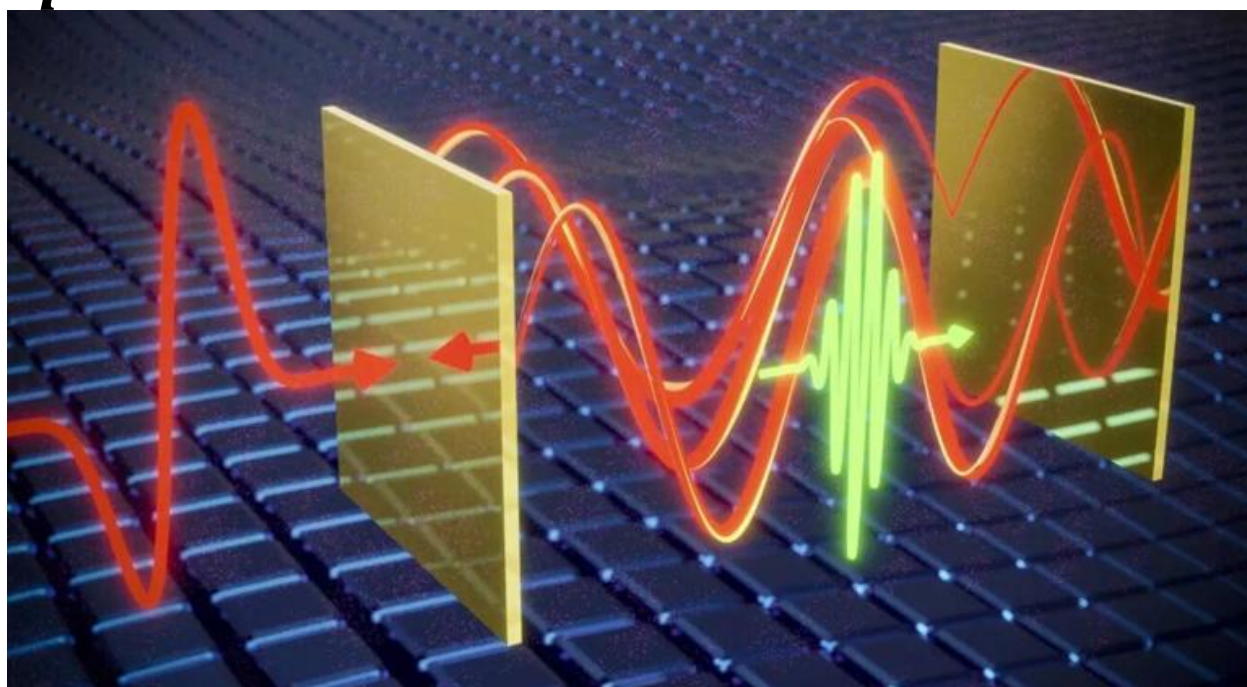
The electrons emitted during the photoelectric effect contain a lot of information about the irradiated material. By measuring the quantum state of the photoelectron, our technique can precisely address the question of "how quantum is the electron." In the future, we hope that our technique will allow us to follow how the quantum properties of electrons evolve over time from quantum to classical.

The new experimental measurement technique is called KRAKEN.

More information: Hugo Laurell et al, Measuring the quantum state of photoelectrons, *Nature Photonics* (2025). DOI: [10.1038/s41566-024-01607-8](https://doi.org/10.1038/s41566-024-01607-8)

Provided by Lund University

Measuring invisible light waves via electro-optic cavities



Experimental principle of electro-optic cavities (EOCs) measuring the multiple echoes of the THz light field (red) with a visible probe pulse (green) during a nonlinear interaction inside a Fabry-Pérot cavity (gold mirrors). Credit: Max Planck Society

Researchers have developed a novel experimental platform to measure the electric fields of light trapped between two mirrors with a sub-cycle precision.

*These electro-optic Fabry-Pérot resonators will allow for precise control and observation of light-matter interactions, particularly in the terahertz (THz) spectral range. The study is [published](#) in the journal *Light: Science & Applications*.*

The researchers are from the Department of Physical Chemistry at the Fritz Haber Institute of the Max Planck Society and the Institute of Radiation Physics at Helmholtz Center Dresden-Rossendorf.

By developing a tunable hybrid-cavity design, and measuring and modeling its complex sets of allowed modes, the physicists can switch between nodes and maxima of the light waves exactly at the location of interest. The study opens new avenues for exploring quantum electrodynamics and ultrafast control of material properties.

In a significant advancement in the field of cavity electrodynamics, the team has introduced a novel method to measure electric fields inside cavities. By utilizing electro-optic Fabry-Pérot resonators, they have achieved sub-cycle timescale measurements, allowing for insight into light and matter, exactly where their interaction takes place.

Cavity electrodynamics explores how materials placed between mirrors interact with light, altering both their properties and dynamic behavior. This study focuses on the terahertz (THz) spectral range, where low-energy excitations dictate the fundamental material properties. The ability to measure novel states, which simultaneously behave like light and matter excitations, within the cavity will provide a clearer understanding of these interactions.

The researchers have also developed a hybrid cavity design, incorporating a tunable air gap with a split detector crystal within the cavity. This new design allows for precise control over internal reflections, leading to selective interference patterns on-demand. These observations are supported by mathematical models, providing a key to decode the complicated cavity dispersion and a deeper understanding of the underlying physics.

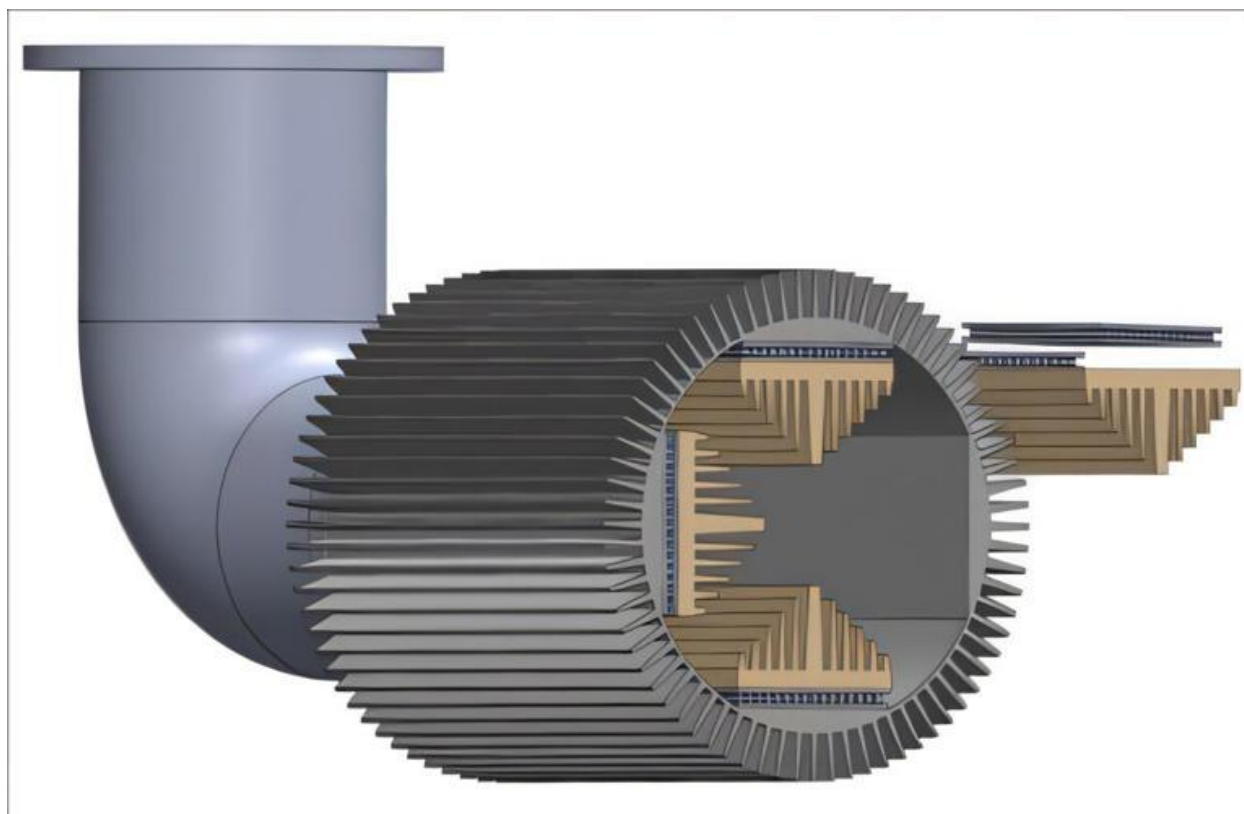
This research lays the groundwork for future studies in cavity light-matter interactions, offering potential applications for quantum computing, material science, and beyond. Michael S. Spencer, first author of the study noted, "Our work opens new possibilities for exploring and steering the fundamental interactions between light and matter, providing a unique toolset for future scientific discoveries."

Prof. Dr. Sebastian Maehrlein, the leader of the research group, summarizes, "Our EOCs provide a highly-accurate field-resolved view, inspiring novel pathways for cavity quantum electrodynamics in experiment and theory."

More information: Michael S. Spencer et al, *Electro-optic cavities for in-situ measurement of cavity fields*, *Light: Science & Applications* (2025). DOI: [10.1038/s41377-024-01685-x](https://doi.org/10.1038/s41377-024-01685-x)

Provided by Max Planck Society

Prototype turns car and helicopter exhaust into thermoelectric energy



Researchers design and test a waste-heat recovery system, illustrated here, that attaches to a car tailpipe and converts heat from exhaust into energy. The fanned grooves on the outside of the pipe are the cold side of the device's heatsink and the triangular components inside the pipe are plate-fin heat exchangers. Credit: ACS Applied Materials & Interfaces (2025). DOI: 10.1021/acsami.4c18023

Combustion engines, the engines in gas-powered cars, only use a quarter of the fuel's potential energy while the rest is lost as heat through exhaust.

Now, a study [published](#) in ACS Applied Materials & Interfaces demonstrates how to convert exhaust heat into electricity. The researchers present a prototype thermoelectric generator system that could reduce fuel consumption and carbon dioxide emissions—an opportunity for improving sustainable energy initiatives in a rapidly changing world.

Fuel inefficiency contributes to greenhouse gas emissions and underscores the need for innovative waste-heat recovery systems. Heat-recovery systems, called thermoelectric systems, use semiconductor materials to convert heat into electricity based on a temperature difference.

However, many existing thermoelectric device designs are heavy and complex, requiring additional cooling water that's used to maintain the necessary temperature difference. Now, a team of researchers led by Wenjie Li and Bed Poudel has developed a compact thermoelectric generator system to efficiently convert exhaust waste heat from high-speed vehicles like cars, helicopters and unmanned aerial vehicles into energy.

The researchers' new thermoelectric generator contains a semiconductor made of bismuth-telluride and uses heat exchangers (similar to those used in air conditioners) to capture heat from vehicle exhaust pipelines. The team also incorporated a piece of hardware that regulates temperature, called a heatsink.

The heatsink significantly increases the temperature difference, which directly influences the system's electrical output. The prototype achieved an output power of 40 watts, about enough to power a lightbulb. Importantly, the results indicate that high airflow conditions, like those found in exhaust pipes, enhance efficiency, thereby increasing the system's electrical output.

In simulations mimicking high-speed environments, the waste-heat system demonstrated great versatility; their system produced up to 56 W for car-like exhaust speeds and 146 W for helicopter-like exhaust speeds, or the equivalent of five and 12 lithium-ion 18650 batteries, respectively. The researchers say their practical system can be integrated directly into existing exhaust outlets without the need for additional cooling systems.

As the demand for clean energy solutions escalates, they add that this work could pave the way toward practical integration of thermoelectric devices into high-speed vehicles.

More information: Rabeya Bosry Smriti et al, Thermoelectric Energy Harvesting for Exhaust Waste Heat Recovery: A System Design, *ACS Applied Materials & Interfaces* (2025). DOI: [10.1021/acsami.4c18023](https://doi.org/10.1021/acsami.4c18023)

Provided by American Chemical Society

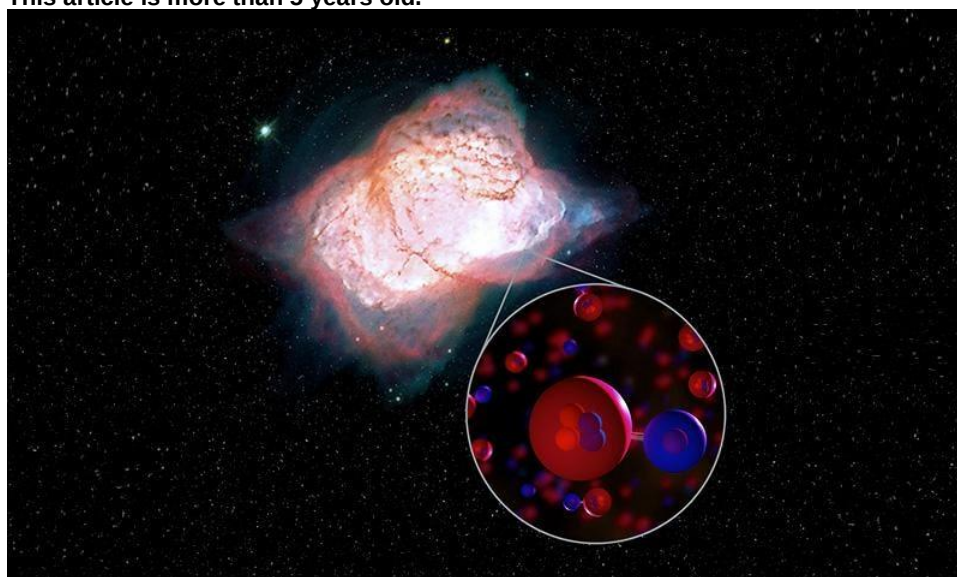
INNOVATIONSCIENCE

Scientists Didn't Really Find The First Molecule In The Universe

Apr 19, 2019,02:00am EDT

Updated Apr 19, 2019,

This article is more than 5 years old.

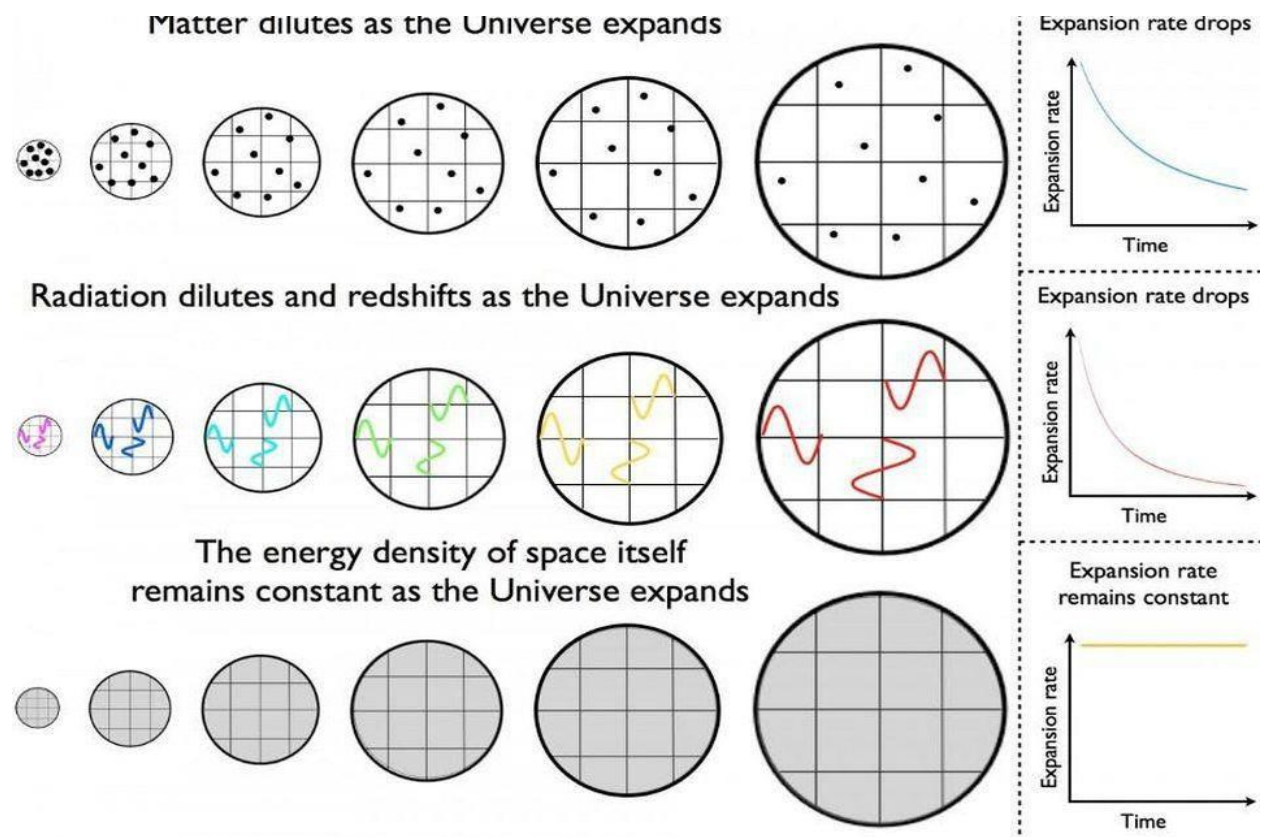


The helium hydride molecule, long known to exist in the lab and long thought to be present in space... [+]

The Universe's first molecule is found at last! That's what [the headlines have been proclaiming](#) this week, as [NASA's Stratospheric Observatory for Infrared Astronomy \(SOFIA\)](#) has observed a hitherto elusive substance known as

helium hydride. Part of it is absolutely true, as helium hydride really was the first molecule formed in the very, very early Universe, and this is the first time its presence has been detected in space, rather than synthesized in laboratories here on Earth.

But part of it's not true. The helium hydride we've found doesn't come from those early times. In fact, 100% of the helium hydride that was part of the first molecules ever made in the Universe was permanently destroyed long ago. We've never seen it, and most likely, we never will. Here's why.



How matter (top), radiation (middle), and a cosmological constant (bottom) all evolve with time in... [+]

PROMOTED

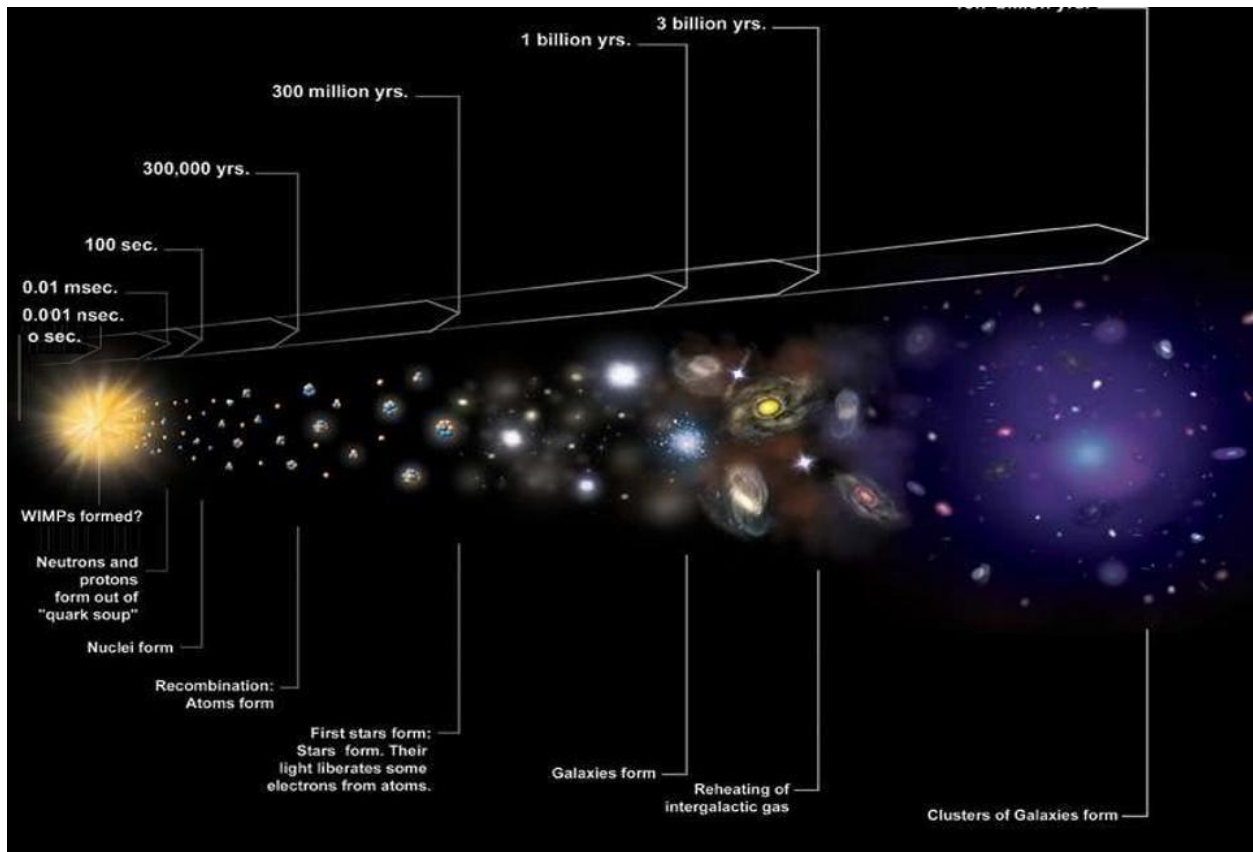
Try to imagine, if you can, the Universe as it was in the much earlier stages of the hot Big Bang. When we look at the Universe today, we see that it's full of matter all clumped together in stars, galaxies, clusters, and along an enormous

cosmic web. We see the evidence that this Universe is expanding, with distant galaxies and clusters expanding away from one another at faster rates the farther away they are. In addition, we also see the Universe filled with a bath of low-energy radiation in all directions.

This means, as time goes on, the Universe gets:

- larger, sparser, clumpier, and colder.

Which implies, of course, that if we look backwards in time, the opposite was true.

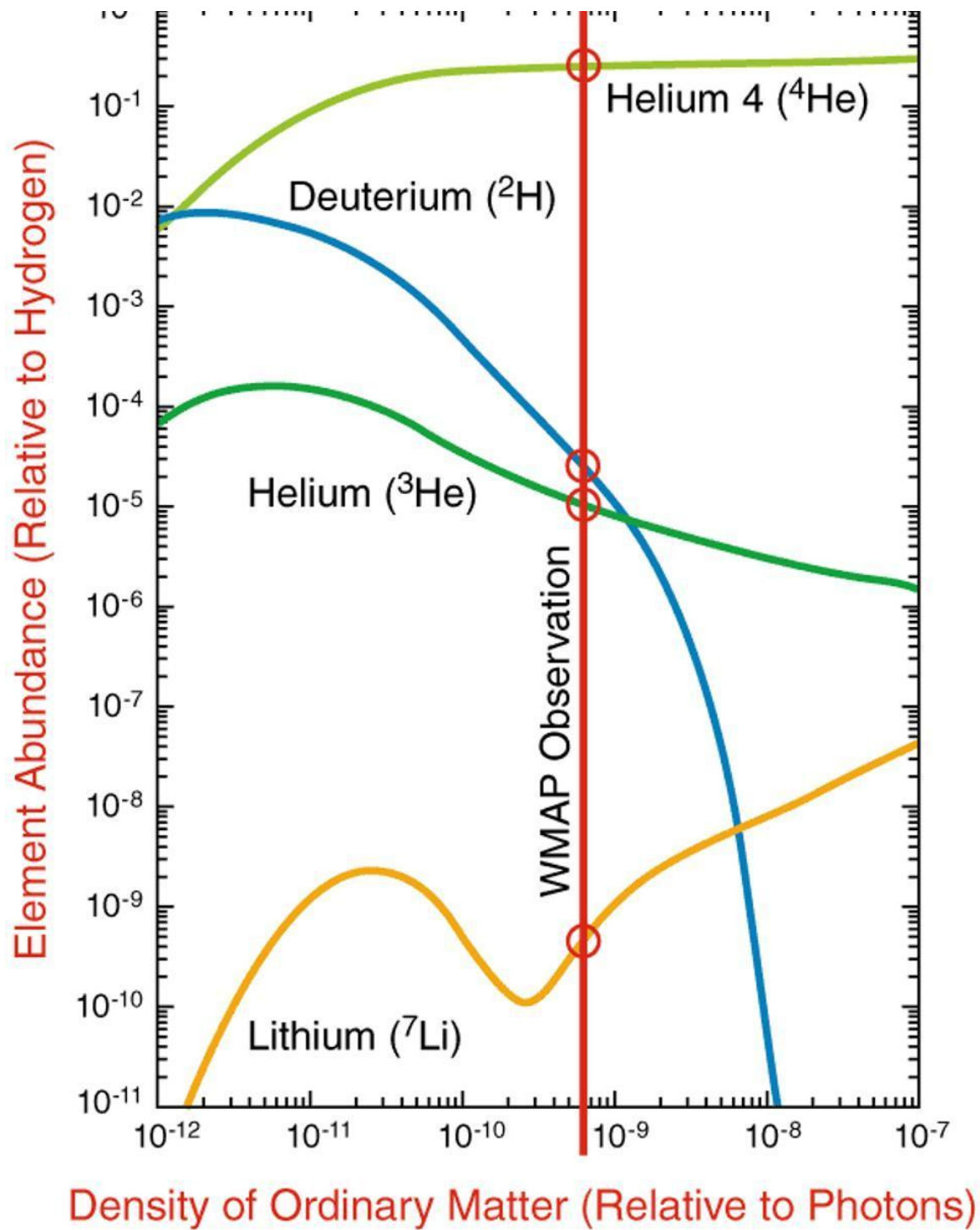


A visual history of the expanding Universe includes the hot, dense state known as the Big Bang and... [+]

We see our Universe as it is today, some 13.8 billion years after the Big Bang. As we look farther and farther away, we're seeing the Universe as it was when

it was younger; we're basically looking back in time. The earliest galaxies were smaller, bluer, and contained fewer heavy elements than ours do, as it's only via the build-up of many generations of stars living and dying that we arrive at galaxies like our modern Milky Way.

In fact, we can go back to even earlier times: before we had formed any stars or galaxies. For the first few tens of millions of years after the Big Bang, gravitation hasn't yet had enough time to work to pull the first neutral atoms together into clumps, meaning we hadn't yet ignited nuclear fusion in them. The only fusion took place during the earliest, hottest, densest stage of the Big Bang, and gave us hydrogen, helium, and not much else.



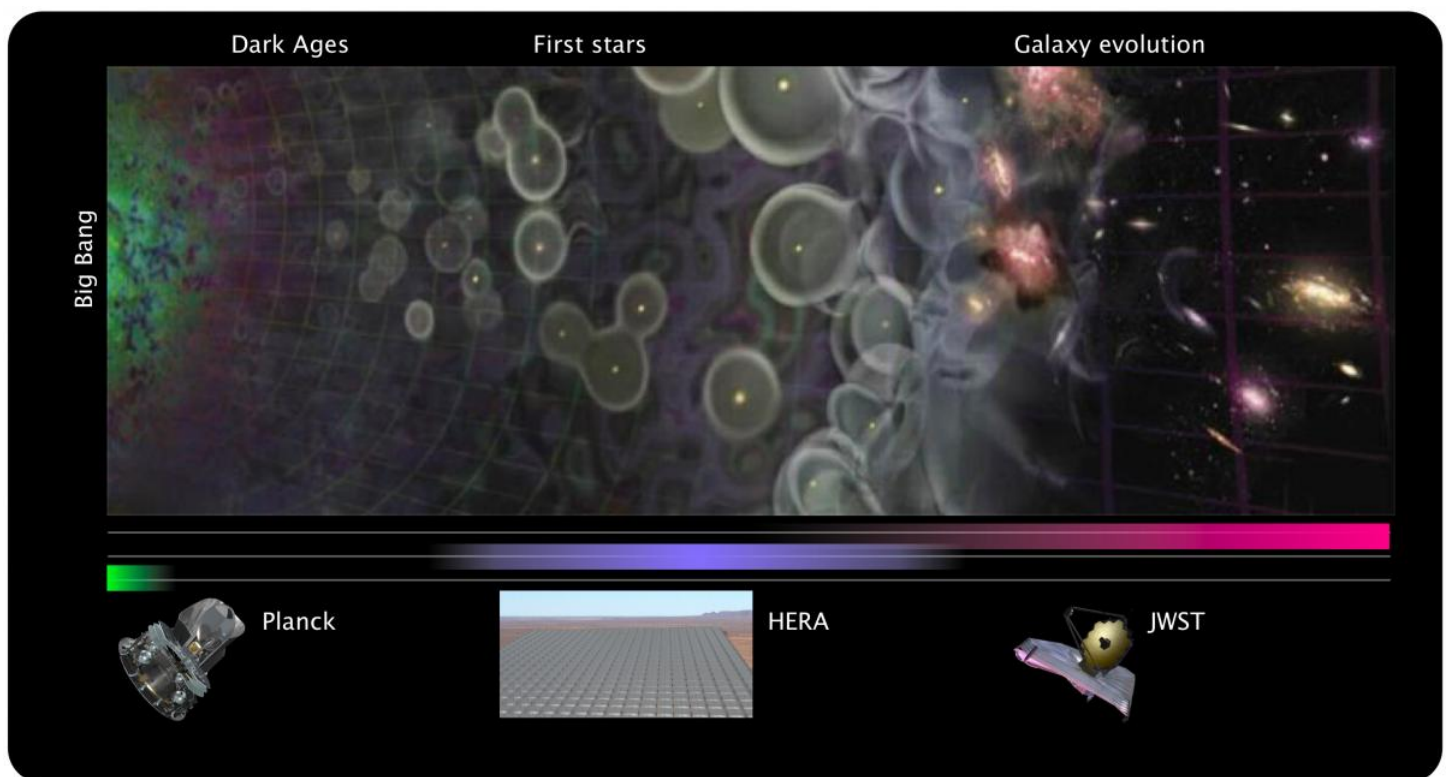
NASA/WMAP Science Team
WMAP101087

Element Abundance graphs: Steigman, Encyclopedia of Astronomy
and Astrophysics (Institute of Physics) December, 2000

The predicted abundances of helium-4, deuterium, helium-3 and lithium-7 as predicted by Big Bang... [+]

In fact, after that nuclear fusion took place during the first few minutes of our cosmic history, the Universe needed hundreds of thousands of years to cool by sufficient amounts so that we could stably form neutral atoms. Before that, the photons within it were energetic enough that they continuously knocked every single electron off of whichever atomic nucleus it happened to encounter and bind to.

When the Universe was just a few minutes old, the elements within it were (by weight) about 75% hydrogen, 25% helium, and a tiny fraction of deuterium, helium-3, and lithium. As it cooled over the millennia to come, all of the photons — including the most energetic ones that were primarily responsible for ionization — lost energy. As a result, these atomic nuclei, with different



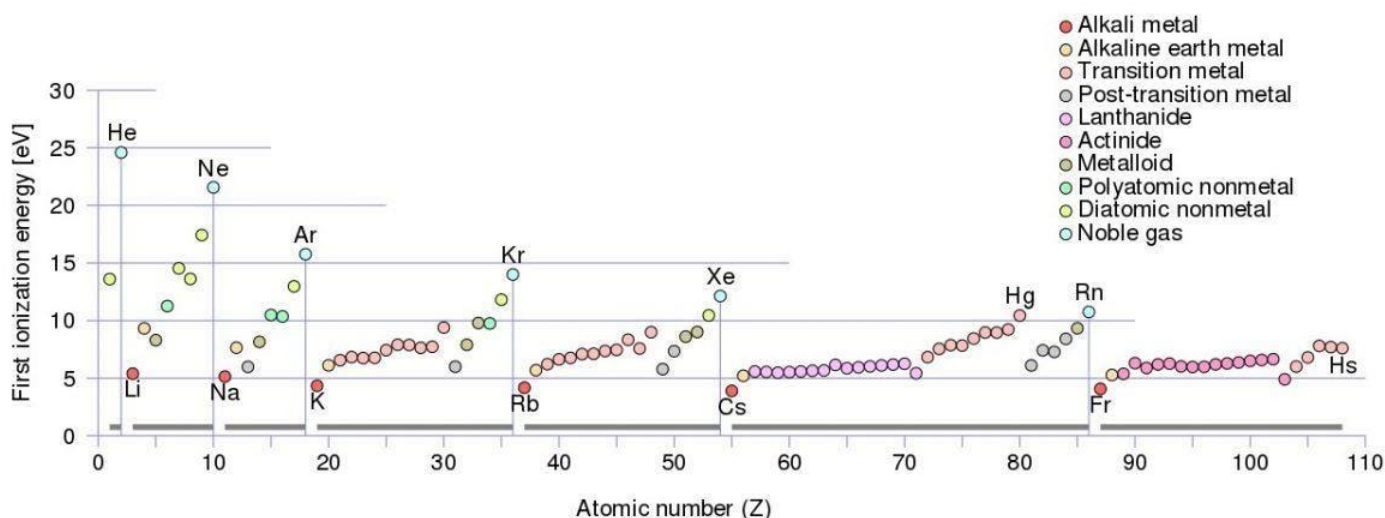
masses and different charges, begin gaining electrons at different times.

Although atomic nuclei were formed after only a few minutes in the Universe, things were very hot... [+]

At the earliest times, everything is completely ionized, with helium and hydrogen nuclei both having no electrons at all.

After approximately 32,000 years, the Universe cools enough so that one electron can start binding to a helium nucleus. Remember, it takes two electrons to form a neutral helium atom, so helium is just halfway there at this point.

After another 100,000 years, when the Universe reaches an age of 132,000 years, that second electron can finally bind to helium without getting kicked off. We've got our first stable, neutral atom: helium. But helium doesn't form

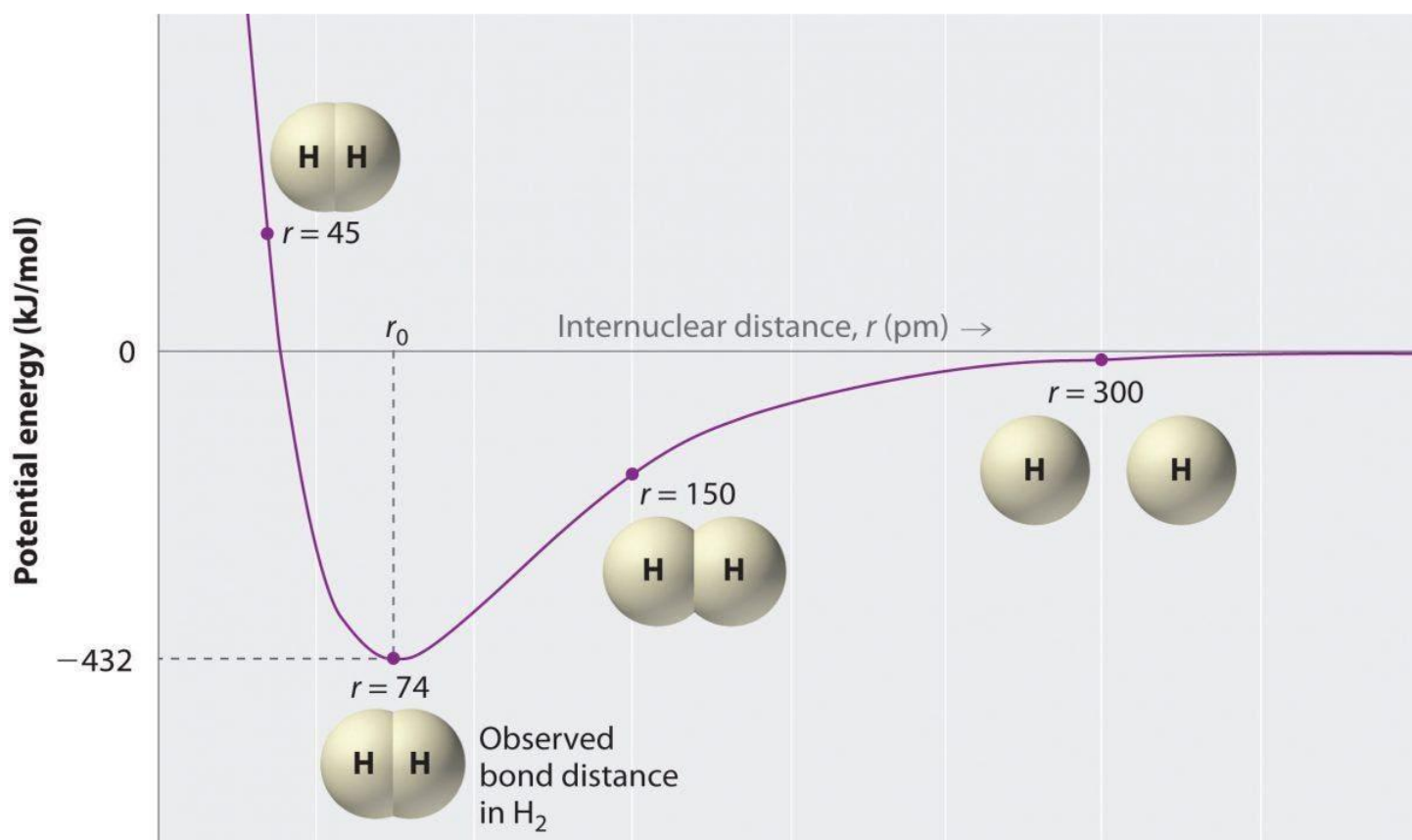


bonds very easily with other atoms: it's an inert, noble gas.

Elements in the first group of the periodic table, particularly lithium, sodium, potassium,... [+]

It isn't until the Universe is around 380,000 years old that individual protons and electrons bind together to form hydrogen atoms. Hydrogen atoms can easily bond with other hydrogen atoms, producing the molecular hydrogen (H_2) we're all familiar with.

But there was an in-between time — after helium atoms form but while hydrogen is still ionized — where the first true molecules form. A molecule, remember, is simply defined wherever you have a molecular bond between one atom (or ion) and another. You might be used to molecules forming from neutral atoms binding together exclusively (like O_2 , oxygen), but atom-ion pairs also form molecular bonds, such as ionized carbon (C^+) with neutral fluorine atoms (F), which bind together (forming CF^+) and [emit a photon](#)



[through a process known as radiative association.](#)

When two atoms, or an ion and an atom, are well-separated, they are unbound. It's often... [+]

Well, when the Universe is in that in-between time, where neutral helium (He) exists but all of the hydrogen is ionized (H^+), those two species can also bind together through [radiative association](#). When a helium atom and a hydrogen

ion collide, they form a molecule known as helium hydride (HeH^+), and a characteristic photon is emitted which signifies the strength of the molecular bond.

Although it doesn't appear as much in the news as physics or astronomy, the chemistry of compounds like helium hydride has a long and rich history. Helium hydride itself was discovered via its creation in the laboratory nearly a century ago: [back in 1925](#). In theory, it should also exist in the environment of interstellar space: both in the early Universe, when it became the first molecule, but also later, when astrophysical processes create ionize hydrogen plasmas in the presence of neutral helium.

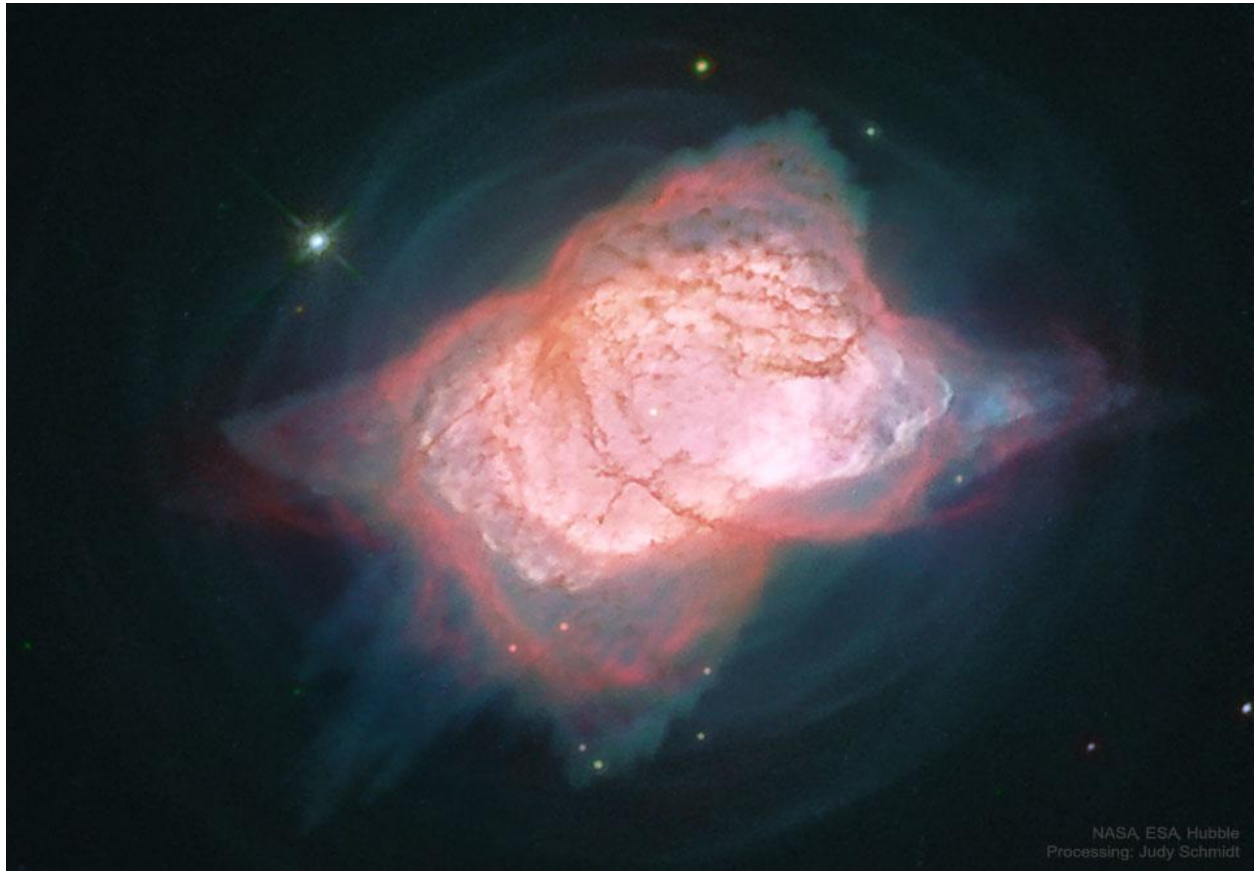


Near the end of a Sun-like star's life, it begins to blow off its outer layers into the depths of... [+]

All of the early Universe's helium hydride should have been destroyed when hydrogen became neutral, as helium hydride is far less energetically favorable than the formation of neutral hydrogen. Once you cool below a certain critical threshold, your helium hydride will interact with neutral hydrogen,

preferentially forming hydrogen molecules (H_2) and isolated helium atoms (He). The Universe's first molecule didn't last long; by the time perhaps 500,000 years passed, it was all gone.

But later on, even in the modern Universe, there's a perfect candidate location where helium hydride should exist in our Universe today: in the ionized plasmas of dying Sun-like stars. With temperatures high enough to ionize hydrogen, but plenty of neutral helium expelled from the dying stars outer layers, these planetary nebulae should be ideal homes for helium hydride.

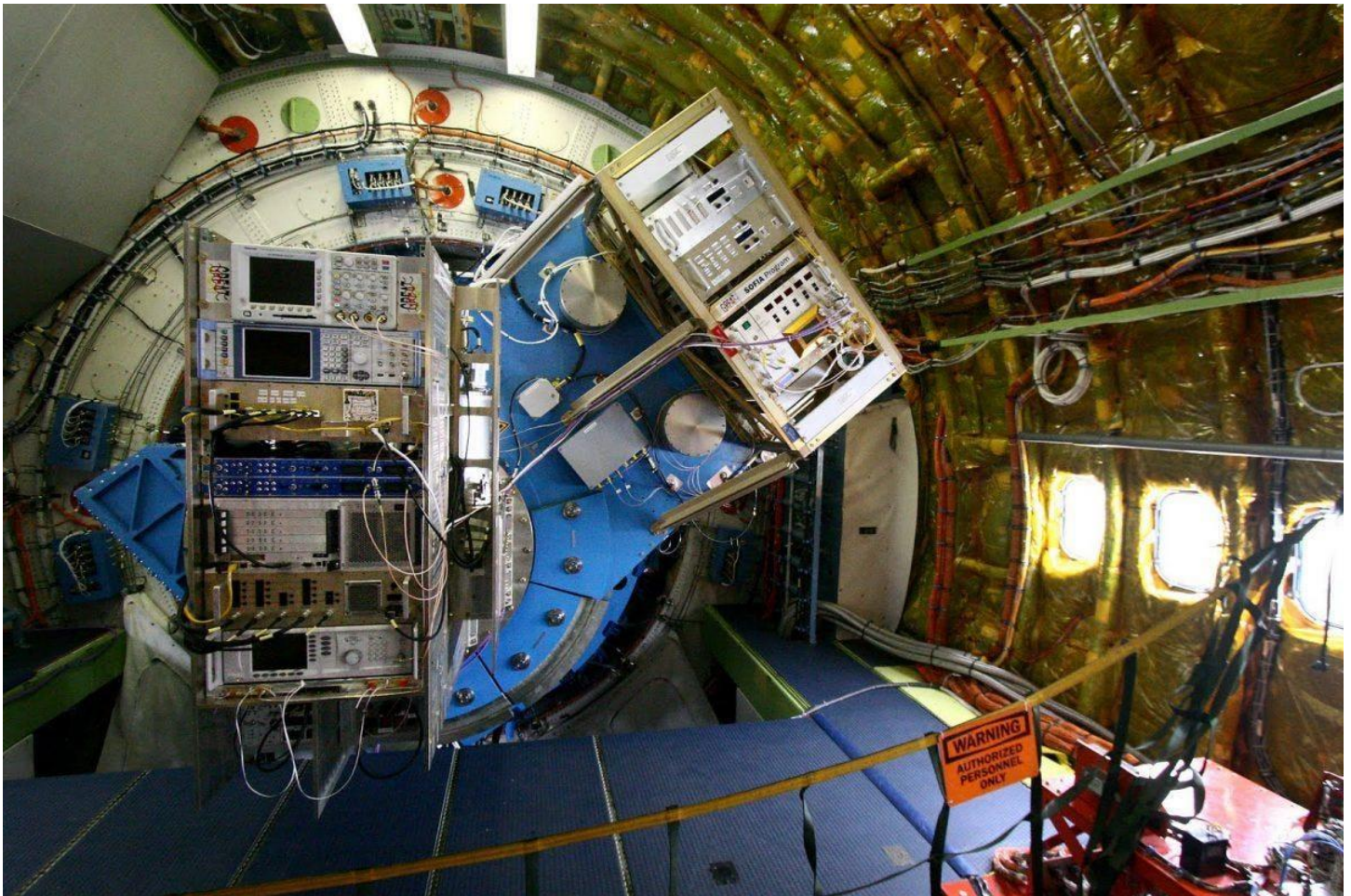


The planetary nebula NGC 7027 was long thought to have the right conditions for helium hydride to... [+]

Although it's been more than 40 years since planetary nebulae were suggested as homes for helium hydride, observations had never caught up with it. Part of

the reason is that helium hydride's signature emissions come from a rotational transition that emits at very low energies: producing photons at 149.1 microns, placing it in the far-infrared portion of the spectrum.

You cannot see this from the ground, as the atmosphere obscures it. You can try to see it from space, but the instruments launched aboard observatories like Herschel and Spitzer were insufficient to uncover it. But that's where NASA's SOFIA comes in. It flies up to 45,000 feet, above the obscuring atmosphere. But, because it returns to Earth, its instruments can be easily upgraded. And upgrading the German Receiver at Terahertz Frequencies



(GREAT) instrument was just what astronomers needed.

NASA's SOFIA telescope, which flies on board a modified Boeing 747, is uniquely suited to making... [+]

This new study determined, for the first time, that helium hydride ions [really do exist in space](#). By observing the planetary nebula NGC 7027 with this newly upgraded instruments, scientists were able to see this characteristic transition that's an unmistakable signature of helium hydride. According to Rolf Güsten, lead author of [the new study published in Nature](#),

"It was so exciting to be there, seeing helium hydride for the first time in the data. This brings a long search to a happy ending and eliminates doubts about our understanding of the underlying chemistry of the early universe."

This is the first proof we have that helium hydride can, and does, exist in the natural environment of space.



NASA's Stratospheric Observatory for Infrared Astronomy (SOFIA) with open telescope doors. This... [+]

The largest lesson to learn from all of this is that there's an incredible value to straddling the border between ground-based and space-based astronomy. Going to space is great because you no longer need to contend with the interfering effects of Earth's atmosphere. Staying on the ground is great because you don't have to pay for launch costs, your telescope size isn't limited by the size of the launch vehicle, and your instruments are upgradable.

But a unique instrument like SOFIA gives us the best of both worlds. As Hal Yorke, director of the SOFIA Science Center, said,

"This molecule was lurking out there, but we needed the right instruments making observations in the right position — and SOFIA was able to do that perfectly."

Helium hydride was long thought to be the first molecule in the Universe, but we'd never been able to detect its natural presence in space before. At long last, we have proof of its existence, and with it, further confirmation of our picture of how the Universe came to be the way it is today.

Universe's First Molecule Detected in Space for the First Time Ever



published April 17, 2019

Astronomers just found evidence of helium hydride — the first molecule to ever form in the universe — swirling around a distant planetary nebula like this one. This ultraviolet image is of the planetary nebula NGC 7293, also known as the Helix Nebula. (Image credit: NASA/JPL-Caltech/SSC)

A few hundred thousand years after the [Big Bang](#), the hot, young soup of our universe cooled enough for the smallest building blocks of life to combine into atoms for the first time. One balmy, 6,700-degree-Fahrenheit day (3,700 degrees Celsius), a [helium atom](#) glommed onto a single proton — actually a positively charged hydrogen ion — and the universe's very first molecule was formed: helium hydride, or HeH⁺.

Scientists have studied lab-made versions of this primordial molecule for nearly a century, but they have never found traces of it in our modern universe — until now. In a new study published today (April 17) in the [journal Nature](#), astronomers report on their use of an airborne telescope to detect HeH⁺ smoldering in the cloud of gas around a dying star some 3,000 light-years away.

According to the researchers, this discovery, which has been more than 13 billion years in the making, shows conclusively that HeH⁺ is formed naturally in conditions similar to those found in the early universe.

"Although HeH⁺ is of limited importance on Earth today, the chemistry of the universe began with this ion," the team wrote in the new study. "The unambiguous detection reported here brings a decades-long search to a happy ending at last."

The first molecule in the universe

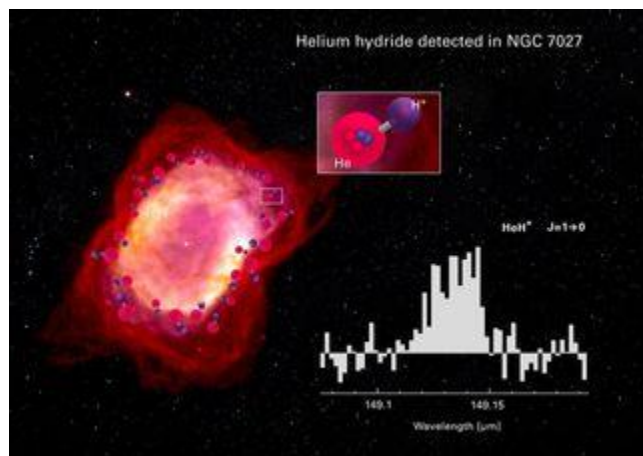
HeH⁺ is the strongest known acid on Earth and was first synthesized in a lab in 1925.

Because it is made from hydrogen and helium — the two [most abundant elements in the universe](#) and the first to emerge from the nuclear reactor of the Big Bang 13.8 billion years

ago — scientists have long predicted that the molecule was the very first one to form when the cooling universe allowed protons, neutrons and electrons to exist side by side [in atoms](#). Scientists can't [rewind the universe](#) to hunt for this fledgling molecule where it was born, but they can look for it in parts of the modern universe that best replicate those superhot, superdense conditions — in the young nebulae of gas and plasma that explode out of dying stars.

These so-called [planetary nebulae](#) form when sun-like stars reach the end of their lives, blast away their outer shells and shrivel into white dwarfs to slowly [cool into crystal balls](#). As those dying stars cool, they still radiate enough heat to strip nearby hydrogen atoms of their electrons, turning the atoms into the bare protons that are required for HeH⁺ to form. Detecting HeH⁺ in even the closest planetary nebulae to Earth is tricky, because it glows at an [infrared wavelength](#) that is easily obscured by our own planet's atmosphere. In the new study, researchers got around that atmospheric haze by using a high-tech telescope mounted on a moving aircraft called SOFIA (the Stratospheric Observatory for Infrared Astronomy).

Over the course of three flights in 2016, the team trained SOFIA's telescope on a planetary nebula called NGC 7027, about 3,000 light-years from Earth. The nebula's central star is one of the hottest known in the sky, the researchers wrote, and is estimated to have shed its outer envelope only about 600 years ago. Because the surrounding nebula is so hot, young and compact, it's an ideal spot for hunting HeH⁺ wavelengths. According to the researchers, that's exactly where SOFIA found them.



The researchers detected infrared lines emitted by HeH⁺ molecules in the planetary nebula NGC 7027, a hot, compact nebula about 3,000 light-years away from Earth. (Image credit: NIESYTO design, William B. Latter and Rolf Güsten and NASA/ESA)

"The discovery of HeH⁺ is a dramatic and beautiful demonstration of nature's tendency to form molecules," study co-author David Neufeld, a professor at Johns Hopkins University in Baltimore, [said in a statement](#). "Despite the unpromising ingredients that are available, a mixture of hydrogen with the [unreactive noble gas helium](#), and a harsh environment at thousands of degrees Celsius, a fragile molecule forms."

Researchers provide mathematical solutions to study 2D light interaction in photonic crystal lasers



Credit: Pixabay/CC0 Public Domain

Laser diodes are semiconductors that generate light and amplify it using repeated reflection or "optical feedback." Once the light has achieved desirable optical gain, laser diodes release it as powerful laser beams.

Photonic crystal surface-emitting lasers (PCSELs) are advanced laser diodes where the optical gain is typically distributed laterally to the propagating light within a photonic crystal (PC) structure. They differ from traditional lasers by separating gain, feedback, and emission functions, offering scalable single-mode power and innovative designs. This leads to enhanced performance and new application possibilities.

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In a paper that was [published](#) in the *IEEE Journal of Selected Topics in Quantum Electronics* on 20 November 2024, researchers have developed a method to numerically simulate the interaction of light waves within PCSELS.

The researchers examined how light waves interact within a triangular-lattice PCSEL, where the PC forms a triangular grid structure. They found that the two-dimensional light wave interaction or "coupling" within triangular-lattice PCSEL was stronger than that in square lattice PCSEL. This increased coupling offers greater optical feedback, which is beneficial for efficient lasing.

The researchers focused on six plane light waves propagating through the crystal and coupling through a process called Bragg diffraction. They then performed numerical simulations of 2D coupling of these plane wave in triangular-lattice PCSEL. Finally, they compared the 2D coupling with those seen in square lattice PCSEL.

The team derived analytical equations for both mode frequencies and coupling constants, which can be used alongside experimental band structure measurements to aid the design of transverse magnetic (TM) triangular lattice PCSELS.

"These equations improve in-plane 2D coupling for TM-mode triangular-lattice PCSELS, which is particularly beneficial for low-index contrast devices," notes Professor Stephen John Sweeney, a senior IEEE member and co-author of the study.

The researchers also derived the general form of the coupled wave equations for unit cells in the crystal lattice, which can further aid the experimental design of PCSELS with superior efficiency. Additionally, the team identified the "fundamental lasing mode" of triangular-lattice PCSEL, which is the pattern of the electromagnetic field that offers the most efficient laser output.

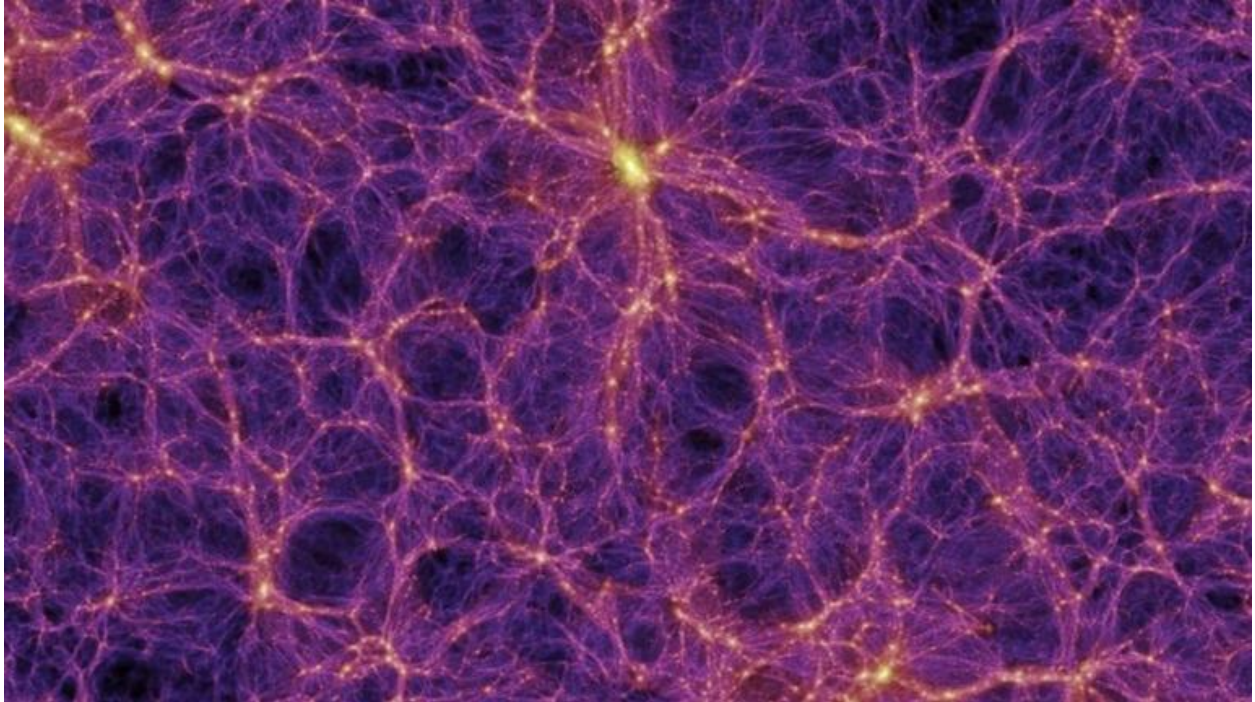
The findings establish parallels between TM and transverse electric (TE) polarization behaviors, while emphasizing the unique advantages TM modes offer in certain configurations, particularly in low index contrast devices.

The derived analytical models and coupling equations provide a foundation for experimental optimization of photonic crystal structures, enabling targeted enhancements in device efficiency and performance. They have the potential to significantly influence the next generation of PCSEL designs, offering enhanced scalability, single-mode operation, and broader applicability across industries.

More information: Matthew N Robinson et al, Two-Dimensional Coupled Wave Theory for Triangular Lattice TM-Polarised Photonic Crystal Surface Emitting Lasers, *IEEE Journal of Selected Topics in Quantum Electronics* (2024). DOI: [10.1109/JSTQE.2024.3502794](https://doi.org/10.1109/JSTQE.2024.3502794)

Provided by Institute of Electrical and Electronics Engineers

Largest Structure In The Near Universe Discovered – 130,000 Times More Massive Than Our Galaxy



In simulations of the universe like this one, you can find humongous structures like the one discovered. - Image Credit: Springel et al. (2005)© IFL Science

Mapping the distribution of matter in the universe is an important quest for cosmology and astrophysics. There is a battle going on between the universe's accelerated expansion and gravity trying to keep things all together. Some absolutely enormous structures have been found in the distant universe, but even closer to us there are gargantuan ones. Meet Quipu.

Quipu is a structure spanning 1.3 billion light-years. That means it would fit 13,000 galaxies like the Milky Way one after the other. It has a total mass of 2×10^{15} solar masses or as much as 130,000 Milky Ways. The two numbers reveal it couldn't possibly be a conga line of galaxies. There is one main strand of clusters of galaxies from which many strands depart.

This structure reminded the discoverer of the [Quipu](#), the Incan system used for counting, primarily, but also record keeping. There is the occasional hypothesis that there might be more language in it than we currently understand. It involves

color-coded cords all attached to a larger strand. Each strand has knots tied in certain locations to deliver numerical information. Similarly, Quipu the cosmic structure has over-densities with larger clusters along its strands.

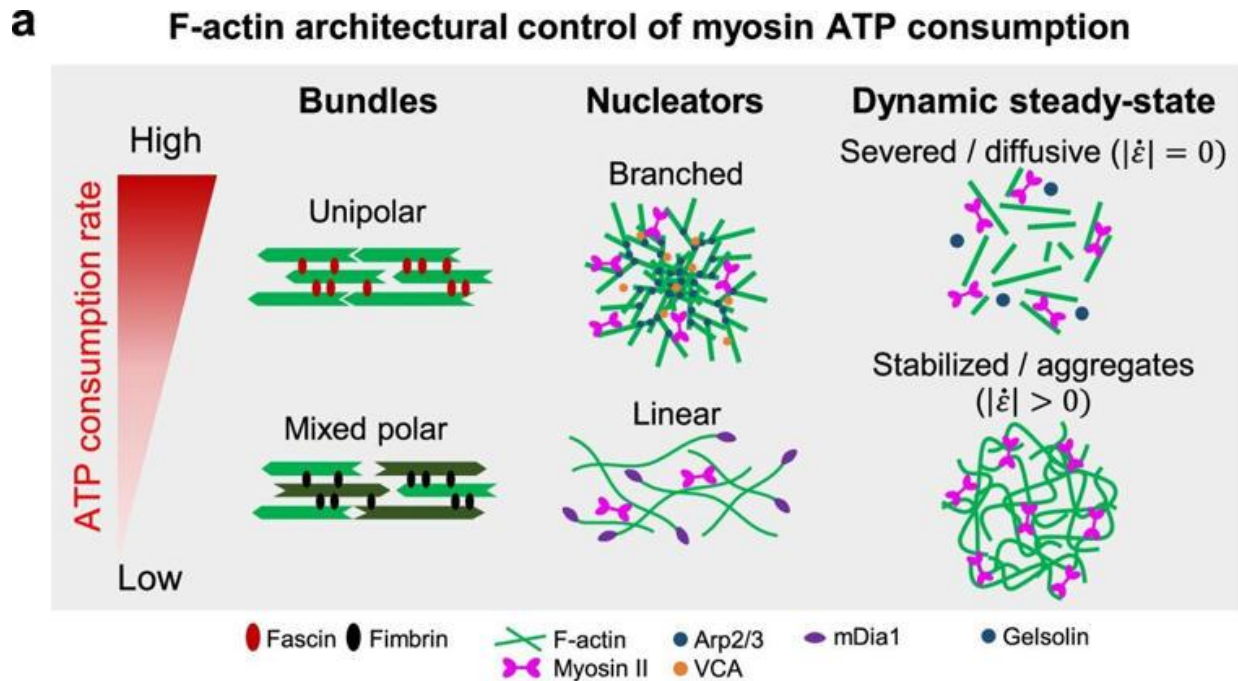
Quipu is one of five large cosmic structures discovered between 424 million and 815 million light-years from Earth. Together, they contain 45 percent of all galaxy clusters, 30 percent of all galaxies, and a quarter of all matter within that region of the near Universe – but they occupy only 13 percent of its volume, making them clear over-densities with respect to the rest of the region.

It is not surprising that there are regions that are more densely populated by galaxies, and regions that are less populated. The whole universe is organized in the so-called [cosmic web](#), where galaxies and clusters are organized in strands and nodes, with mostly empty space in between. Those regions are called the voids.

Quipu is the largest of these structures in the near universe. [Much larger structures](#) have been found in the far universe that have called into question our models. Quipu instead is perfectly sized for it. Simulations of the cosmos expect the presence of structures like Quipu out there.

The presence of such a large structure could affect cosmological measurements. This has been suggested as a possible solution to the famous Hubble tension, the disagreement between multiple methods to estimate the expansion rate of the universe. The team looked for the effect in the data, but they feel that statistical confidence on the finding is too poor.

Building artificial cells to measure energy flow in living systems



F-actin architecture controls the ATP consumption rate of myosin II. Credit: Nature Communications (2024). DOI: 10.1038/s41467-024-47593-x© Provided by Phys.org

Living systems are defined by a continuous flow of energy, which is essential for physical development, wound healing, and our immune response to diseases like cancer. But measuring the energy flow of a specific process, like force generation, is complicated by the more than 10,000 different kinds of molecular proteins interacting inside each of our cells.

Scientists at Yale's Systems Biology Institute have made an artificial cell to enable precise measurement of energy consumption and force generation in our cells. The work, from the lab of Michael Murrell, associate professor of Biomedical Engineering and Physics, was [published](#) in *Nature Communications*.

The artificial cells comprised key proteins responsible for cell force generation—a cytoskeleton, acting like the bones and muscle in the human body, wrapped in an outer membrane.

Their findings revealed that the amount of energy consumed varies with different morphological features. For example, cells with thicker cytoskeletons consumed less energy than cells with branch-like architecture, and longer cytoskeletons exerted increased force.

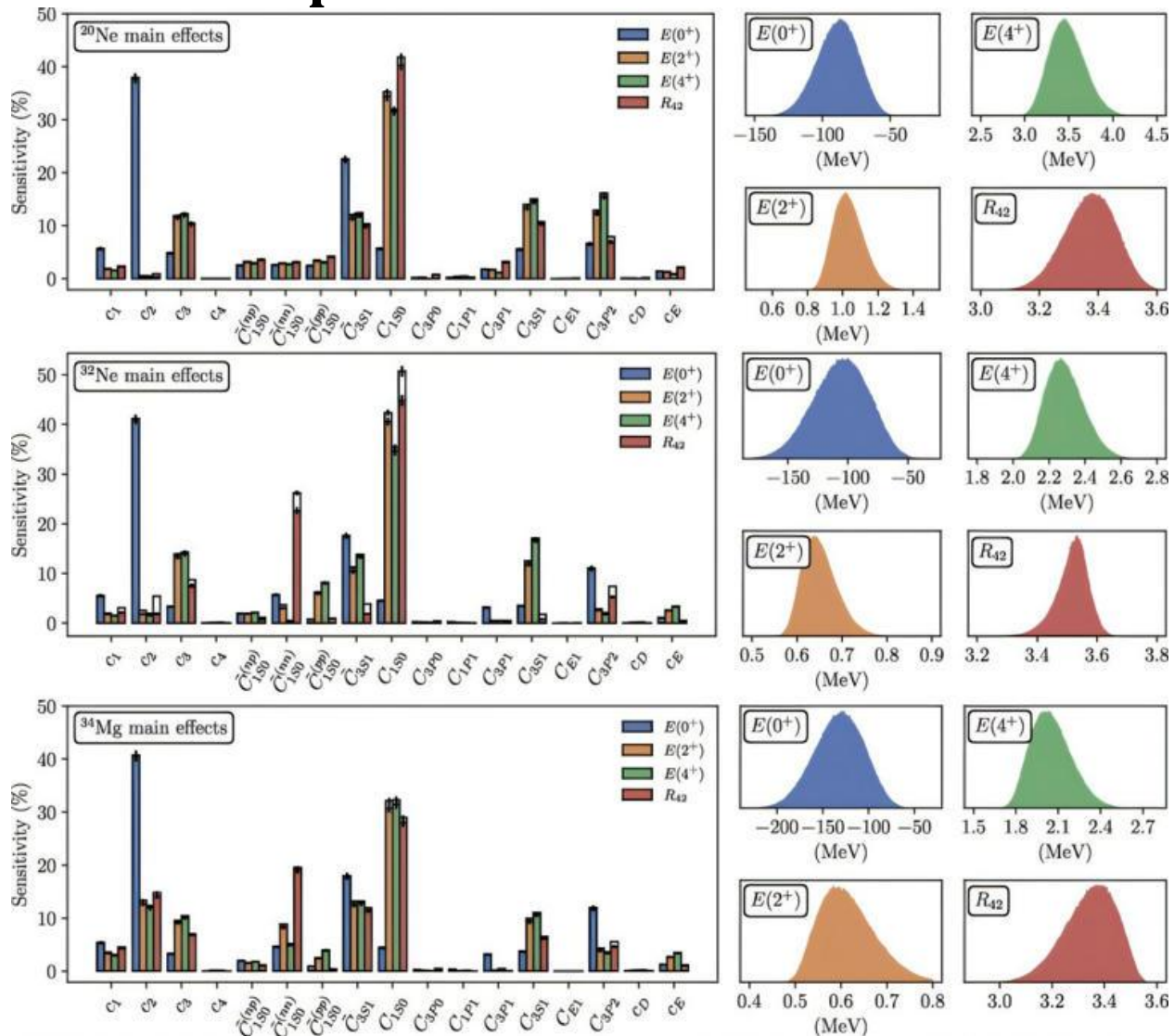
Unraveling the principles of energy consumption will enhance our understanding of biological organization, which underlies various cellular processes including cancer progression.

Ryota Sakamoto, a postdoctoral fellow in the Murrell Lab, was first author of the study.

More information: Ryota Sakamoto et al, F-actin architecture determines the conversion of chemical energy into mechanical work, *Nature Communications* (2024). DOI: [10.1038/s41467-024-47593-x](https://doi.org/10.1038/s41467-024-47593-x)

Provided by Yale University

Strong nuclear force calculations explain multiscale phenomena in atomic nuclei



Results of the global sensitivity analysis for the structure of $^{20,32}\text{Ne}$ and ^{34}Mg . Credit: Physical Review X (2025). DOI: 10.1103/PhysRevX.15.011028

Atomic nuclei exhibit multiple energy scales simultaneously—ranging from hundreds down to fractions of a megaelectronvolt. A new study demonstrates that these drastically different scales can be explained through calculations based on the strong nuclear force. The research also predicts that the atomic nucleus neon-30 exhibits several coexisting shapes.

"This discovery is incredibly important for understanding the stability limits of visible matter and how they can be anchored in our theory of the strong force," says Christian Forssén, professor at the Department of Physics at Chalmers University of Technology.

Together with Andreas Ekström, professor at the same department, they have been part of the research group that has now [published](#) their findings in *Physical Review X*. In addition to Chalmers, the researchers behind the study are active at Oak Ridge National Laboratory and the University of Tennessee in the United States.

The Chalmers researchers contributed by constructing the model for the strong force that binds protons and neutrons within the atomic nucleus and by developing emulation methods to analyze how components of the strong force influence the formation of deformed atomic nuclei.

Multiscale phenomena linked to the strong nuclear force

Atomic nuclei are characterized by binding energies in the hundreds of megaelectronvolts while simultaneously exhibiting collective excitations measured in fractions of a megaelectronvolt. The research group's extensive theoretical analysis now demonstrates that this multiscale physics can be explained through calculations grounded in a microscopic description of the strong nuclear force. The study also predicts that the neon-30 nucleus exhibits coexisting spherical and deformed shapes.

Multiscale nuclear phenomena have been observed for a long time, but tying these phenomena closer to the fundamental theory of the strong nuclear force, quantum chromodynamics, has been a significant challenge. The strong force is central to all visible matter in the universe, and a deeper understanding of it can explain everything from how elements are formed in the universe to the quantum mechanical structure and binding of atomic nuclei.

New computational methods

The research team has developed new computational methods that make it possible to analyze the connection between multiscale and emergent phenomena and the fundamental theory that describes the strong force.

The methods revolve around effective theories of quantum chromodynamics and model order reduction for highly accurate emulation of solutions to the Schrödinger equation. The researchers applied two- and three-nucleon forces in an approach that first breaks and then restores rotational symmetry in the neon-30 nucleus and then developed an emulator to study the strong force's parameter dependencies in the wave function of the atomic nucleus.

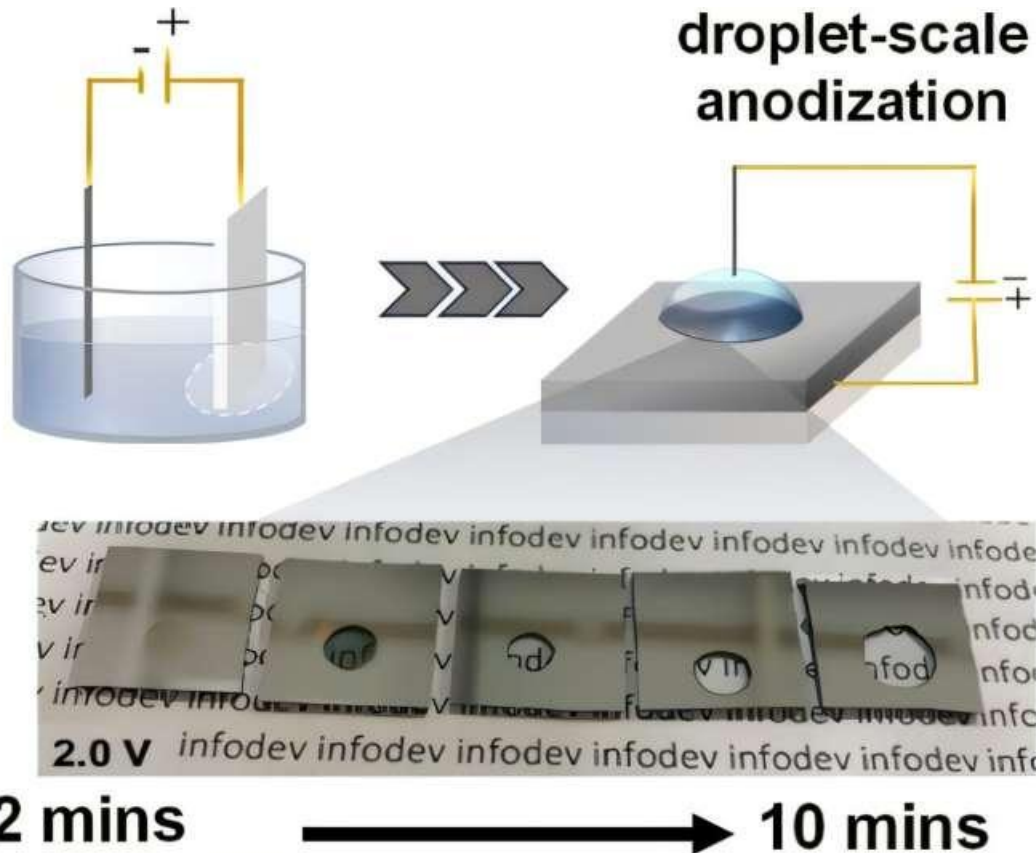
"Our new methods, combined with statistical analyses, link the microscopic description of atomic nuclei and the strong force. This is an important step in our continued efforts to predict the properties of atomic nuclei across the entire nuclide chart," says Ekström.

More information: Z. H. Sun et al, Multiscale Physics of Atomic Nuclei from First Principles, *Physical Review X* (2025). DOI: [10.1103/PhysRevX.15.011028](https://doi.org/10.1103/PhysRevX.15.011028)

Provided by Chalmers University of Technology

Transparent aluminum: Tiny acid droplets turn metal into glass-like material

by Timothy James M. Dimacali, [Ateneo de Manila University](#)



The researchers made transparent aluminum oxide (TAIOx) by applying microdroplets of acidic solution onto ordinary aluminum and applying a controlled electric current. Credit: Budlayan et al., 2025

Transparent aluminum oxide (TAIOx), a real material despite its sci-fi name, is incredibly hard and resistant to scratches, making it perfect for protective coatings on electronics, optical sensors, and solar panels. On the sci-fi show *Star Trek*, it is even used for starship windows and spacefaring aquariums.

Current methods of making TAIOx are expensive and complicated, requiring high-powered lasers, vacuum chambers, or large vats of dangerous acids. That may change thanks to research co-authored by Filipino scientists from the Ateneo de Manila University.

Instead of immersing entire sheets of metal into acidic solutions, the researchers applied microdroplets of acidic solution onto small aluminum surfaces and applied an [electric](#)

[current](#). Just two volts of electricity—barely more than what's found in a single AA household flashlight battery—was all that was needed to transform the metal into glass-like TAIOx.

The findings were [published](#) in the journal *Langmuir*.

This process, called "droplet-scale anodization," is not only simpler than existing manufacturing methods but also environmentally friendly, cutting down on chemical waste and energy use.

The technique relies on a special effect called "electrowetting," where an [electric field](#) changes the properties of a liquid droplet, allowing [precise control](#) over the anodization process.

This new approach might make TAIOx cheaper and more accessible for applications in everything from touchscreens and lenses to ultra-durable coatings for vehicles and buildings. It could also lead to advances in miniaturized electronics, as scientists now have a way to convert [metal surfaces](#) into insulating, transparent layers on a microscopic scale.

More information: Marco Laurence M. Budlayan et al, Droplet-Scale Conversion of Aluminum into Transparent Aluminum Oxide by Low-Voltage Anodization in an Electrowetting System, *Langmuir* (2025). DOI: [10.1021/acs.langmuir.4c03303](https://doi.org/10.1021/acs.langmuir.4c03303)

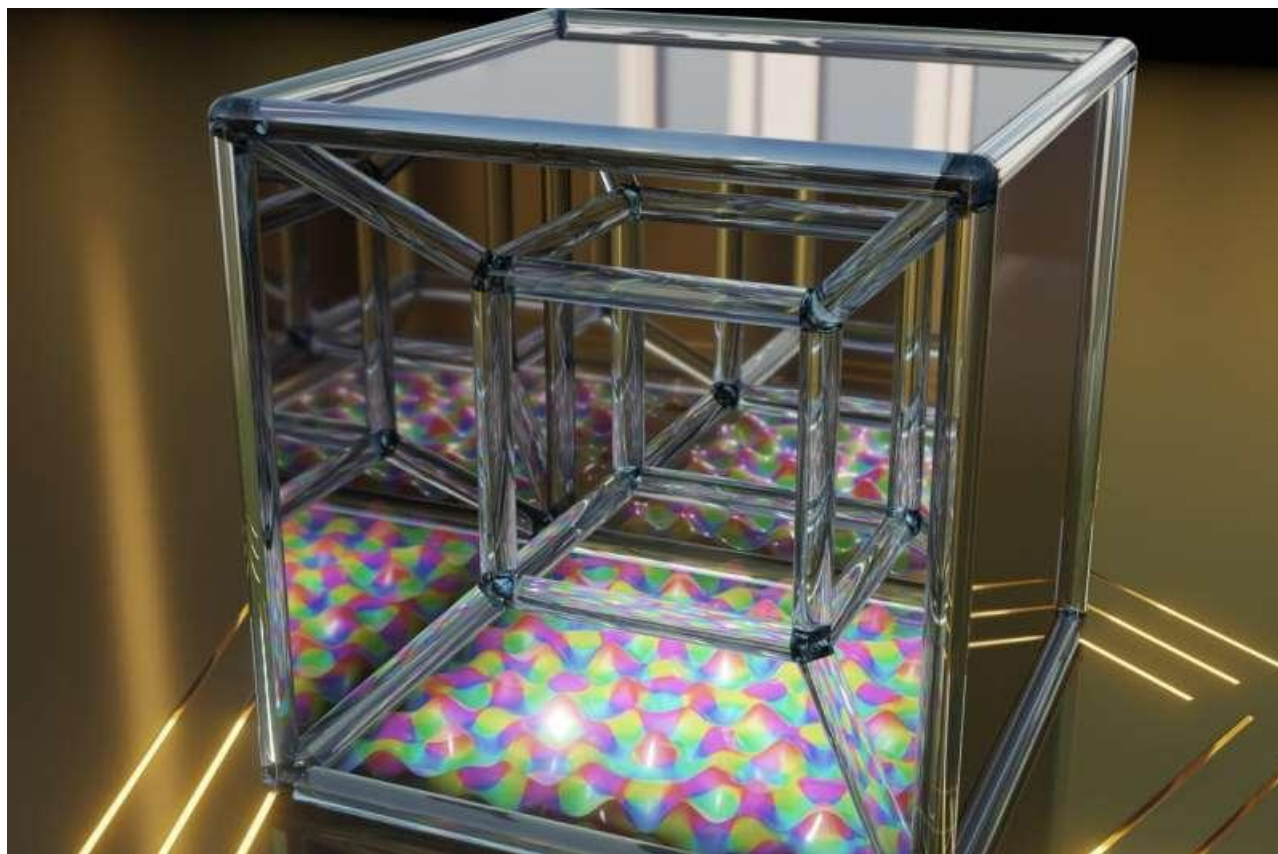
Journal information: [Langmuir](#)

Provided by [Ateneo de Manila University](#)

FEBRUARY 13, 2025

Greetings from the fourth dimension: Scientists glimpse 4D crystal structure using surface wave patterns

by [Technion - Israel Institute of Technology](#)



In the illustration: A tesseract (a four-dimensional cube) and the "shadow" it casts on a plane—the quasicrystal discovered by Shechtman. According to Prof. Bartal, "The fact that a quasicrystal is a 'shadow' of a periodic crystal in a higher dimension is not new in itself. What we discovered is that the projection includes not only the structure but also topological properties such as vortices."). Credit: Florian Sterl, Sterltech Optics

In April 1982, Prof. Dan Shechtman of the Technion–Israel Institute of Technology made the discovery that would later earn him the 2011 Nobel Prize in Chemistry: the quasiperiodic crystal. According to diffraction measurements made with an electron microscope, the new material appeared "disorganized" at smaller scales, yet with a distinct order and symmetry apparent at a larger scale.

This form of matter was considered impossible, and it took many years to convince the scientific community of the discovery's validity. The first physicists to theoretically explain this discovery were Prof. Dov Levine, then a doctoral student at the University of Pennsylvania and now a faculty member in the Technion Physics department, and his advisor, Prof. Paul Steinhardt.

The key insight that enabled their explanation was that quasicrystals were, in fact, periodic—but in a higher dimension than the one in which they exist physically. Using this realization, the physicists were able to describe and predict mechanical and thermodynamic properties of quasicrystals.

The concept of higher spatial dimension extends our familiar three-dimensional space—length, width, and height—by introducing additional directions which are perpendicular to all three. This is difficult to visualize, as we can only perceive the world around us as a three-dimensional space, and even more challenging to measure. An example of a four-dimensional object is the tesseract, also known as hypercube.

Just as a cube consists of six square facets, a tesseract comprises eight cubic cells. Although we cannot fully visualize a tesseract, we can represent it through its projections, much like looking at the shadow of a three-dimensional cube on a two-dimensional piece of paper.

In a new study [published in Science](#), researchers from the Technion, together with the University of Stuttgart and University of Duisburg-Essen in Germany, shed new light on this phenomenon. In their study, led by Prof. Guy Bartal and Dr. Shai Tsesses from the Andrew and Erna Viterbi Faculty of Electrical and Computer Engineering, Prof. Harald Giessen from the University of Stuttgart, and Prof. Frank Meyer zu Heringdorf from the University of Duisburg-Essen, the research group demonstrated that not only do the higher dimensional crystals dictate the mechanical properties of quasiperiodic crystals, they also determine their topological properties.

Time-resolved vector 2PPE-PEEM imaging of a $Q = -2$ pentagonal plasmonic quasi-lattice mode. Similar features appear to be disappearing and reappearing at different locations in different times. Credit: *Science* (2025). DOI: 10.1126/science.adt2495

Topology is a branch of mathematics that investigates the geometric properties that remain unchanged under continuous deformations. The topology of higher-dimensional spaces focuses on the properties of objects in more than three dimensions and can assist researchers, for example, in studying the structure of the universe and developing quantum computing algorithms.

The researchers examined quasiperiodic interference patterns of electromagnetic surface waves and discovered, to their surprise, that although the patterns appeared different, their topological properties in two dimensions could not be used to differentiate between them. They found the only way to distinguish between the patterns was by referring to an "original" higher-dimensional crystal.

This understanding agrees with the explanation given by Levine and Steinhardt, which was based on an earlier discovery by British mathematician, Sir Roger Penrose (2020 Nobel Prize laureate in Physics) and later conveyed by Nicolaas de Bruijn.

The researchers also discovered another intriguing phenomenon: Two different topological patterns of surface waves appeared identical when measured after a specific time interval. This interval was extremely short, measured in attoseconds—a billionth of a billionth of a second. The original theory by Levine and Steinhardt again explains this phenomenon as a "competition" between the topological and thermodynamic (energetic) properties of the crystals.

The findings were achieved using two methods: near-field scanning [optical microscopy](#) conducted in Prof. Guy Bartal's lab by Dr. Kobi Cohen and two-photon photoemission electron microscopy, measured in collaboration between the University of Stuttgart and the University of Duisburg-Essen in Germany. The discoveries reported in the manuscript pave the way for new methods to measure the thermodynamic properties of quasiperiodic crystals.

In the near future, the researchers plan to expand their findings to other physical systems and examine more deeply the interplay between thermodynamic and topological properties. Potentially, the unique higher-dimensional [topological properties](#) of quasicrystals could be used in the future to represent, encode, and transfer information.

More information: Shai Tseses et al, Four-dimensional conserved topological charge vectors in plasmonic quasicrystals, *Science* (2025). DOI: [10.1126/science.adt2495](https://doi.org/10.1126/science.adt2495)

Journal information: [Science](#)

Provided by [Technion - Israel Institute of Technology](#)

Advancing quantum materials: A new approach to controlling electronic states

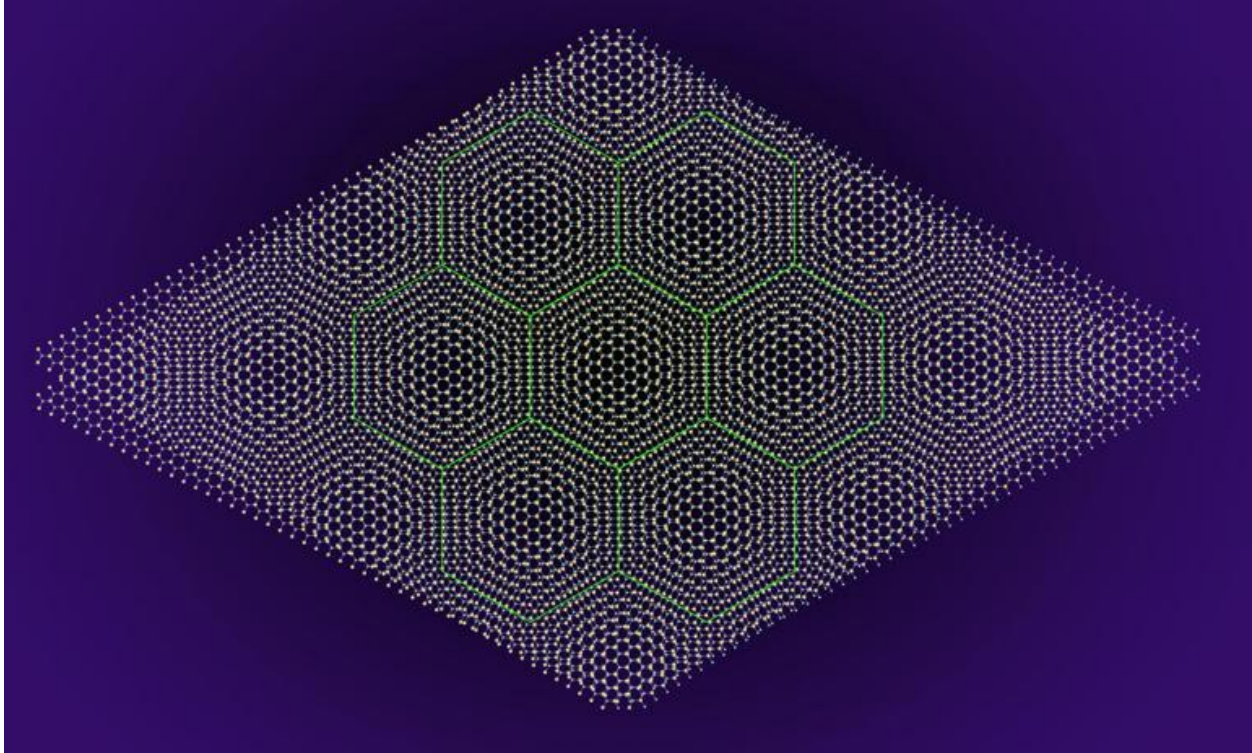


Illustration of twisted double bilayer tungsten diselenide in which the correlated physics of different valleys can be controlled to unprecedented levels. Credit: Joerg Harms / MPSD

A collaborative team of researchers from the Max Planck Institute for Structure and Dynamics of Matter (MPSD), Nanjing University, Songshan Lake Materials Laboratory (SLAB), and international partners has introduced a new method to regulate exotic electronic states in two-dimensional materials.

Building on the foundations laid by their [previous work](#) on twisted van der Waals materials, the team of physicists has now discovered a novel way to manipulate correlated electronic states in twisted double bilayer tungsten diselenide (TDB-WSe₂). This breakthrough offers new possibilities for developing advanced quantum materials and devices.

By precisely twisting two bilayers of WSe₂ near a 60-degree angle and applying a perpendicular electric field, the researchers have achieved control over the interaction between two distinct electronic bands, known as the K-valley and Γ -valley bands. This tuning has led to the observation of a "valley charge-transfer

insulator"—an exotic state where electron movement is highly correlated, and electrical conductivity is suppressed.

"This work reveals that we can control the electronic phases of matter using the valley degree of freedom, which acts as a new 'knob' to adjust the material's properties," explains Lei Wang, professor of physics at Nanjing University and senior author of the study. "Our findings provide a deeper understanding of how to engineer correlated insulating states, which is crucial for future quantum technologies."

The ability to manipulate these correlated states without altering the chemical composition or introducing significant disorder is a significant advancement. Traditionally, achieving such control required changing the material itself or applying large magnetic fields. The team's approach offers a more straightforward and reversible method by using electric fields to adjust the relative position of the electronic bands and reveals a new form of flat band at the Γ -valley.

This research demonstrates a continuous transition from a Mott–Hubbard insulator to a valley charge-transfer insulator by shifting the K-valley band across the Γ -valley Hubbard bands using gate control. This tunable behavior opens the door to exploring new quantum phases, with potential applications in superconductors, quantum computers, and other next-generation technologies.

Published in *Nature Communications*, the [study](#) represents a collaborative effort among several international institutions and underscores the growing importance of twisted van der Waals materials in quantum materials research.

"This is just the beginning," says Lede Xian, Professor and Group Leader of the Max Planck Partner Group at SLAB. "We believe that our work opens up new pathways for investigating and utilizing strongly correlated materials, which are essential for the next generation of quantum devices."

"This discovery opens up new possibilities for controlling matter at the atomic level," adds Angel Rubio, Director of the Theory Department at the MPSD. "We are excited to see potential applications and how it can be used to create unique functionalities."

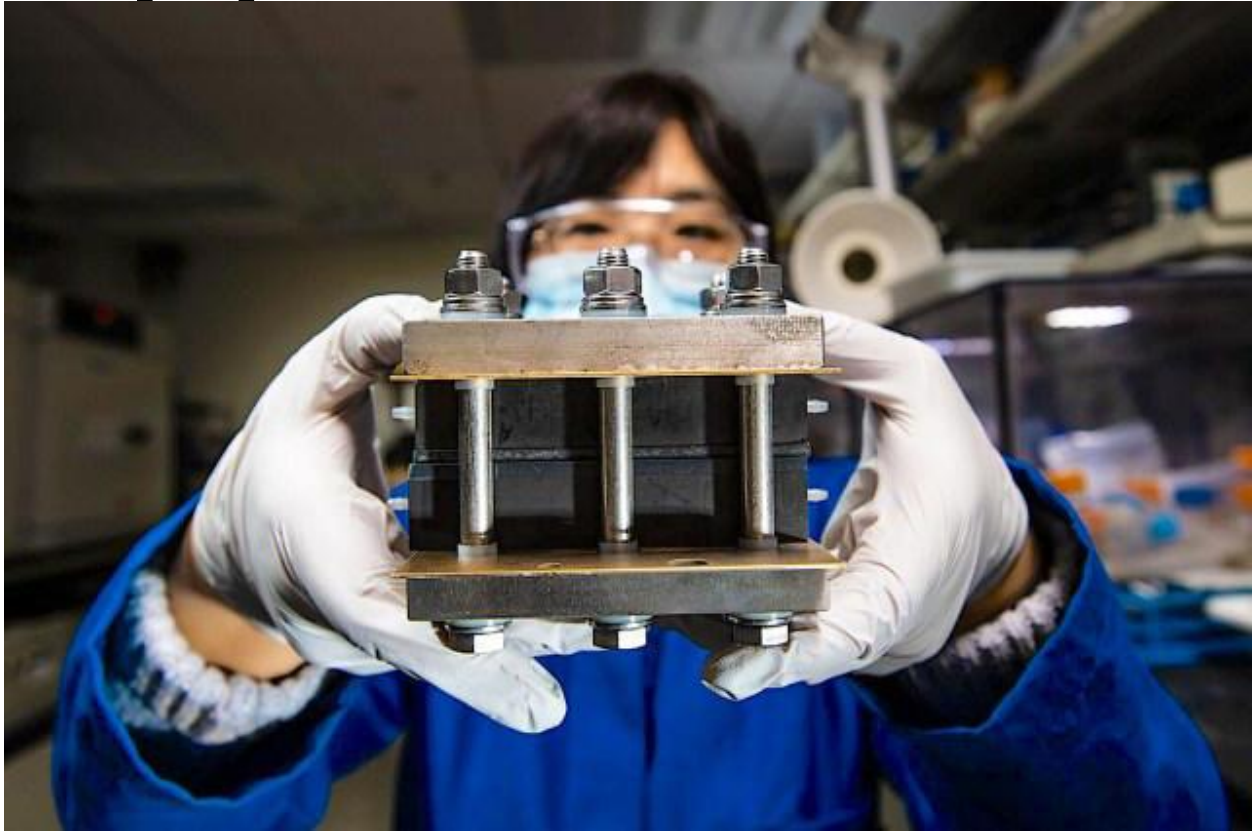
Further advancements in Moiré materials engineering could lead to new, tunable properties that are difficult to achieve through conventional methods, pushing the frontiers of material science. "This is a highly interesting situation where changes in structural registry lead to a new type of correlated phenomena," concludes Rubio.

This latest research highlights the rapid progress in the field and builds upon the pioneering insights from earlier studies by the team on twisted van der Waals materials. As scientists continue to uncover new mechanisms of control, the potential for groundbreaking applications in quantum computing, energy-efficient electronics, and beyond remains vast and promising.

More information: LingNan Wei et al, Valley charge-transfer insulator in twisted double bilayer WSe₂, *Nature Communications* (2025). DOI: [10.1038/s41467-025-56490-w](https://doi.org/10.1038/s41467-025-56490-w)

Provided by Max Planck Institute for the Structure and Dynamics of Matter

Scientists develop new tool that could revolutionize the future of energy storage: 'A superpower for ... researchers'



Storing cleaner energy for later use is important as we continue to switch from dirty fuels.

Government battery experts have [developed](#) what could be the equivalent of an "easy button" for anyone interested in creating the next power pack breakthrough.

In fact, the team at Pacific Northwest National Laboratory in Washington called it the EZBattery Model, and it's a fast-paced research tool [available](#) for free online.

"This new model is like a superpower for energy storage researchers," Pacific project lead Jie Bao [said](#) in a news release.

The in-depth calibration and diagnostic software is for redox flow batteries, a type of pack [picking up interest](#) in labs around the world.

They aren't like typical batteries. Flow setups have two tanks that hold specialized liquids. Pumps, piping, vanadium metal, and a membrane that prevents unwanted liquid transfers are the main parts, [according](#) to CleanTechnica and [ScienceDirect](#).

It works by converting chemical energy into electricity.

"Flow battery systems are designed [with] two external electrolyte storage reservoirs and separated from the electricity converter unit. The electricity conversion process takes place within the electrochemical cell after the electrolytes are being transported to the cell with the aid of [a] pump," [per](#) ScienceDirect.

The description makes it easy to see why a cheat sheet for development could be helpful.

And CleanTechnica [reported](#) that flow packs have the potential to answer growing power demand from data centers, which consume about 4.4% of U.S. electricity, [according](#) to the government. That's because they could store [renewable](#) energy for much longer stretches. Energy officials would prefer 10 or more hours compared to the four- to six-hour timeframe commonly available, per the story.

Pacific's software is made to reduce testing time by completing simulations that had taken hours or days in less than a second. It provides for analysis of multiple design types, as well, all [according](#) to the team.

"The physics-based approach lends itself to easily integrate and capture intricate details of [the] battery," Bao [added](#).

Researchers from around the world are digging deep into their chemistry, physics, and kinetic energy data banks as they try to find reliable and efficient ways to store intermittent power from the wind and sun. Scotland's government is investing in so-called [water batteries](#) that consist of two large reservoirs. When there's a glut of wind power, the juice is leveraged to pump water into the top reservoir, representing stored energy that can later be released to the bottom one, turning a turbine as it falls.

For their part, lithium-ion batteries — such as [Tesla's Megapacks](#) — are being deployed stateside and abroad. Each one can power 3,600 homes for an hour, [according to Tesla](#). A sodium battery in China can power [12,000](#) homes.

Storing cleaner energy for later use is important as we continue to [switch](#) from dirty fuels, which limits production of [heat-trapping](#) air pollution. The fumes are [linked](#) by NASA to increased risks for [power-cutting](#) severe weather, among other hazards.

Even homeowners can utilize battery [tech](#) to [save money](#) and as [blackout](#) protection. Powerwall and other home-based packs can store electricity from rooftop [solar panels](#), which a government study estimated saves the average user [\\$691](#) a year after expenses. [EnergySage](#) is a free online tool that can help you find the best deals and any tax incentives that are available.

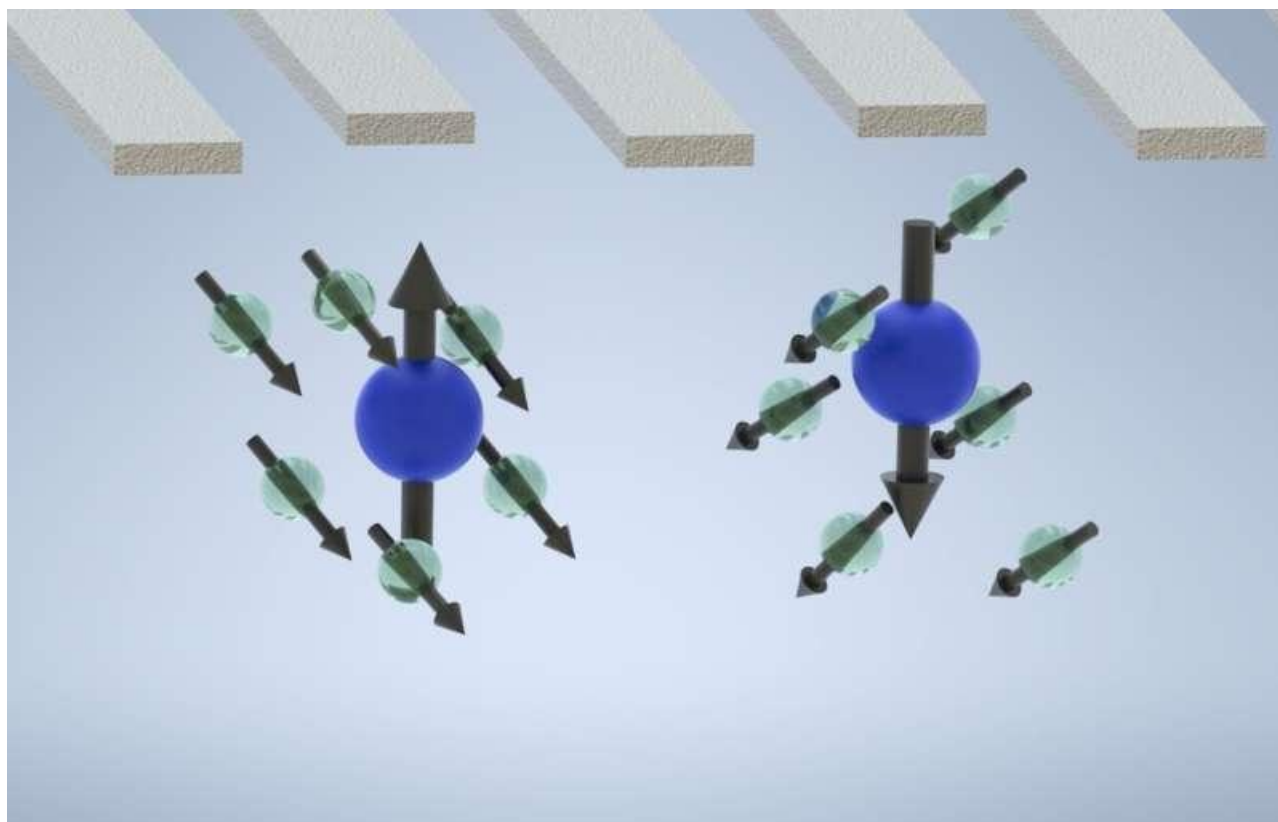
At Pacific, the goal is to make sure there's a steady flow of better tech thanks to quick research.

"To get the best-performing long-duration energy storage system that will power our homes and the grid, we need to be able [to] iterate quickly and efficiently," Bao [said](#).

FEBRUARY 20, 2025

Newly realized nuclear-spin dark state promises reduced quantum decoherence

by Ingrid Fadelli , Phys.org



Two electrons (blue) in a state gate-defined quantum dot were used to create a nuclear-spin dark state. The dark state is a collective state of the nuclear spins (green) that minimizes their interaction with the electrons. Credit: John Nichol

Quantum computers, which operate leveraging quantum mechanics phenomena, could eventually tackle some optimization and computational problems faster and more efficiently than their classical counterparts. Instead of bits, the fundamental units of information in classical computers, quantum computers rely on qubits (quantum bits), which can be in multiple states at once.

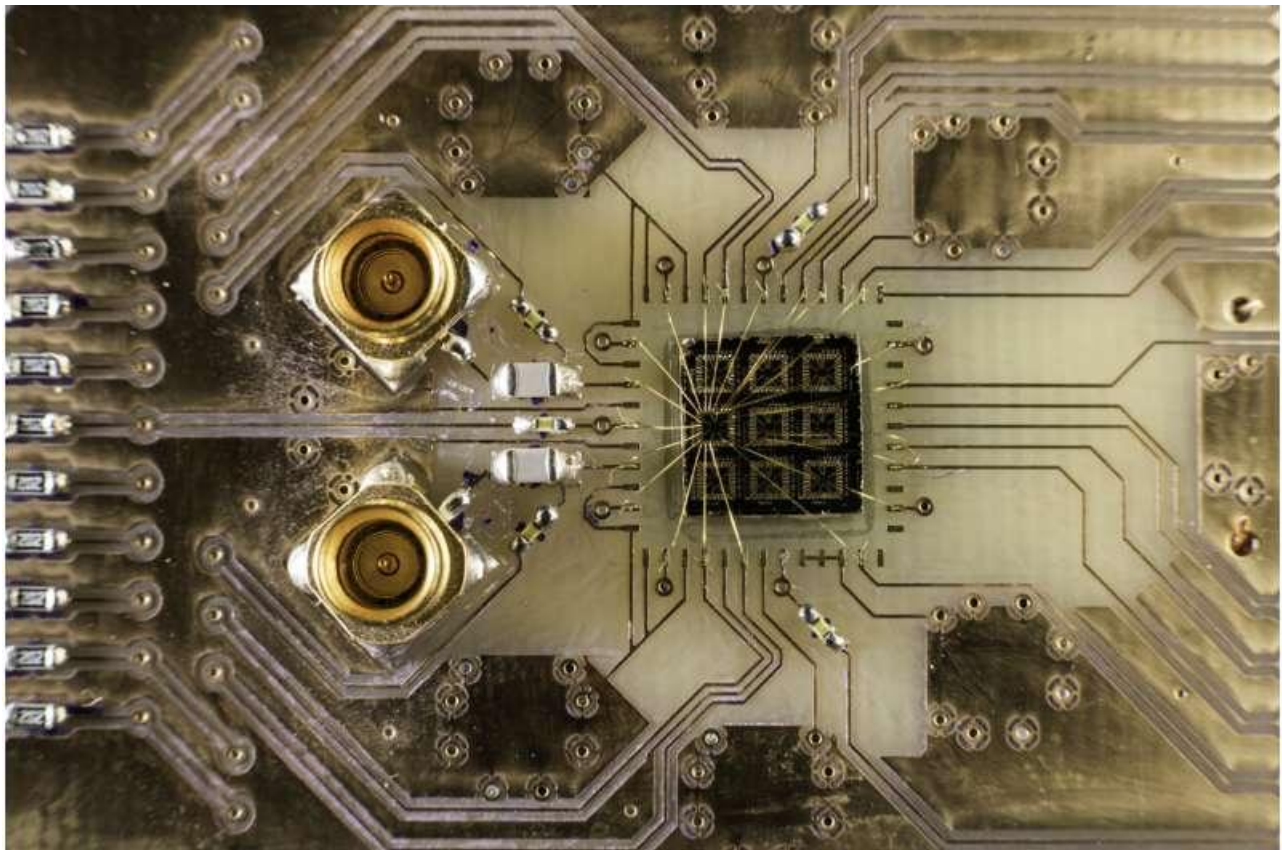
Silicon-based quantum dots, semiconductor-based structures that trap individual electrons, have been widely used as qubits, as the spin state of the electrons they confine can be leveraged to encode information. Despite their promise, many quantum computers developed so far are susceptible to decoherence, which entails the disruption of qubit states due to their interaction with the surrounding environment.

Researchers at the University of Rochester recently set out to experimentally realize a so-called nuclear-spin dark state, a condition that has been theorized to improve the performance of quantum computers, suppressing undesirable interactions and thus reducing decoherence. Their paper, [published](#) in *Nature Physics*, demonstrates the potential of this state for reducing decoherence in [quantum systems](#) and thus potentially improving control over quantum information processing.

"The motivation for this project was to explore a realization of the central spin problem in a new setting," John Nichol, senior author of the paper, told Phys.org. "The central spin model is a widely studied system where one spin (the central spin) interacts with many other spins. This important model is used to understand phenomena including decoherence of qubits."

The central spin model is a promising framework that predicts various phenomena, including the formation of so-called dark states. While various theoretical studies are built on this model, testing it in experimental settings has proved challenging due to the large number of spins required to demonstrate the effects it predicts.

"We were inspired to use the semiconductor [silicon](#) to explore this physics because while it still has a lot of [nuclear spins](#), it doesn't have as many as other semiconductors," said Nichol. "We thought silicon would provide us with a more controllable platform in which to study central-spin physics."



A quantum-dot chip mounted on a circuit board. Credit: J. Adam Fenster / University of Rochester.

Typically, the nuclear spins in semiconductors interact with electron spins via the so-called hyperfine interaction. To realize the nuclear-spin dark state, researchers need to arrange nuclear spins following a specific configuration, to prevent their interactions with electron spins.

"We used a system of electrons in a silicon gate-defined double quantum dot," explained Nichol. "Using voltage pulses, we manipulated the electron spins to generate dynamic nuclear polarization, which is the process of polarizing the nuclei with the electrons. During the process of dynamic nuclear polarization, the nuclei in the semiconductor became synchronized in such a way to cancel their interaction with the electrons."

The findings gathered by Nichol and his colleagues appeared to confirm theoretical predictions about nuclear-spin dark states. The researchers realized a nuclear-spin dark state in a gate-defined silicon double quantum dot, demonstrating that such states can exist in real devices.

Notably, they found that the dark state they realized significantly suppressed interactions between nuclear and electron spins. In addition, these interactions remained suppressed for as long as the nuclei maintained their carefully engineered synchronization.

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"The existence of the dark state had been predicted many years ago, but conclusive experimental evidence of its formation had to wait until now," said Nichol. "Its existence is surprising in part because the dark state involves the synchronized evolution of thousands of nuclear spins, and the fact that they can undergo this collective evolution in a real system is surprising."

Demonstrating that dark states can exist in silicon devices could have important implications for future research. Silicon is easily accessible and widely used to develop various electronic devices, including classical and quantum computing systems. Therefore, this recent study could soon pave the way for other demonstrations of nuclear-spin dark states in silicon quantum dots.

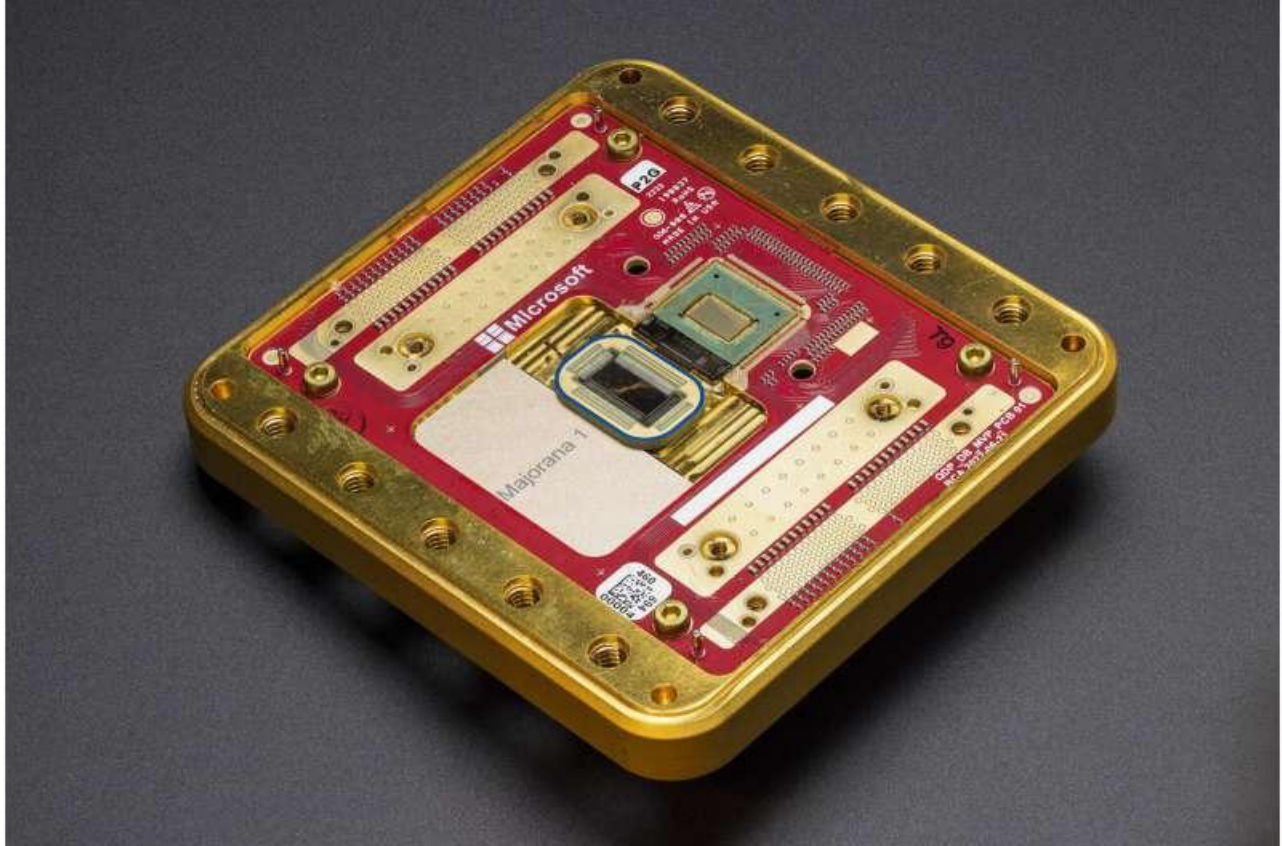
"We hope someday the dark state can be useful, especially for quantum applications," added Nichol. "We have many unanswered questions about this dark state and are eager to explore them in future research. In our next studies, we plan to explore the properties of the dark state, including how robust it is to external factors. We will also focus on how it can be used. For instance, predictions suggest that the [dark state](#) should be an excellent quantum memory, and we are curious to see if this pans out."

More information: Xinxin Cai et al, The formation of a nuclear-spin dark state in silicon, *Nature Physics* (2025). DOI: [10.1038/s41567-024-02773-w](https://doi.org/10.1038/s41567-024-02773-w).

Journal information: [Nature Physics](#)

FEBRUARY 20, 2025

Microsoft joins quantum race with breakthrough chip



Credit: Microsoft

Tech giant Microsoft unveiled a new computer chip on Wednesday that it says could transform everything from fighting pollution to developing new medicines, joining Google and IBM in arguing that the promise of quantum computing is closer to reality.

The US-made [chip](#), called Majorana 1, can fit in the palm of a hand but packs a revolutionary design that Microsoft believes will solve one of the biggest challenges in quantum computing—making these super-powerful machines reliable enough for real-world use.

"We took a fresh approach and basically reinvented how quantum computers could work," said Chetan Nayak, a senior scientist at Microsoft.

The company says its breakthrough was confirmed in research [published](#) Wednesday in the scientific journal *Nature*.

The new Majorana 1 chip uses a special approach to building quantum computers that could make them more stable and easier to scale up than the work done by Google or IBM, which are considered leaders in the field.

While the chip represents a major advance, Microsoft acknowledges that more engineering work lies ahead before quantum computers become practical tools.

However, the company says this breakthrough could make that reality possible within "years rather than decades."

Unlike regular computers that process information as 1s and 0s, quantum computers harness the strange properties of atomic particles, measured as qubits, to potentially solve problems that would take today's most powerful supercomputers thousands of years.

Microsoft says its new chip design could lead to quantum computers capable of tackling major challenges, like finding ways to break down harmful microplastics in the ocean or developing materials that can repair themselves when damaged.

Quantum research is seen as a critical field and both the United States and China have been investing heavily in the area, while Washington has also placed restrictions on the export of the sensitive technology.

The US Department of Defense has shown strong interest in the technology, selecting Microsoft as one of just two companies to advance to the final phase of its quantum computing program.

Google in December unveiled its Willow quantum chip, which dramatically reduced computing errors and performed a calculation in minutes that would take a traditional supercomputer millions of years, marking a significant advance toward practical quantum computing.

More information: Interferometric single-shot parity measurement in InAs–Al hybrid devices, *Nature* (2025). DOI: [10.1038/s41586-024-08445-2](https://doi.org/10.1038/s41586-024-08445-2)

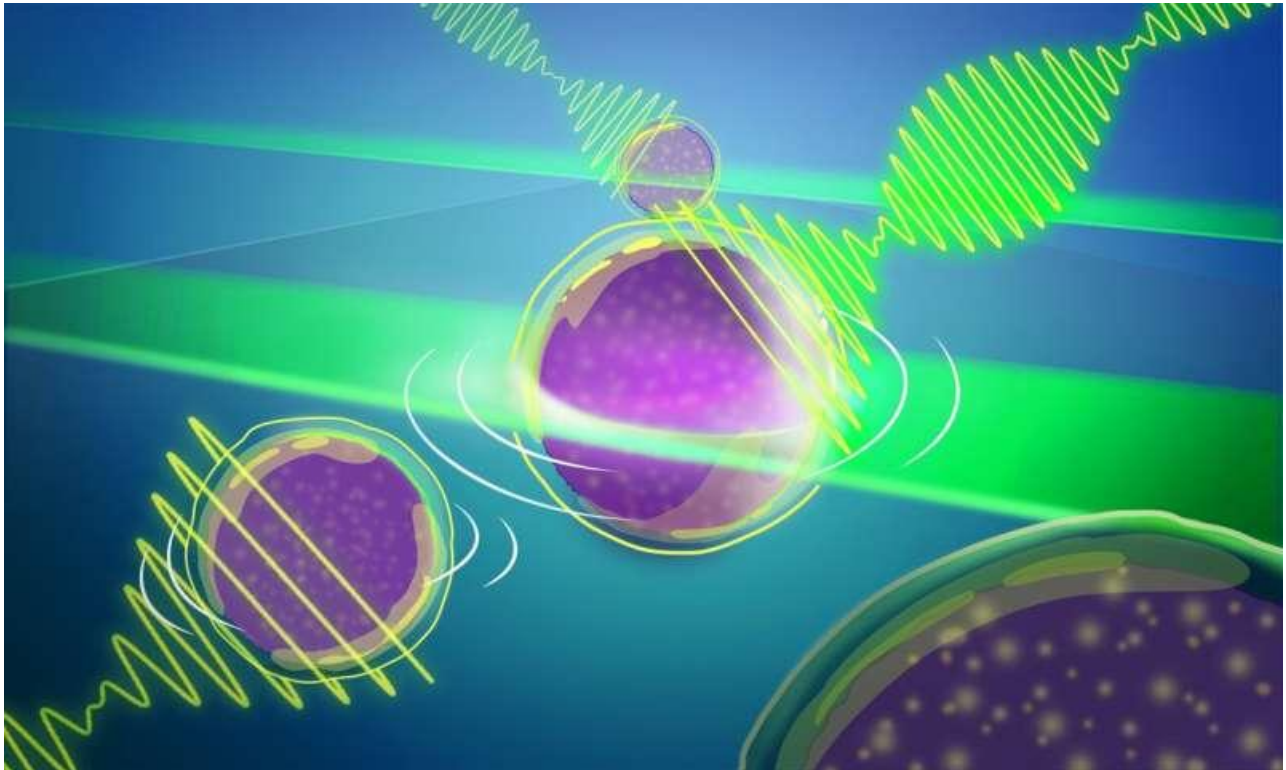
Journal information: [Nature](#)

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FEBRUARY 20, 2025

Pushing the limits of 'custom-made' microscopy: 3-D imaging of light-sensitive samples now 1,000 times faster

by [European Molecular Biology Laboratory](#)



An artist's representation of the new Brillouin microscopy approach that allows entire light-sheets to interact with 3D biological samples. The scattered light reveals a unique optical interference signal that can be recorded with a custom-developed spectrometer, tremendously speeding up image acquisition. Credit: Daniela Velasco/EMBL

EMBL tech developers have made an important leap forward with a novel methodology that adds an important microscopy capability to life scientists' toolbox. The advance represents a 1,000-fold improvement in speed and throughput in Brillouin microscopy and provides a way to view light-sensitive organisms more efficiently.

"We were on a quest to speed up [image acquisition](#)," said Carlo Bevilacqua, optical engineer in EMBL's Prevedel team and lead author on a paper [published](#) about this [technological development](#) in *Nature Photonics*.

"Over the years, we have progressed from being able to see just a pixel at a time to a line of 100 pixels, to now a full plane that offers a view of approximately 10,000 pixels."

The technology is based on a [phenomenon first predicted](#) in 1922 by French physicist Léon Brillouin. He showed that when light is shone on a material, it interacts with naturally occurring thermal vibrations within, exchanging energy and thereby slightly shifting the frequency (or color) of the light. Measuring the spectrum (colors) of the [scattered light](#) reveals information about a material's physical characteristics.

Using Brillouin scattering for microscopy purposes came much later—in the early 2000s—when other technological advancements enabled scientists to measure tiny frequency shifts with high precision and sufficient throughput. This allowed them to compute [mechanical properties](#) of living [biological samples](#).

However, at that point, scientists were only able to view one pixel at a time. The process was therefore quite time-consuming, and it severely limited how the microscopy method could be used in biology.

In 2022, Bevilacqua and others in the Prevedel group were able to first expand the field of view to a line, and now with this latest development, to a full 2D field of view, which also helps speed up 3D imaging.

"Just as the development of light-sheet microscopy here at EMBL marked a revolution in [light microscopy](#) because it allowed for faster, high-resolution, and minimally phototoxic imaging of biological samples, so too does this advance in the area of mechanical or Brillouin imaging," said Robert Prevedel, Group Leader and senior author on the paper.

"We hope this new technology—with minimal light intensity—opens one more 'window' for life scientists' exploration."

More information: Bevilacqua, C. et al. Full-field Brillouin microscopy based on an imaging Fourier transform spectrometer, *Nature Photonics* (2025). DOI: [10.1038/s41566-025-01619-y](https://doi.org/10.1038/s41566-025-01619-y)

Journal information: [Nature Photonics](#)

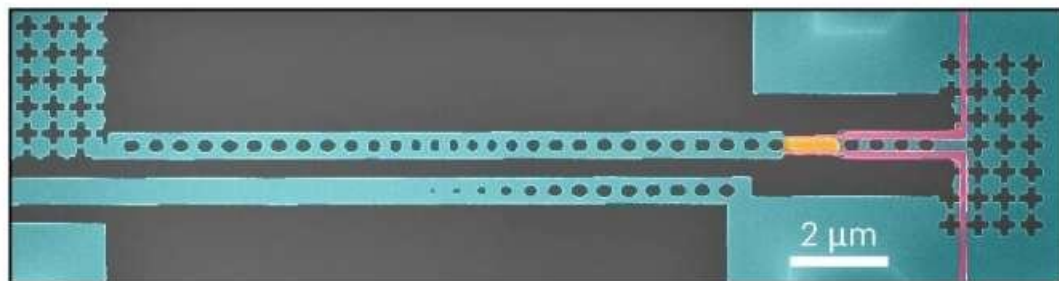
Provided by [European Molecular Biology Laboratory](#)

FEBRUARY 20, 2025

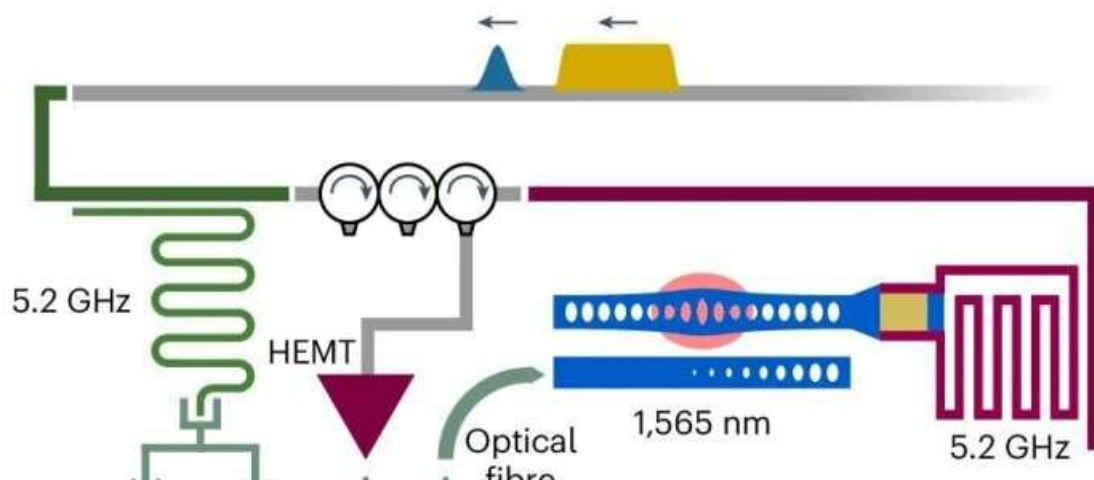
Microwave-to-optics transduction: Research demonstrates readout technique for superconducting qubits

by Rigetti Computing Inc.

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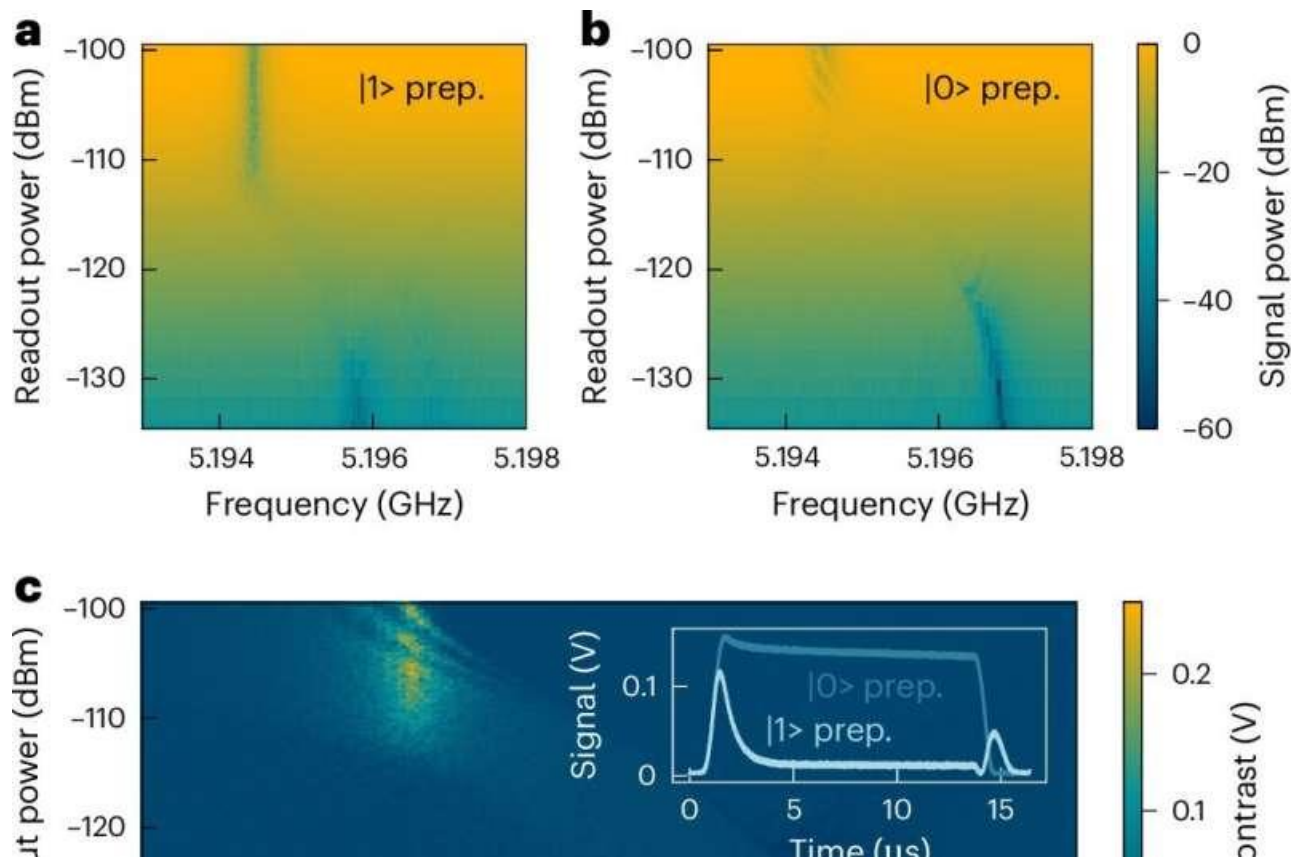
Transducer performance. Credit: *Nature Physics* (2025). DOI: 10.1038/s41567-024-02742-3
Joint research demonstrating the ability to readout superconducting qubits with an optical transducer was [published](#) in *Nature Physics*.

Quantum computing has the potential to drive transformative breakthroughs in fields such as advanced material design, artificial intelligence, and drug discovery. Of the quantum computing modalities, superconducting qubits are a leading platform towards realizing a practical quantum computer given their fast gate speeds and ability to leverage existing semiconductor industry manufacturing techniques.

However, fault-tolerant quantum computing will likely require 10,000 to a million physical qubits. The sheer amount of wiring, amplifiers and microwave components required to operate such large numbers of qubits far exceeds the capacity of modern-day dilution

refrigerators, a core component of a superconducting quantum computing system, in terms of both space and passive heat load.

A potential solution to this problem may be to replace coaxial cables and other cryogenic components with optical fibers, which have a considerably smaller footprint and negligible thermal conductivity. The challenge lies in converting the [microwave signals](#) used to control qubits into infrared light that can be transmitted through fiber.



Microwave qubit readout. Credit: *Nature Physics* (2025). DOI: 10.1038/s41567-024-02742-3

This is where microwave-to-optical transduction comes into play, a field dedicated to the coherent conversion of microwave photons to optical photons. QphoX, a Dutch quantum technology startup, has developed transducers with piezo-optomechanical technology that are capable of performing this conversion, forming an interface between [superconducting qubits](#) and fiber-optics.

To demonstrate the potential of this technology, researchers from the companies QphoX, Rigetti and Qblox connected a transducer to a superconducting qubit, with the goal of measuring its state using light transmitted through an optical fiber. Remarkably, it was discovered that not only is the transducer capable of converting the signal that reads out the qubit, but that the qubit can also be sufficiently protected from decoherence introduced by thermal noise or stray optical photons from the [transducer](#) during operation.

"Microwave-to-optics transduction is a rapidly emerging technology with far-reaching implications for quantum computing. Our work demonstrates that transducers are now

ready to interface with superconducting qubit technology. This is an exciting and crucial demonstration, with the potential for this technology being far-reaching and potentially transformative for the development of quantum computers," says Dr. Thierry van Thiel, lead author of the work and Lead Quantum Engineer at QphoX.

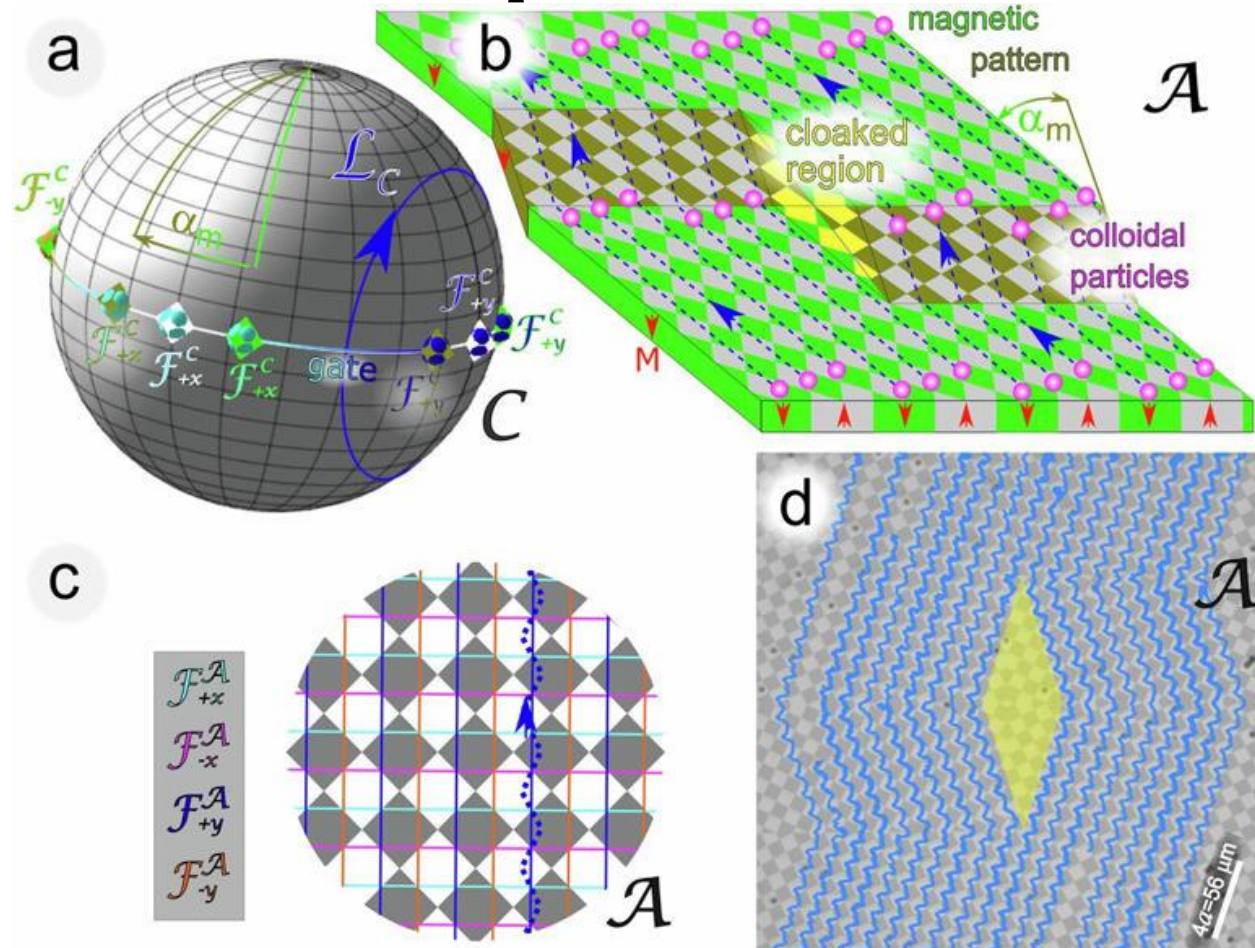
"Developing more efficient ways to design our systems is key as we work towards [fault tolerance](#). This innovative, scalable approach to qubit signal processing is the result of our strong partnerships with QphoX and Qblox and showcases the value of having a modular technology stack. By allowing our partners to integrate their technology with ours, we are able to discover creative ways to solve long-standing engineering challenges," says Dr. Subodh Kulkarni, Rigetti CEO.

"Realizing industrial-scale quantum computers comes with solving several critical bottlenecks. Many of these lie in the scalability of the readout and control of qubits. As Qblox is entirely focused on exactly this theme, we are proud to be part of this pivotal demonstration that shows that QphoX microwave-to-optical transducers are a solid route to scalable [quantum computing](#). We look forward to the next steps with Rigetti and QphoX to scale up this technology," says Dr. Niels Bultink, Qblox CEO.

More information: T. C. van Thiel et al, Optical readout of a superconducting qubit using a piezo-optomechanical transducer, *Nature Physics* (2025). DOI: [10.1038/s41567-024-02742-3](https://doi.org/10.1038/s41567-024-02742-3)

Journal information: [Nature Physics](#)
Provided by Rigetti Computing Inc.

Magnetic 'invisibility cloak' hides obstacles within particle streams



Cloaking by a twin boundary pattern. Credit: Nature Communications (2025). DOI: 10.1038/s41467-025-57004-4

Researchers at the University of Bayreuth have developed a method that makes objects on a magnetic field invisible within a particle stream. Until now, this so-called cloaking had only been studied for waves such as light or sound. They [report](#) their results in *Nature Communications*.

Making objects invisible is no longer a purely fictional idea from fantasy or sci-fi films. At least to some extent, cloaking also works in research: manipulating objects in such a way that they become invisible to certain waves such as light or sound.

The Bayreuth researchers are extending cloaking to particle motions. Cloaking for particle streams on miniaturized chemical laboratories, so-called lab-on-a-chip

devices, can help to transport active ingredients in a targeted manner without exposing them to undesirable premature chemical reactions.

Cloaking refers to a physical method that wraps an object in a kind of invisibility cloak, which makes it unrecognizable. So far, cloaking has only been studied with waves—such as light or sound waves. It involves guiding waves around an object or obstacle, much like water in a river flowing around a rock.

As a result, the waves reach their destination as if the obstacle were not there—so it becomes "invisible." Anna Rossi, Thomas Märker, Nico Stuhlmüller, Daniel de las Heras and Thomas Fischer from the Chair of Experimental Physics and Theoretical Physics at the University of Bayreuth have now developed a method to implement cloaking for particle motion.

The research team lets small particles, so-called colloids, flow in a magnetic field of a checkerboard pattern. The colloids are paramagnetic, so they only behave magnetically when they are near a magnet or an external magnetic field. Calculated changes of the magnetic field create areas on the chessboard that remain untouched by particle transport and thus become "invisible."

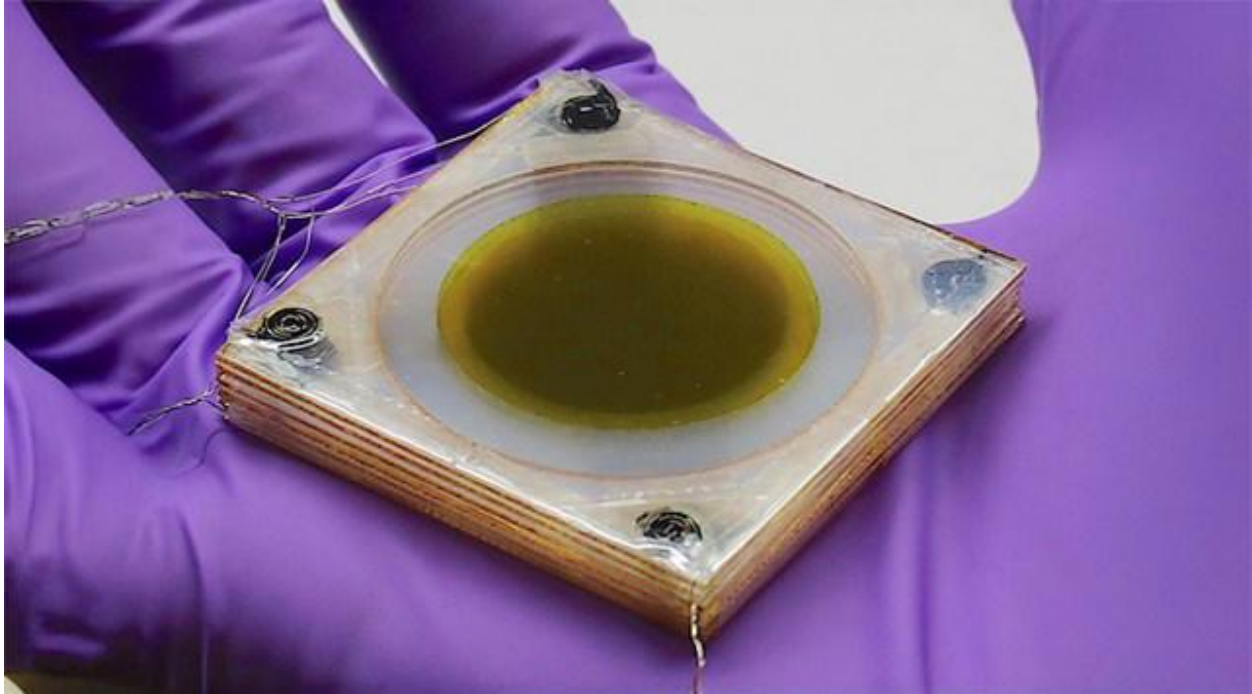
The cloaked areas alter the motion only while the colloids are circumventing the obstacle, but not after they have passed the cloak. The particles arrive at their destination at the same time as particles on the route without obstacles.

"We have also shown experimentally that if the obstacle shape is chosen correctly, the size of the obstacle does not matter—it can be any size, and the particles still arrive at their destination in time," says Ms. Rossi.

More information: Anna M. E. B. Rossi et al, Topologically cloaked magnetic colloidal transport, *Nature Communications* (2025). DOI: [10.1038/s41467-025-57004-4](https://doi.org/10.1038/s41467-025-57004-4)

Provided by Bayreuth University

Scientists develop ultra-futuristic clothing to combat 'critical health issue': 'The potential ... cannot be overstated'



scientists develop ultra-futuristic clothing to combat 'critical health issue': 'The potential ... cannot be overstated'

A breakthrough cooling device developed at UCLA drops temperatures by 16 degrees Fahrenheit without traditional air conditioning, reported [Tech Xplore](#).

This compact device, made of six thin polymer films, could soon power wearable [tech](#) that keeps you comfortable in hot weather while [saving money](#) on cooling costs.

The prototype can lower temperatures up to 25 degrees Fahrenheit at the heat source in just 30 seconds. [Traditional AC units](#) rely on energy-hungry vapor compression and use carbon dioxide coolants. This new technology runs only on [electricity](#), which can come from [solar panels](#) or other clean energy sources.

"Our long-term goal is to develop this technology for wearable cooling accessories that are comfortable, affordable, reliable and energy-efficient—especially for people who work in very hot environments over long hours," said

principal investigator Qibing Pei, a professor of materials science and engineering at the UCLA Samueli School of Engineering, per Tech Xplore.

"As average temperatures continue to rise with [climate change](#), coping with heat is becoming a critical health issue. We need a variety of solutions to the problem and this could be the basis for one."

The device works through a simple but intelligent design. Each layer is coated with carbon nanotubes. When electricity flows, the layers squeeze together in pairs. When it stops, they spring apart to press against neighboring layers. This accordion-like motion pumps heat away continuously.

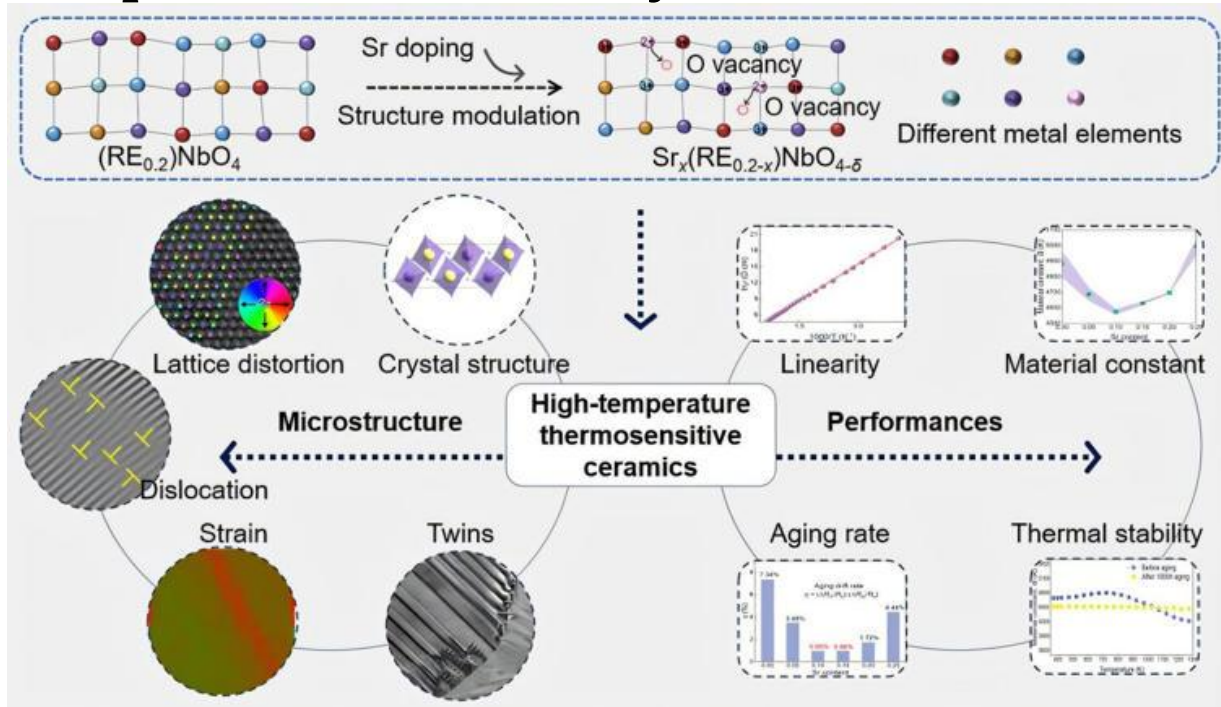
"The polymer films use a circuit to shuttle charges between pairs of stacked layers, which makes the flexible cooling device more efficient than air conditioners," said Hanxiang Wu, one of the study's co-lead authors and a postdoctoral scholar working in Pei's lab.

The technology could transform how we [stay cool](#).

"Because we can use thin flexible films, electrocaloric cooling would be most ideal for next-generation wearables that can keep us cool under strenuous conditions," Pei said. "It could also be used to cool electronics with flexible components."

The team has filed a patent application, bringing this innovation closer to consumer use. "The potential of efficient wearable cooling in driving energy savings and mitigating climate change cannot be overstated," said Sumanjeet Kaur, a materials staff scientist at Lawrence Berkeley National Laboratory and its Thermal Energy Group leader.

Researchers make progress in high-temperature thermally sensitive ceramics



Relationship between microstructure and properties of high-temperature thermosensitive ceramics. Credit: Prof. Chang Aimin's group

To meet the demands of extreme high-temperature environments, such as aerospace engines and thermal systems in new energy vehicles, high-temperature thermosensitive sensors need to demonstrate high stability and sensitivity.

Conventional materials often struggle with performance under these conditions, while emerging high-entropy materials offer superior thermal and chemical stability due to their entropy-stabilization effect. However, their strong lattice disorder reduces carrier mobility, leading to poor electrical transport performance and limiting the accuracy of resistance-temperature responses at high temperatures.

Thus, developing new thermosensitive materials that balance lattice stability and carrier transport efficiency is essential for enhancing high-precision sensing technologies.

To address this challenge, researchers from the Xinjiang Technical Institute of Physics and Chemistry of the Chinese Academy of Sciences, have successfully developed high-entropy thermosensitive ceramics based on rare-earth niobates (ReNbO_4 , where Re represents rare-earth elements) with fergusonite-type structures, using an oxygen vacancy regulation strategy.

The synergistic effect between entropy stabilization (induced by multi-component rare-earth ion doping at A-sites) and Sr^{2+} aliovalent doping significantly increases oxygen vacancy concentration, thereby optimizing the material's electron transport properties and lattice stability.

The study, [published](#) in *Small*, demonstrates that the oxygen vacancy-induced entropy stabilization strategy simultaneously modulates the material's microstructure, forming stabilized features such as twin domains, lattice distortions, and dynamic reconstruction, which effectively enhances both the linearity of the temperature-resistance response and high-temperature stability.

The synthesized material exhibits exceptional environmental adaptability (operable across a wide temperature range from 223 K to 1423 K), high thermal stability (with an aging drift of less than 1% after 1,000 hours of high-temperature aging), and a temperature coefficient of resistance (0.223 %/K at 1423 K), providing theoretical guidance for designing novel thermally sensitive ceramics for extreme environments.

More information: Hao Sun et al, Synergistic Entropy Engineering with Oxygen Vacancy: Modulating Microstructure for Extraordinary Thermosensitive Property in ReNbO_4 Materials, *Small* (2025). DOI: [10.1002/smll.202408952](https://doi.org/10.1002/smll.202408952)

Provided by Chinese Academy of Sciences

String theory is not dead yet

Scientists seeking the secrets of the universe would like to make a model that shows how all of nature's forces and particles fit together. It would be nice to do it with Legos. But perhaps a better bet would be connecting everything with strings.

Not literal strings, of course - but tiny loops or snippets of vibrating energy. And the "fit together" needs to be mathematical, not via properly shaped pieces of plastic. For decades now, many physicists have pursued the hope that equations involving an especially tiny "string" could provide the theory that solves nature's ultimate subatomic mysteries.

String theory, as it's called, has acquired a sort of fuzzy cultural acclaim, showing up in popular TV shows like *The Big Bang Theory* and *NCIS*. Among physicists, reaction to the theory has been mixed. After several promising bursts of discovery in the 1980s and '90s, strings fell somewhat out of favor for not delivering on their promises. Among those was providing the proper way to include gravity in the quantum theory of subatomic particles. Another was revealing the math that would show nature's multiple fundamental forces to be just different offspring of one unified force. Still promises unkept.

Yet during the time since string theory's retreat from the limelight, a considerable cadre of string devotees have labored to tie all the loose ends together. Success remains elusive, but real progress has been made. Questions plaguing physicists about not only the smallest bits of matter but also the properties of the entire universe may yet yield to string theorists' efforts.

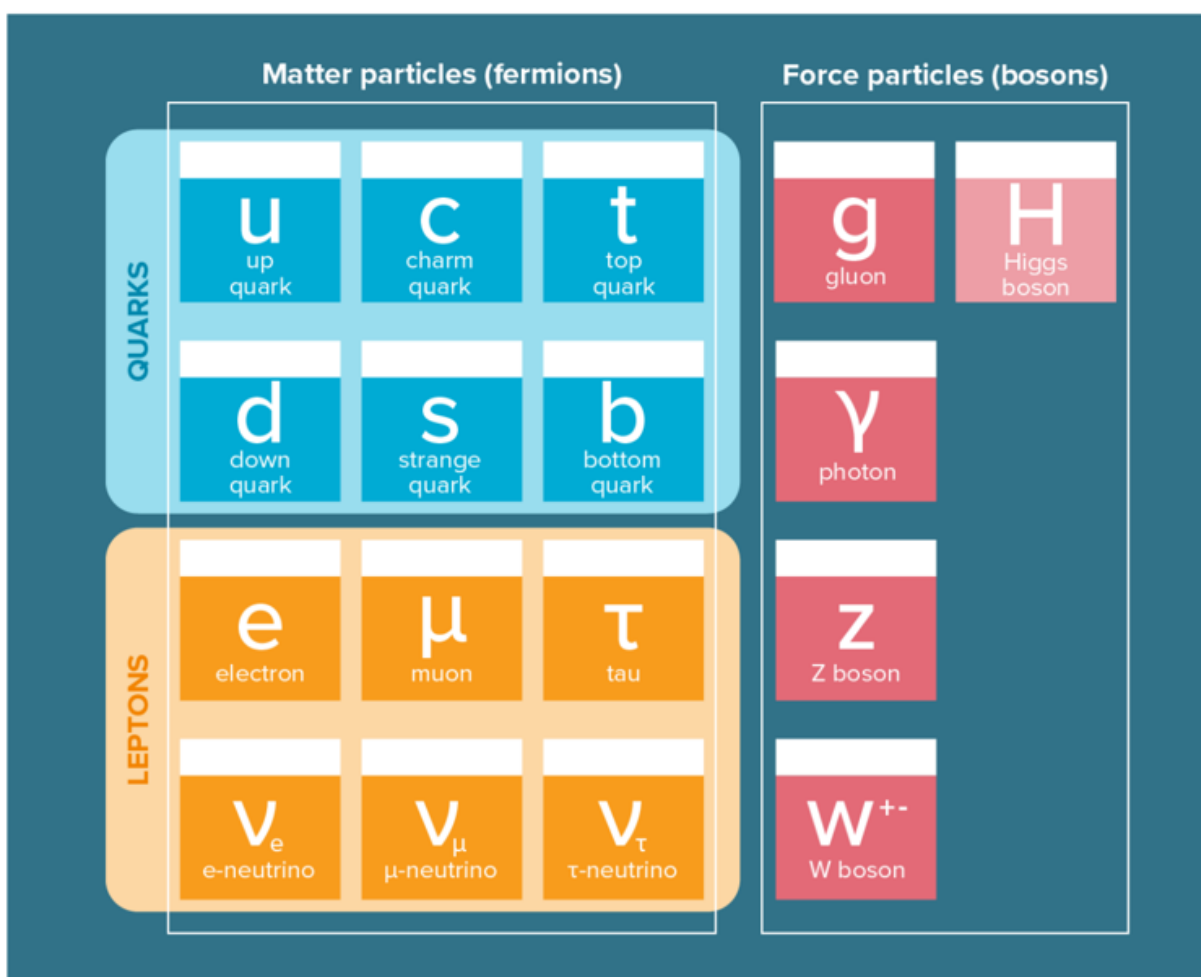
In Search Of The Theory Of Everything

"Many of the unsolved problems in particle physics and cosmology are deeply intertwined," write physicists [Fernando Marchesano](#), [Gary Shiu](#) and [Timo Weigand](#) in the 2024 [Annual Review of Nuclear and Particle Science](#). String theory may provide the path to solving those problems.

Reality's equations

One major approach in this quest is figuring out whether string theory can explain what is known as the Standard Model of particle physics. Developed in the last part of the 20th century, the Standard Model provides a sort of roster listing all of nature's basic particles. Some provide the building blocks of matter; others transmit forces between the matter particles, governing how they behave.

Standard Model of elementary particles



SOURCE: CERN

KNOWABLE MAGAZINE

The Standard Model of particle physics describes nature's known forces and subatomic particles. They include quarks, leptons and bosons. Protons and neutrons are composed of up and down quarks. Leptons include electrons and neutrinos. Photons transmit the electromagnetic force; gluons hold particles together in the atomic nucleus; and W and Z particles transmit the weak nuclear force, important for some forms of radioactivity. The Higgs boson is involved in conferring some particles with mass. Credit: CERN

It's pretty simple to draw a chart displaying those particles. You need 12 spots for matter particles - six quarks and six leptons. You need four spots for force particles (collectively known as bosons) plus a spot for the Higgs boson, a particle needed to explain why some particles have mass. But the mathematics underlying the chart is unfathomably complex, a combination of equations that make hieroglyphics seem self-explanatory.

Those equations work superbly for explaining the results of virtually all particle physics behavior. But the Standard Model cannot be the whole story of the universe. "Despite the incredible success of the Standard Model in describing the observed particle physics up to the currently accessible energy scales, there are compelling arguments for why it is incomplete," Marchesano and collaborators write.

For one thing, its equations do not encompass gravity, which has no spot on the Standard Model chart. And Standard Model math leaves many questions unanswered, such as why some of the particles have the precise masses that they do. Standard Model math also does not include the mysterious dark matter that lurks within and between galaxies, nor does it explain why empty space is infused with [a form of energy that causes the universe to expand](#) at an accelerating rate.

Some physicists investigating these problems believe that string theory can help, since a string version of the Standard Model will contain additional math that could account for its shortcomings. In other words, if string theory is correct, the Standard Model would be just one segment of string theory's full mathematical description of reality. The problem is that string theory describes many different versions of reality. That's because the strings exist in a realm with multiple dimensions of space beyond the ordinary three. Kind of like the Twilight Zone on steroids.

String theorists concede that daily life proceeds just fine in a three-dimensional world. Therefore, the extra dimensions of the string world must be too small to notice: They have to shrink, or "compactify," into submicroscopic size. It's like the way an ant living on a vast sheet of paper would perceive a two-dimensional surface without ever realizing the paper had a third, very small dimension.

Not only must string theory's extra dimensions shrink, but they also can shrink into innumerable different configurations, or geometries, of the vacuum of space.

One of those possible geometries might be the right shape of the shrunk dimensions to explain the properties of the Standard Model.

"Standard Model ... features, questions, and puzzles can be reformulated in terms of the geometry of extra dimensions," Marchesano and collaborators write.

Because string theory math can be expressed in several different forms, theorists have to explore multiple possible avenues to find the most fruitful formulation. So far, string approaches have been found that describe many features of the Standard Model. But different compactification geometries of the vacuum are needed to explain each feature. The challenge, Marchesano and colleagues point out, is to find one geometry for the vacuum that combines all those features at once, while also incorporating features that describe the known universe.

A successful compactification of the extra dimensions, for instance, would produce a vacuum in space that contained the right amount of "dark energy," the source of the universe's accelerating expansion. And candidates for the cosmic dark matter should appear in the string math as well. In fact, a whole additional set of force and matter particles emerges from string equations involving a mathematical property called supersymmetry. "Almost all string theory models that resemble the Standard Model display supersymmetry at the compactification scale," write Marchesano and his coauthors.

Versions of string theory containing supersymmetric particles go by the moniker "superstring theory." Such "superparticles" have long been suspected of comprising the universe's dark matter. But attempts to detect them in space or create them in particle accelerators have so far been unsuccessful.

As for gravity, particles conveying the gravitational force appear naturally in string theory math - one of the theory's big attractions to begin with. But the fact that many formulations of string theory include gravity does not tell you which formulation provides the correct description of the real world.

Tests are possible

If string theory is correct, [fundamental particles of nature](#) would not be the zero-dimensional pointlike objects of standard theory. Instead, different particles would result from different modes of vibration of a one-dimensional string, either

a loop or a snippet with ends attached to multidimensional spatial objects called branes. Such strings would roughly be smaller than an atom to the extent that an atom is smaller than the solar system. Very small, with no feasible way of detecting them directly. The amount of energy needed to probe scales so tiny is far beyond the reach of any practical technology.

But if string theory can account for the Standard Model, it would also contain other features of reality that would be accessible to experiments, such as types of particles not included on the Standard Model chart. "String constructions that realize the Standard Model always contain additional sectors ... at an energy scale that could be tested in the near future," Marchesano and colleagues write.

Ultimately, string theory remains a hopeful candidate for putting all the pieces of the cosmic puzzle together. If it works out, scientists could finally unravel the mysteries about how quantum physics' relation to gravity, and the properties of nature's particles and forces, are all deeply linked. "String theory," write Marchesano and colleagues, "has all the ingredients to help us understand this profound connection."

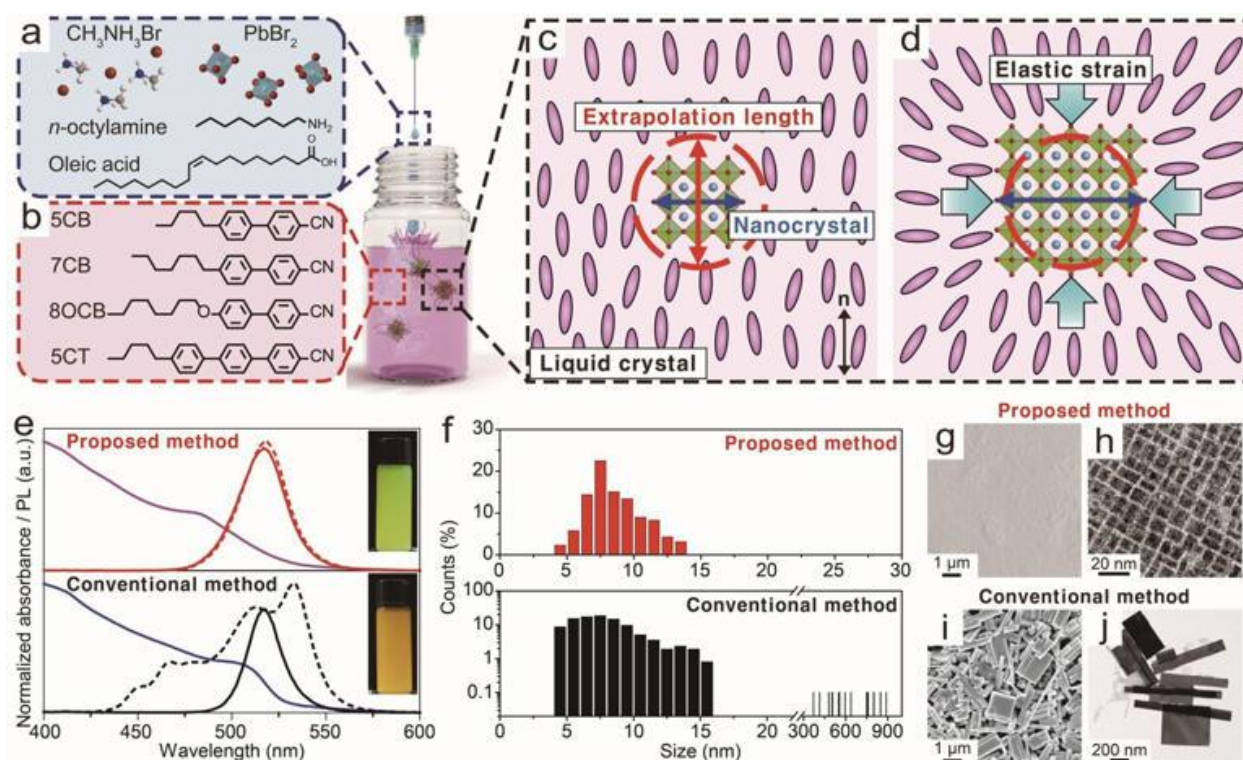
[10.1146/knowable-112124-2](https://www.knowable-magazine.com/10.1146/knowable-112124-2)

Tom Siegfried is a science journalist in Avon, Ohio. His book [The Number of the Heavens](#), about the history of the multiverse, was published in 2019 by Harvard University Press.

This article originally appeared in [Knowable Magazine](#), an independent journalistic endeavor from Annual Reviews. Sign up for the [newsletter](#).

The post [String theory is not dead yet](#) appeared first on [Astronomy Magazine](#).

Liquid crystal method enables large-scale production of uniform perovskite nanocrystals



(a-d) Schematic illustrations of controlled synthesis of perovskite nanocrystals in a liquid crystalline antisolvent and (e-j) the corresponding results. Credit: POSTECH

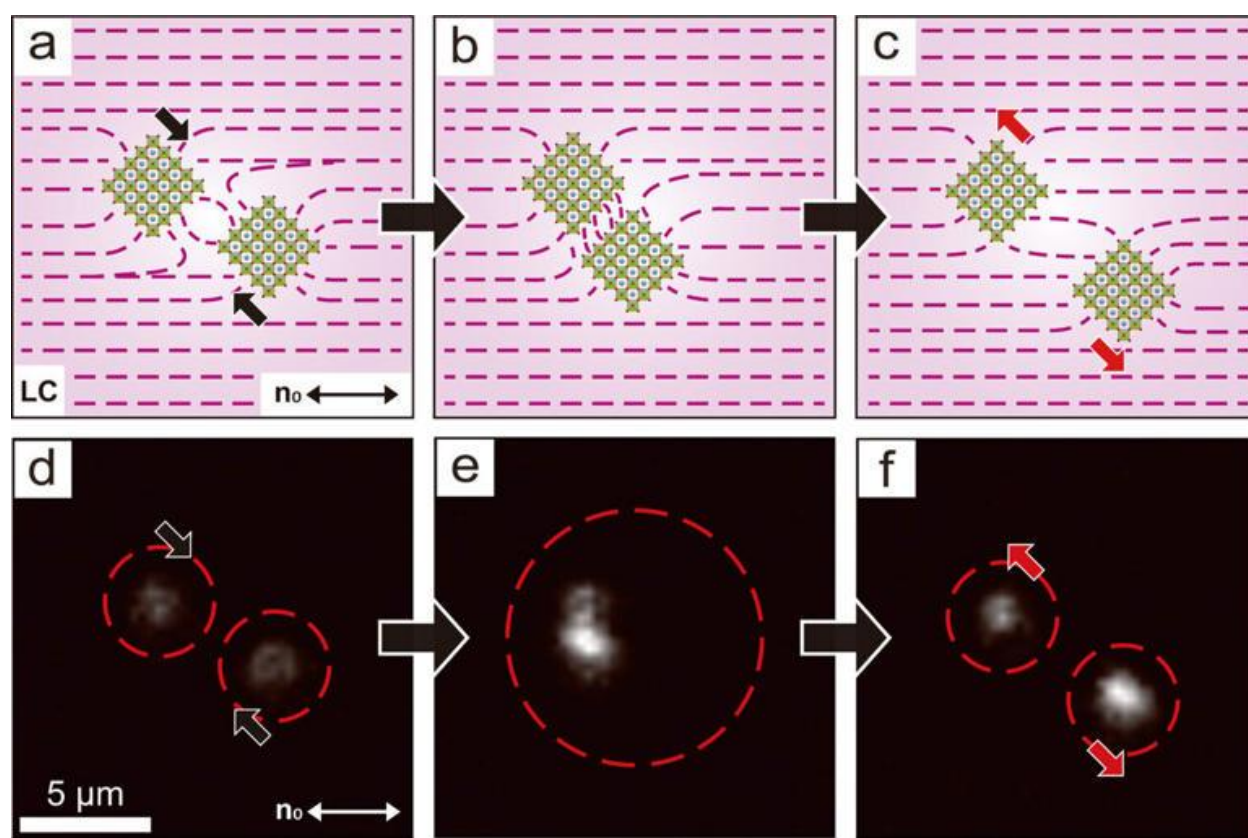
A research team at POSTECH has developed a method for synthesizing perovskite nanocrystals (PNCs), a next-generation semiconductor material, in a more uniform and efficient manner. This study is expected to serve as a key breakthrough in overcoming the complexities of conventional synthesis methods and accelerating the commercialization of various optoelectronic devices, such as light-emitting diodes (LEDs) and solar cells, that utilize nanocrystals.

This study was conducted by Professor Young-Ki Kim and Professor Yong-Young Noh from the Department of Chemical Engineering at POSTECH, along with Ph.D. candidate Jun-Hyung Im, Dr. Myeonggeun Han (Samsung Electronics), and Dr. Jisoo Hong (Princeton University). The research was recently [published](#) in *ACS Nano*.

PNCs have great potential in next-generation solar cells and high-efficiency displays, as their ability to absorb and emit light can be precisely controlled based on particle size and shape through the quantum confinement effect.

However, conventional methods used to synthesize PNCs such as hot-injection and ligand-assisted reprecipitation (LARP) have limitations in producing uniformly sized and shaped particles due to high synthesis temperatures and complex experimental conditions. As a result, additional processing steps were required to obtain particles with the desired properties, which in turn reduced productivity and restricted industrial applications.

The POSTECH research team has developed a synthesis method that precisely controls the size and shape of PNCs using a liquid crystal (LC) as an antisolvent in the LARP method. LC is an intermediate phase of matter that possesses both liquid-like fluidity and crystal-like long-range molecular ordering. In LC phases, molecules are aligned to a preferred orientation (defined by the director), which leads to elasticity. Therefore, when an external force is applied to an LC medium, LC molecules are reoriented, producing considerable elastic strains.



Elastic interactions of PNCs in LC media. Schematic illustrations describing the elastic interaction associated with the (a, b) attraction and (c) repulsion of PNCs in LC media. In situ fluorescence confocal microscopy (FCM) images of elastic interactions of PNCs in LC media, where LC molecules are aligned along the x-axis. FCM images are measured at (d) 0, (e) 166, and (f) 258 s. n_0 indicates the far-field director of LCs. Credit: ACS Nano (2025). DOI: 10.1021/acsnano.4c13217

Inspired by this property, the team precisely controlled the growth of PNCs by simply replacing the antisolvent in the conventional LARP method with LC while maintaining the other synthesis conditions. The elastic strains of LCs restricted the growth of PNCs upon reaching the extrapolation length (ξ) of LCs, enabling mass production of uniformly sized PNCs without the need for additional purification processes.

The research team also discovered that the interaction between ligands binding to the surface of PNCs and LC molecules plays a crucial role in reducing surface defects. Since LC molecules have a long, rod-like structure, ligands can be densely arranged between them. As a result, ligands bind more densely to the surface during nanocrystals formation, thereby minimizing surface defects and enhancing luminescence properties.

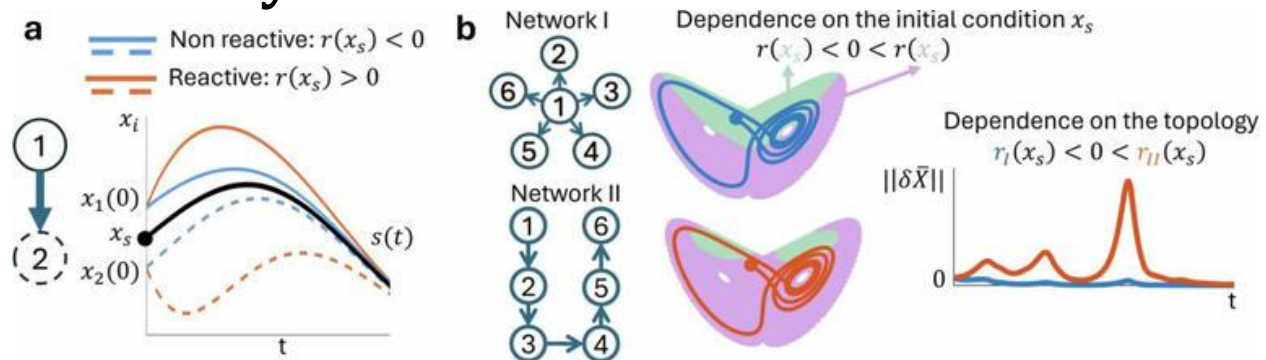
Professor Kim explained, "The synthesis method developed by our research team is highly compatible with existing synthesis techniques, such as ligand exchange and microfluidic synthesis, and will enhance the performance of various optoelectronic devices, including LEDs, solar cells, lasers, and photodetectors.

"This technology enables the large-scale production of uniform, high-performance nanocrystals at room temperature, and we anticipate it will help accelerate the commercialization of nanocrystal-based optoelectronic devices."

More information: Jun-Hyung Im et al, Controlled Synthesis of Perovskite Nanocrystals at Room Temperature by Liquid Crystalline Templates, *ACS Nano* (2025). DOI: [10.1021/acsnano.4c13217](https://doi.org/10.1021/acsnano.4c13217)

Provided by Pohang University of Science and Technology

From fireflies to drones: Researchers uncover strategy for synchronization efficiency



The reactivity of the synchronization dynamics of networks. Credit: Nature Communications (2024). DOI: 10.1038/s41467-024-52486-0

Researchers from The University of New Mexico School of Engineering looked to the natural world to explain how synchronized systems can work more efficiently and made a significant discovery. Their results were [published](#) in the journal *Nature Communications*.

Francesco Sorrentino, professor in the Department of Mechanical Engineering, and Amirhossein Nazerian, Ph.D. candidate in Mechanical Engineering, explored the mathematics of synchronization and uncovered that biological systems use different, distinct stages during oscillation to work more efficiently.

The results are described in a publication titled "The efficiency of synchronization dynamics and the role of network syncreactivity."

"In terms of energy that is required for connected systems of oscillators to synchronize, our strategy shows we can have several orders of magnitude in energy savings," Nazerian said.

Synchronization of coupled systems occurs frequently in nature, from the connection between the heart and the lungs to the collaborative flickering of a group of fireflies. Lessons from these biological systems could improve the design and management of power grids, drones and other technology by allowing them to preserve energy during oscillation.

"We looked at this from a mathematical point of view and asked how systems in nature, in the human body, and in ecological and social systems synchronize. In nature, efficiency is very important, whether in animals or in cells, as these systems cannot afford to waste energy," Sorrentino said.

Many papers have explored synchronization through the lens of stability, but the authors believe there has not been research emphasizing efficiency and studying the stages of oscillation until now. The discovery also reveals opportunities for improved coupling, or communication, between components in an oscillating system.

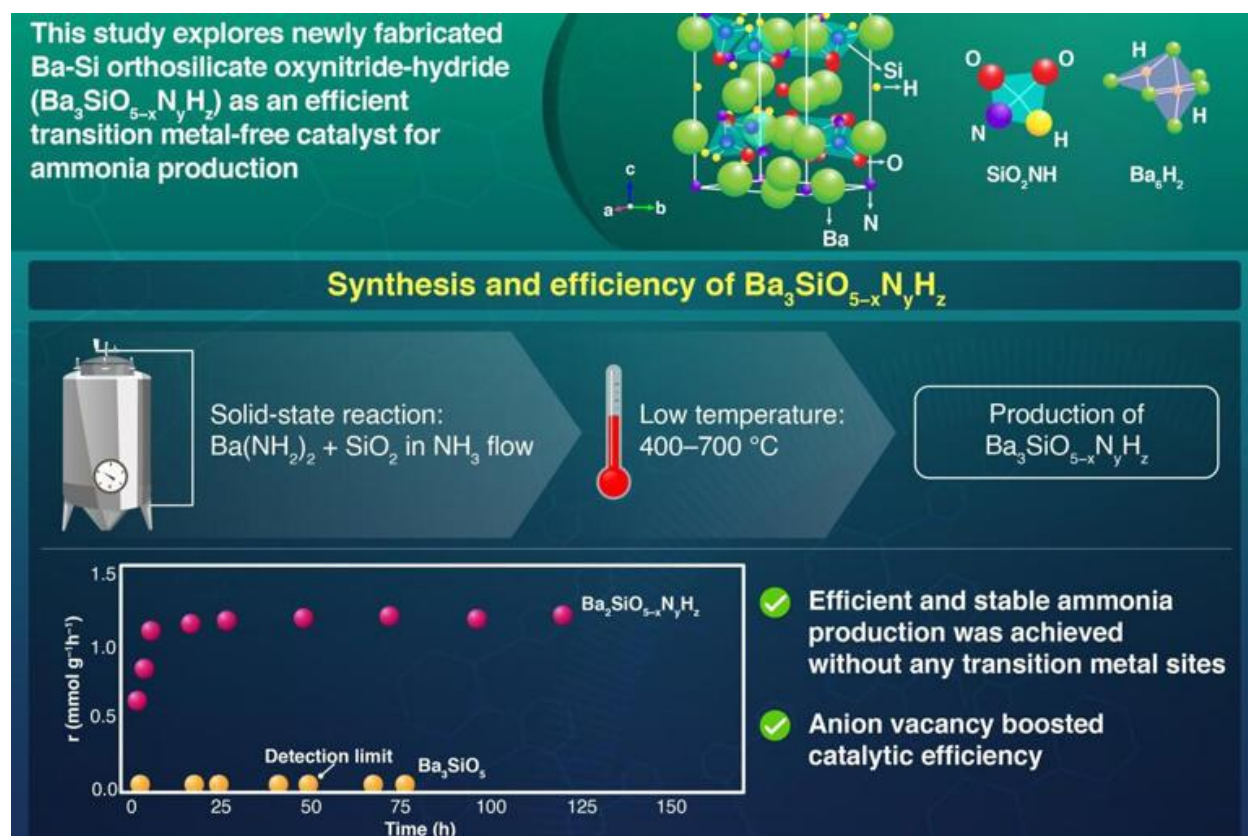
Understanding the varied stages of oscillation allows scientists to manipulate the coupling strength by strongly reducing energy expenditure. The UNM team and Matteo Lodi at the University of Genoa conducted the theoretical elements of the study, then their collaborator Joseph Hart at the U.S. Naval Research Lab validated their results with experiments.

The strategy published by the team involves adapting the coupling strength based on the stage of oscillation of the system. The results indicate that the energy expenditure required for synchronization can be reduced if coupling between the oscillating systems is only activated when needed.

More information: Amirhossein Nazerian et al, The efficiency of synchronization dynamics and the role of network syncreactivity, *Nature Communications* (2024). DOI: [10.1038/s41467-024-52486-0](https://doi.org/10.1038/s41467-024-52486-0)

Provided by University of New Mexico

Transition metal-free catalyst promises greener, efficient ammonia synthesis



This synthesis temperature is much lower than the synthesis temperatures (1100–1400 °C) of conventional silicate materials such as Ba_3SiO_5 , $\text{Ba}_3\text{Si}_6\text{O}_9\text{N}_4$, and $\text{BaSi}_2\text{O}_2\text{N}_2$. The synthesized $\text{Ba}_3\text{SiO}_{5-x}\text{N}_y\text{H}_z$ demonstrated exceptional stability as a catalyst for ammonia synthesis even in the absence of any transition metal sites.

It showed higher activity and lower activation energy than the conventional ruthenium-loaded MgO catalyst. On the other hand, Ba_3SiO_5 , $\text{Ba}_3\text{Si}_6\text{O}_9\text{N}_4$, and $\text{BaSi}_2\text{O}_2\text{N}_2$ exhibited no catalytic activity.

The $\text{Ba}_3\text{SiO}_{5-x}\text{N}_y\text{H}_z$ catalyst's ammonia synthesis activity was tested under varying temperatures and pressures, and structural properties were analyzed using advanced instrumentation techniques.

To further improve performance, ruthenium nanoparticles were introduced. The researchers found that $\text{Ba}_3\text{SiO}_{5-x}\text{N}_y\text{H}_z$ showed the highest catalytic activity with ruthenium nanoparticles.

"The addition of ruthenium nanoparticles significantly boosted catalytic performance, enabling more efficient ammonia synthesis under milder conditions. However, the main active site is not ruthenium nanoparticles but the anion vacancy sites on $\text{Ba}_3\text{SiO}_{5-x}\text{N}_y\text{H}_z$, which reduces the apparent energy requirement for ammonia synthesis than conventional catalysts. We also discovered that the anion vacancy-mediated mechanism played a key role in facilitating nitrogen activation, without relying on transition metals," says Kitano.

These findings suggest a more sustainable and energy-efficient path for ammonia synthesis.

The study highlights key benefits: reduced temperature and pressure enhance efficiency, while the transition metal-free pathway cuts emissions and resource dependence, supporting sustainability.

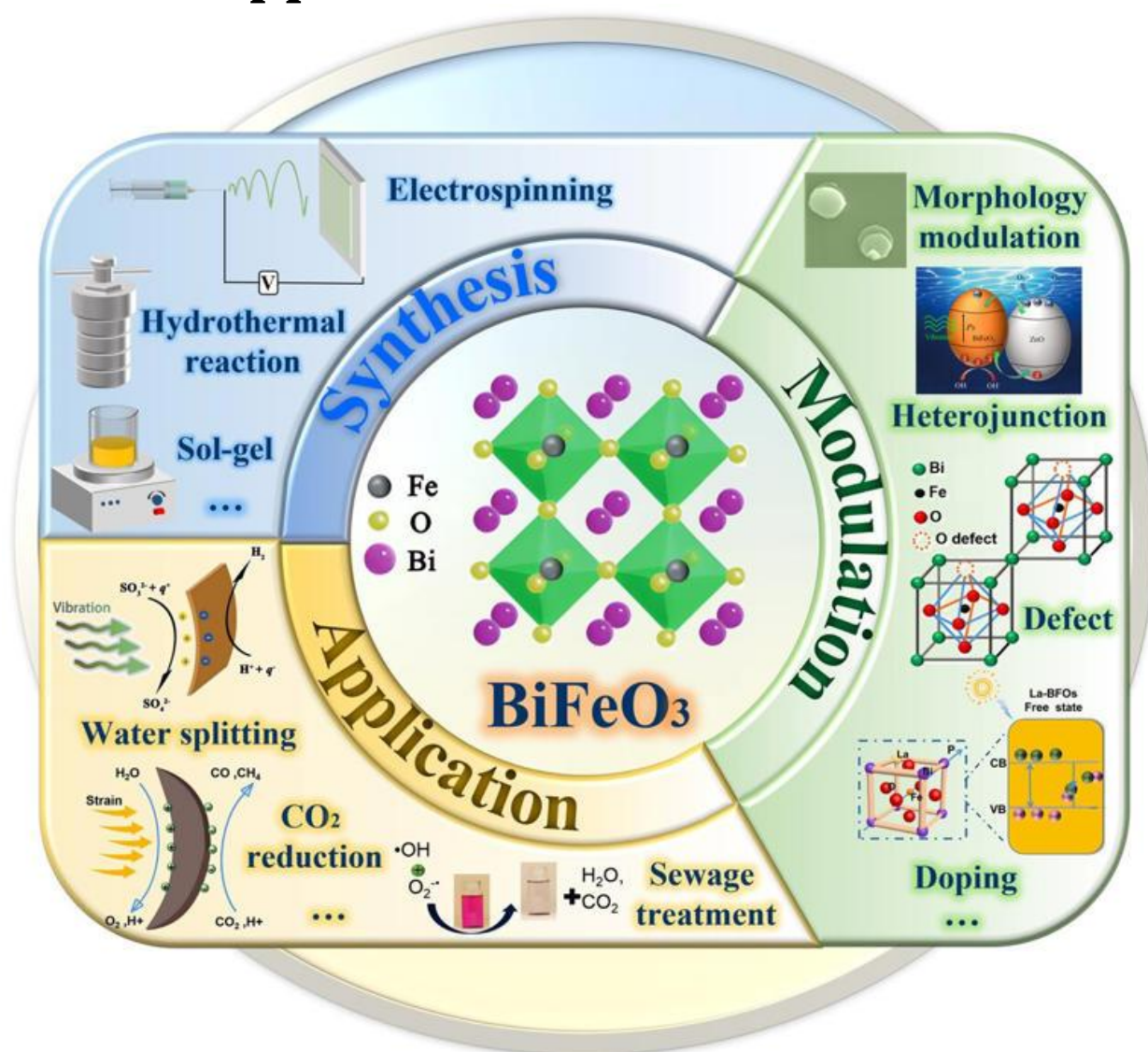
Furthermore, the scalable synthesis and robust performance of $\text{Ba}_3\text{SiO}_{5-x}\text{N}_y\text{H}_z$ catalysts position them as promising candidates for industrial adoption, offering a more sustainable approach to ammonia production at scale. These findings also open avenues for further research in transition metal-free catalysis for other critical processes.

This study represents a significant step toward sustainable ammonia synthesis, addressing a major challenge in industrial chemistry. By demonstrating the potential of the $\text{Ba}_3\text{SiO}_{5-x}\text{N}_y\text{H}_z$ catalyst, the researchers have laid the foundation for a greener and more efficient approach to producing ammonia, an essential chemical.

More information: Zhujun Zhang et al, Anion vacancies activate N_2 to ammonia on Ba–Si orthosilicate oxynitride-hydride, *Nature Chemistry* (2025). DOI: [10.1038/s41557-025-01737-8](https://doi.org/10.1038/s41557-025-01737-8)

Provided by Institute of Science Tokyo

Exploring BiFeO_3 's piezocatalytic potential: From materials engineering to diverse applications



This review provides a systematic overview of recent progress in BFO-based piezocatalysis, highlighting the structural characteristics, synthesis methods, performance optimization strategies, and diverse applications. Credit: Journal of Advanced Ceramics, Tsinghua University Press

Materials scientists have long been exploring advanced materials for environmental and energy applications, with piezocatalysis emerging as a promising technology for sustainable solutions. BiFeO_3 (BFO), a versatile material known for its unique piezoelectric, multiferroic, and optical properties, has

garnered significant attention for its potential in piezocatalysis, specifically for organic pollutant degradation, hydrogen production, CO₂ reduction, and sterilization.

Despite the progress in BFO research, challenges related to its performance optimization and mechanistic understanding persist. A recent review paper by a team of researchers from Harbin Institute of Technology, led by Professor Dawei Wang, presents a comprehensive analysis of BFO-based piezocatalysis, shedding light on its structural features, synthesis methods, optimization strategies, and diverse applications.

The paper, [published](#) in *Journal of Advanced Ceramics*, offers an in-depth discussion of the piezocatalytic mechanisms, including energy band theory, screening charge effects, and displacement current theory, providing new insights into how the piezoelectric effect influences the redox processes during catalytic reactions.

"The multifaceted properties of BFO, coupled with its high piezoelectric performance, make it a highly promising candidate for piezocatalysis. Given the recent attention to BFO and its remarkable performance across various piezocatalytic applications, a comprehensive review of BFO in piezocatalysis is essential to drive further advancements and inspire the development of highly efficient BFO-based piezocatalytic systems," said Dawei Wang, professor at Harbin Institute of Technology, whose research focuses on advanced electronic ceramics and their applications in energy conversion.

In this review, the authors also address the previously underestimated ferroelectric polarization effect of BFO, particularly in CO₂ reduction, and provide a critical evaluation of its role in enhancing piezocatalytic activity. "This review bridges the gap between theoretical and practical applications of BFO in piezocatalysis, offering new perspectives on optimizing BFO-based systems for future applications," Wang added.

The review further explores the challenges associated with large-scale production, performance enhancement, and the need for better mechanistic understanding to push BFO-based piezocatalysis toward more efficient and sustainable systems. It also outlines the future directions of research, including the optimization of BFO synthesis methods, enhancement of piezoelectric

properties, and addressing the real-world challenges for practical piezocatalytic applications.

"This comprehensive review not only provides an understanding of BFO's role in piezocatalysis but also sets the stage for future research to harness its full potential for environmental and energy applications," said Wang.

The work highlights the growing potential of BFO in piezocatalysis, offering both foundational insights and a roadmap for advancing high-efficiency piezocatalytic systems in the future.

Other contributors include Jian Dai, Zhenhao Fan, Hang Xie, Fu Huang, Yunfei Chang from the School of Instrumental Science and Engineering at Harbin Institute of Technology in Harbin, China; Yitao Jiao from the Institute of Applied Physics and Materials Engineering at University of Macau, in Macau, China; a Ahmad Azmin Mohamad from the School of Materials and Mineral Resources Engineering at Universiti Sains Malaysia in Malaysia; Yangke Long from Shenzhen Institute of Information Technology in Shenzhen, China.

More information: Jian Dai et al, Versatile BiFeO₃ Shining in piezocatalysis: From materials engineering to diverse applications, *Journal of Advanced Ceramics* (2025). DOI: [10.26599/JAC.2025.9221046](https://doi.org/10.26599/JAC.2025.9221046)

Provided by Tsinghua University Press

Beyond the speed of light: The strange particle that could reshape the laws of the Universe

As much as we want to tell Mr Sulu to “Take us to warp factor five”, dangerous causality problems, tricky maths and negative energy could get in the way.

Published: February 20, 2025

We've all seen it so often in science-fiction movies that the concept seems utterly plausible: a character enters a command and their starship leaps to warp speed, jumps to hyperspace, or creates a wormhole through space and time.

Whatever the terminology, the result is always the same: they fly through their fictional universe faster than the speed of light, making travel between star systems not only possible, but practical.

In the real Universe that we inhabit, however, a gigantic barrier appears to forbid this. According to Albert Einstein's Special Theory of Relativity, nothing can travel faster than [light](#).

Light travels at a tremendous speed of approximately 3×10^8 metres per second. This means that when we look out into the Universe, we don't see celestial objects as they currently appear – we see how they appeared when the light from them first set out across space.

Within the [Solar System](#), those delays are relatively short. For example, it takes sunlight just over a second to bounce off the surface of the Moon and reach Earth, but it needs eight minutes to cover the distance between [the Sun](#) and our world.

Because of its immense distance from us, if the Sun were to suddenly disappear, we wouldn't notice until eight minutes later - Photo credit: Getty

The further out we look, the longer the delays become and this gives rise to the concept of the light-year as a measure of distance. The nearest star to us, Proxima Centauri, is roughly

4.25 light-years away, meaning that it takes light 4.25 years to get from there to here. Hence, we see the star not as it appears now, but as it was 4.25 years ago.

Across the vast expanse of the Universe, distances are eventually measured in billions of light-years. This is what makes cosmology possible: the further we look into the Universe, the more ancient the objects that we see are, allowing us to chart their [evolution](#) into the stars and galaxies of today.

Wouldn't it be great, though, if we could just travel there and see what those objects look like right now?

As appealing as having a warp drive might sound, there would be some pretty weird consequences. For one thing, it would mess with the concept of causality.

Causality is our common-sense perception that cause precedes effect. But if you watched a faster-than-light spaceship travel towards you, you would see the ship in two places at once. The light carrying the information of the ship's departure wouldn't have arrived at your [eyes](#) before you saw the ship on its way.

Worse still, according to the mathematics of relativity, if velocities exceed the speed of light, then literal time travel becomes possible.

This would give rise to the possibility of full-blown causal paradoxes such as the well-known 'grandfather paradox', in which you travel back in time and kill your own grandfather, thus preventing the possibility of your own birth. And how would that work – would you just cease to exist?

The negative energy within

At first glance, Einstein's theories appear to protect us from such head-melting conundrums because they seem to make it impossible to travel faster than light – so-called 'superluminal motion'.

According to the equations, the energy required to accelerate a ship to such speeds would be infinite. But then researchers began to look more closely at the maths.

In General Relativity – Einstein’s extension of his Special Relativity – he proposed the Universe is made of a malleable fabric, termed the space-time continuum, and he explained [gravity](#) as being warps in this fabric.

No one knows if tachyons exist, but if they do, theory suggests they'd travel faster than light. - Image credit: Science Photo Library

In 1994, physicist [Dr Miguel Alcubierre](#) at the University of Wales, Cardiff, showed that a solution existed within General Relativity that could be interpreted as a warp drive. The trouble was that making it work required an exotic substance known as ‘negative energy’.

Astronomers have since toyed with using the concept of negative energy to explain why the expansion of the Universe appears to be accelerating, but our understanding of physics doesn’t allow for the substance to comfortably exist.

Then, in May 2024, [a group of researchers re-examined the maths](#) to see if they could produce the Alcubierre warp phenomenon using only the kinds of particles and energy that make up planets and people.

Their conclusion: yes, they could. [Dr Jared Fuchs](#) and colleagues at the University of Alabama in Huntsville, in the US, found that they could arrange ordinary matter and energy to create the warp phenomenon and transport people through space. But there was a catch: they could only get it to work at sub-light speed.

“You need a lot of energy to make any small change in space,” says Fuchs. To move a passenger compartment the size of a small room would require a ‘warp bubble’ the size of a small house. And to make that would require squeezing a few times the mass of Jupiter into a volume the size of a small asteroid.

“Now, [is that] possible? Maybe. [Is it] practical? I wouldn’t say so,” says Fuchs. Even if it were possible to make such a device, the old boundary still exists: accelerating it faster than the speed of light would require an infinite amount of energy.

“It’s not going to solve the Star Trek-like future of rapid transport,” Fuchs admits.

The trouble with tachyons

Other researchers are conducting their own investigations into relativity. [Prof Andrzej Dragan](#) and collaborators at the University of Warsaw, Poland, decided to look at possible solutions within Einstein’s equations for particles travelling faster than light.

Physicists have toyed with such concepts before. They even called such hypothetical particles ‘tachyons’, but they essentially regarded them as little more than mathematical curiosities. But Dragan and colleagues found equations to describe tachyon behaviour.

“Mathematically, they make perfect sense,” says Dragan. In other words, our familiar world of subluminal particles could be coexisting with a second family of superluminal ones: the tachyons.

Unfortunately, this still doesn’t mean that you can accelerate a spacecraft to speeds faster than light. To do that, Dragan explains that it would still take the infinite amount of energy that Einstein predicted, as well as an infinite amount of energy to slow a tachyon down to subluminal speeds.

“It wouldn’t be possible to cross the speed of light in either direction,” says Dragan.

Nevertheless, [the research](#) did suggest some fascinating consequences that might explain some of the most puzzling observations that physicists grapple with.

When dealing with the tachyons, Dragan and co-workers ran into the causality problems they had expected. But the more they investigated the details of these, the more they realised something amazing was taking place: the lack of strict cause and effect began to look a lot like the behaviour of our normal everyday subatomic particles.

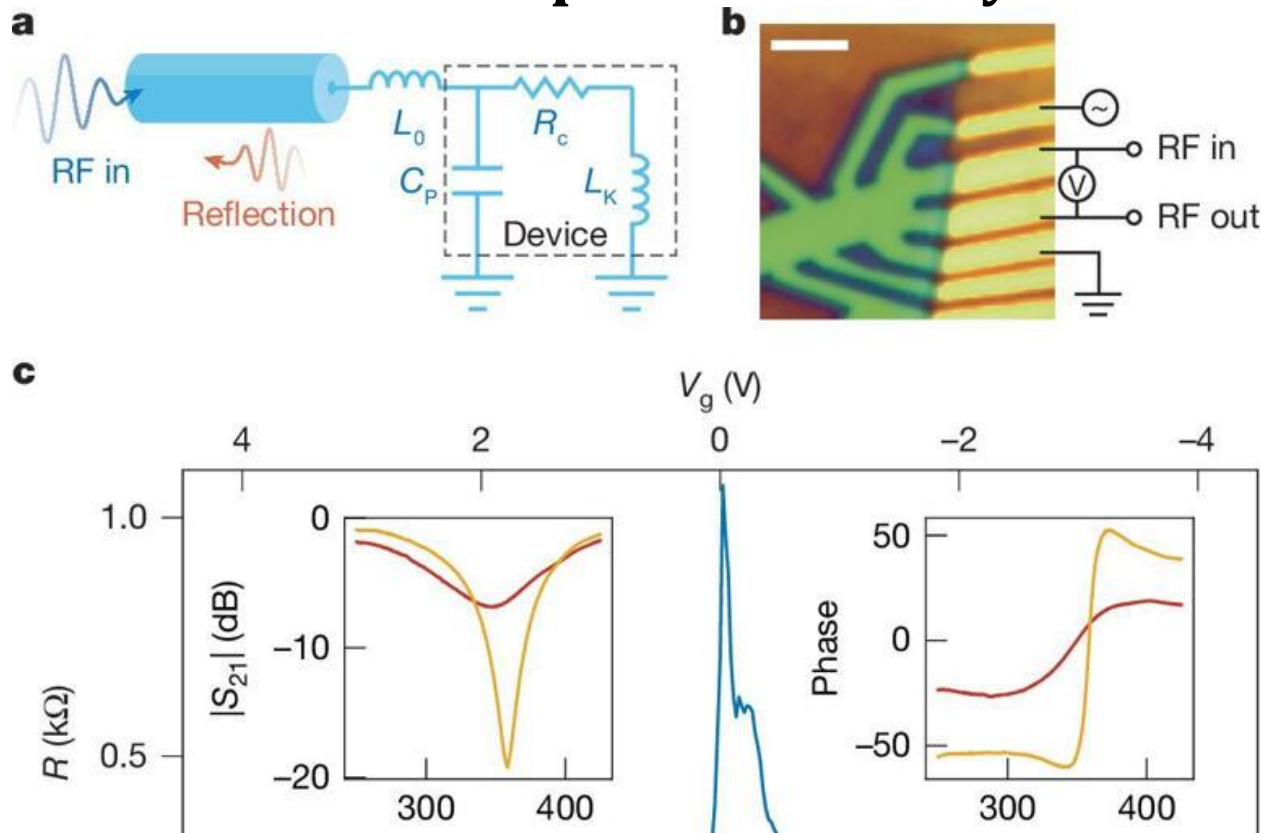
While relativity describes the behaviour of the Universe on its largest scales, [quantum theory](#) describes the subatomic realm as a very different place.

Quantum theory introduces probability into particle interactions. For example, an atom can absorb a photon of light, and while you know it'll re-emit that photon at some stage, you can't predict when and in what direction it'll go.

In other words, the exact cause is hidden from us and all we're left with is an observable effect. Dragan suggests that if a tachyon were to interact with ordinary matter, the outcome of that interaction would be unpredictable – rather like the emission of a photon.

So, while these latest ideas don't seem to open up a route to practical warp drives, they may just be showing us something deeper about the nature of the cosmos and the origins of quantum behavior.

Searching for a universal principle for unconventional superconductivity



Experimental set-up and device characterization. Credit: Nature (2025). DOI: 10.1038/s41586-024-08444-3

You may recognize graphite as the "lead" in a pencil, but besides helping you take notes or fill in countless bubbles on exam answer sheets, it is helping scientists grapple with the secrets of superconductivity.

Superconductivity happens when an electric current is transmitted through wires without the loss of any energy in the form of heat or resistance. Superconducting materials have the potential to revolutionize many aspects of our daily lives, from improving the electrical grid to making more powerful computers.

However, superconductivity generally requires very low temperatures, so low they may become impractical, and the exact mechanisms of superconductivity are not well understood for many superconducting materials.

In their recent [publication](#) in *Nature*, a collaboration of researchers, including UConn Department of Physics Professor Pavel Volkov, detail surprising findings about superconductivity in twisted trilayer graphene.

In 2018, attention focused on the rich physics of superconductivity in multilayer graphene, which is a single layer of carbon atoms. As a single layer, graphene is not superconducting; however, this changes when two layers are stacked and slightly twisted to form twisted bilayer graphene (TBG). Stacking three layers to make twisted trilayer graphene (TTG) together makes the system more stable and robust and was the subject for much of this study.

The twist leads to unique and unconventional superconducting properties in the twisted trilayer graphene. Volkov says that at a so-called "magic" twist angle, quantum interference effects lead to the motion of electrons slowing down enormously as they move through the layers of graphene, allowing them to interact much more strongly with one another, which is likely the driving force of superconductivity.

"A number of observations on twisted trilayer graphene are quite similar to another system of immense interest where interactions are strong—the cuprate high transition temperature superconductors. We're interested in it fundamentally because we don't quite understand how this works," Volkov says.

Indeed, the famous theory of Bardeen, Cooper and Schrieffer, published in 1957, is known to fit many well-known superconductors, Volkov explains. Their theory attributes superconductivity to the electrons forming "Cooper pairs" due to interaction with lattice vibrations. However, it does not match the observations for cuprates and several other material classes, which have since earned the name of "unconventional" superconductors.

Some of them, like cuprates, become superconducting at relatively high temperatures—which in this case is -200°F —while others, including TTG, superconduct only at extremely low temperatures below -450°F . Yet, the presence of strong interactions between the electrons unites these rather different materials.

Scientists hope that studying how superconductivity happens in TTG may help gain an understanding of the origin of unconventional superconductivity and in raising the extremely low temperatures required.

Getting a conclusive answer

Volkov says the graphene system is great for studying superconductivity because it is clean, and fairly easy to control.

"After adding the twist, suddenly it starts to show all the physics that we don't understand," he says. "The hope is that if we start with a system which is perhaps a little bit more in the theoretical control than the messy chemistry of the cuprates, maybe we can understand the general principles behind unconventional, non-BCS superconductors."

Many previous studies in graphene, though they contribute important information, are limited in describing superconductivity, says Volkov, because those experiments focus on the properties of single electrons rather than electron pairs.

"What matters is that electrons form pairs, and somehow you want to probe the properties of those pairs to be able to study superconductivity. That is what this experiment achieves."

Volkov offers an analogy: If an electric field is applied to a superconductor, it will result in an increase in the velocity and acceleration of the electron pairs and a current increasing in time. This phenomenon is known as inductance.

"At an engineering level, a superconductor is just an inductor—the problem is they are typically bad inductors. The better a superconductor is, the worse it is as an inductor."

Volkov says that co-authors Abhishek Bannerjee, Zeyu Hao and Mary Kreidel from the groups of Philip Kim, from Harvard's Department of Physics, and K.C. Fong from Raytheon BBN Technologies, developed electrical circuits that allow the researchers to perform experiments to study the inductance of the superconducting graphene. Then, they were able to directly measure the inertia and density of the Cooper pairs that lead to superconductivity.

Volkov says the question they wanted to answer concerns the structure of the electron pairs. When particles form a pair, their relative motion does not stop, but different kinds of motion can occur. While in the BCS theory, the relative motion of electrons in a pair is uniform, or isotropic, Volkov says there is evidence that

the electrons in unconventional superconductors pair in a non-uniform, or anisotropic way.

"Up to this work, I don't think we had a conclusive answer on whether that pairing is isotropic or anisotropic in twisted graphene," he says. "It's important because the conventional mechanisms of superconductivity, such as what is proposed in BCS theory, typically advocate for uniform isotropic pairing.

"This experiment demonstrates that pairing in TTG is strongly anisotropic, and it reinforces the connection between twisted tri-layer graphene and high transition temperature cuprates, which is remarkable. As scientists, we want to see things that are complex but universal, because there's trivial complexity.

"Every sample is different. Here we find two very different materials, showing quite similar properties, including superconductivity. Given the excellent tunability of TTG, the hope is that maybe we can get our hands on the universal principles of unconventional superconductivity, which are still missing."

'Beautiful experiments'

Volkov says the discovery has been made by studying how temperature and current break the electron pairs apart. For strongly anisotropic pairs, there are always directions along which the pair is easy to break. Thus, even a tiny temperature change can lead to anisotropic pairs breaking apart.

Volkov says they experimented with other parameters to disrupt the Cooper pairs, such as altering the current, and the results further confirm that the Cooper pairs in TTG are highly anisotropic.

To understand more about the underlying electronic state, Volkov developed a theoretical model for the behavior of the TTG inductance as a function of temperature and current, in collaboration with co-authors Patrick Ledwith and Ashvin Vishwanath from Harvard's Department of Physics.

"By measuring the properties of superconducting pairs of electrons, we also get information on the underlying electronic structure and underlying properties of single electrons in that highly anisotropic state," Volkov says.

"That information is something we had to do theoretical modeling for, because it was not conforming to some simple expectations, where the more electrons you put in, the more superconducting pairs you get. That's not how it works here. These beautiful experiments also gave us insights on the behavior of single electrons in TTG."

The take-home message of the paper is the electrons in twisted multilayer graphene behave unlike those described by BCS theory; but remarkably, they share properties with high-temperature cuprates, which may have practical uses.

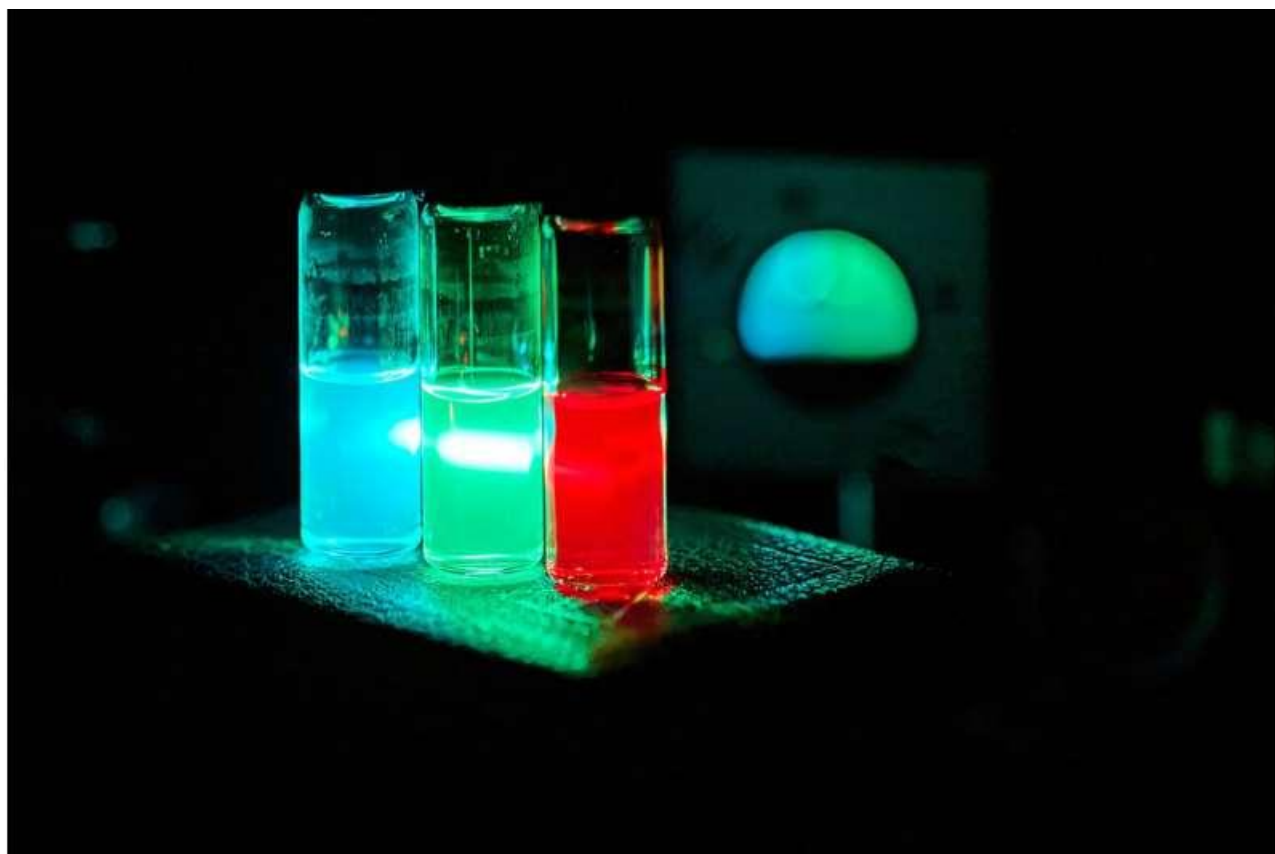
As Volkov says, they need to go back to the drawing board to develop a new theory of the superconducting state that accounts for these extraordinary materials because they may pave the way for a new generation of superconductors for real-world applications.

More information: Abhishek Banerjee et al, Superfluid stiffness of twisted trilayer graphene superconductors, *Nature* (2025). DOI: [10.1038/s41586-024-08444-3](https://doi.org/10.1038/s41586-024-08444-3)

FEBRUARY 24, 2025

Scientists reveal key to affordable, room-temperature quantum light

by Josh DeLozier, [University of Oklahoma](#)



Synthesized QDs suspended in solvents under laser irradiation. Credit: Jonathan Kyncl
Quantum light sources are fickle. They can flicker like stars in the night sky and can fade out like a dying flashlight. However, newly published research from the University of Oklahoma proves that adding a covering to one of these light sources, called a colloidal quantum dot, can cause them to shine without faltering, opening the door to new, affordable quantum possibilities. The [findings](#) are available in *Nature Communications*.

Quantum dots, or QDs, are so small that if you scaled up a single quantum dot to the size of a baseball, a baseball would be the size of the moon. QDs are used in a variety of products, from computer monitors and LEDs to [solar cells](#) and biomedical engineering devices. They are also used in [quantum computing](#) and communication.

A research study led by OU Assistant Professor Yitong Dong demonstrates that adding a crystallized molecular layer to QDs made of perovskite neutralizes surface defects and stabilizes the surface lattices. Doing so prevents them from darkening or blinking.

"In quantum computing, you must be able to control how many photons are emitted at any given time," he said. "QDs are notoriously unstable, so we worked to create a crystal covering that could stabilize their quantum emissions. This material is ideal because it is inexpensive to use and scale and is efficient at room temperature."

Quantum dots have historically had several problems. First, their surfaces can easily become defective. These defects can cause the QDs to fail, often after only 10–20 minutes of use. The crystal coverings deployed by Dong and his collaborators extend the continuous photon emission of QDs to more than 12 hours without any decay, and virtually no blinking.

OU postdoc Chenjia Mi takes a measurement on a custom-designed microscope. Credit: Jonathan Kyncl

Second, [single photon emitters](#) have traditionally operated at extremely low cryogenic temperatures. In fact, they typically require [liquid helium](#) at -452 degrees Fahrenheit, making them impractical for most real-world applications. This research, however, demonstrates that perovskite QDs achieve nearly 100% efficiency at room temperature. This breakthrough makes them significantly easier, cheaper and more appealing to use.

"Although there has been real interest in the exotic optical properties of this material, the sophistication needed to fabricate a single photon emitter was cost-prohibitive," Dong said. "But since perovskite QDs can be used at normal temperatures and synthesized for very little cost, we believe they could become the photonic chip light source for future quantum computing and quantum communication devices."

According to Dong, these findings pave the way for future quantum emitter designs that extend beyond this specific material or [molecular structure](#).

"In my opinion, our research has profound implications for the quantum field," he said. "We've found a way to stabilize these QDs using organic and inorganic molecular crystals, opening the door for others to explore the fundamental optical properties and fundamental physics of these materials. It's really exciting."

More information: Mi, C. et al. Towards non-blinking and photostable perovskite quantum dots, *Nature Communications* (2025). DOI: [10.1038/s41467-027-55619-7](https://doi.org/10.1038/s41467-027-55619-7), www.nature.com/articles/s41467-024-55619-7

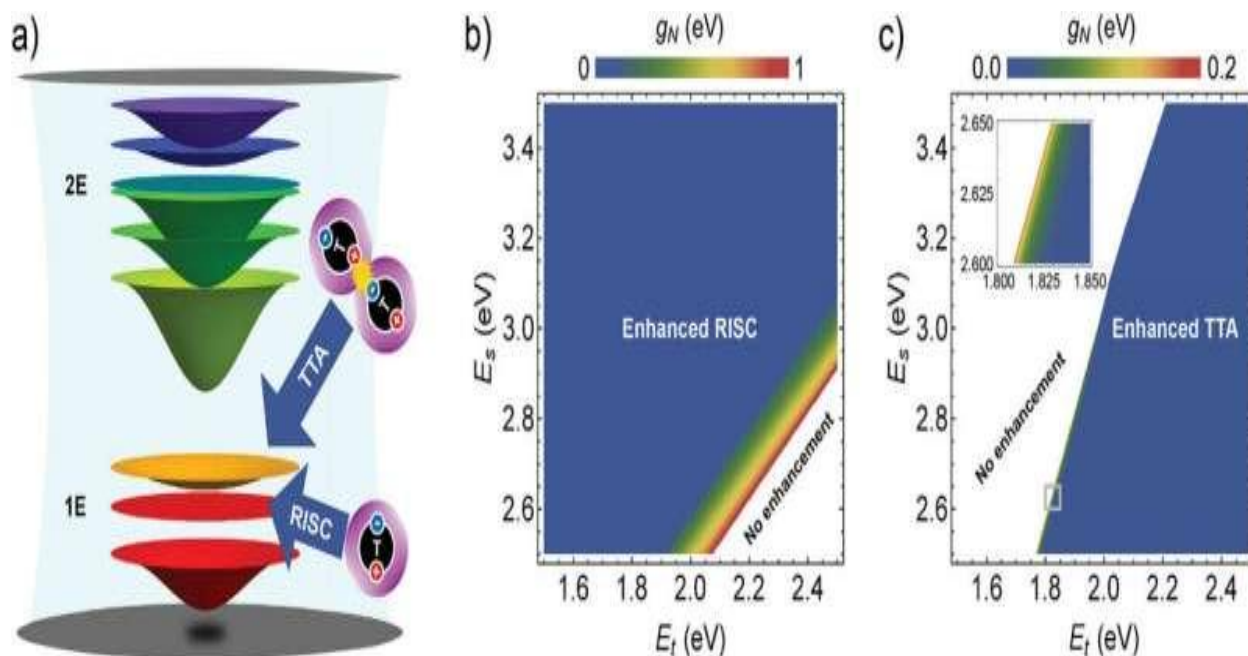
Journal information: *Nature Communications*

Provided by [University of Oklahoma](#)

FEBRUARY 24, 2025

Hybrid states of light and matter may significantly enhance OLED brightness

by [University of Turku](#)



Overview of the study and enhancement maps. Credit: *Advanced Optical Materials* (2025). DOI: 10.1002/adom.202403046

Researchers developed a theoretical model that predicts a substantial increase in the brightness of organic light-emitting diodes (OLEDs) by leveraging novel quantum states called polaritons. Integrating polaritons into OLEDs effectively requires the discovery of new materials, making practical implementation an exciting challenge.

OLED technology has become a common light source in a variety of high-end display devices, such as smartphones, laptops, TVs or smart watches.

While OLEDs are rapidly reshaping lighting applications with their flexibility and eco-friendliness, they can be quite slow at converting electric current into light, with only a 25% probability in emitting photons efficiently and rapidly. The latter is an important condition for boosting the brightness of OLEDs, which tend to be dimmer than other light technologies.

Researchers from the University of Turku, Finland, and Cornell University, U.S., have now proposed a predictive model to overcome this problem. Their research is [published](#) in *Advanced Optical Materials*.

OLEDs are electronic components made from organic carbon-based compounds that produce light when an electric current is applied to them. In OLED displays, the pixels themselves emit light, unlike [liquid crystal displays](#), which use LED backlighting.

When sandwiched between two semi-transparent mirrors, the organic emitters can couple with the confined light, creating new hybrid states of light and matter called polaritons.

By fine-tuning these states, it is possible to find a sweet spot where the remaining 75% dark states start becoming bright polaritons instead.

"While the general idea of using polaritons in OLED technology is not entirely original, a theory that examines the boundaries of performance gains has been missing. In this work, we carefully examined where the [polariton](#) sweet spot lies in different scenarios.

"We found that the strength of the polaritonic effect in OLEDs' performance depends on the number of coupled [molecules](#). The fewer, the better," says Associate Professor Konstantinos Daskalakis from the University of Turku.

"With the molecules we studied and a single coupled molecule, the efficiency improved significantly. The dark-to-bright conversion rate increased by a whopping factor of 10 million at best," says Postdoctoral Researcher Olli Siltanen.

With a large number of molecules, the polaritonic effect was negligible. Therefore, the dark-to-bright conversion rate of present-day OLEDs cannot be enhanced simply by equipping them with mirrors.

"The next challenge is to develop feasible architectures facilitating single-molecule strong coupling or invent new molecules tailored for polariton OLEDs. Both approaches are challenging, but as a result, the efficiency and brightness of OLED displays could be significantly improved," Daskalakis explains.

The widespread adoption of OLEDs has been hindered by efficiency, but more importantly by brightness limitations, particularly when compared to traditional inorganic LEDs. The results of this study provide a path forward, laying the foundation for OLEDs that are not only more efficient but also capable of achieving performance levels previously thought impossible.

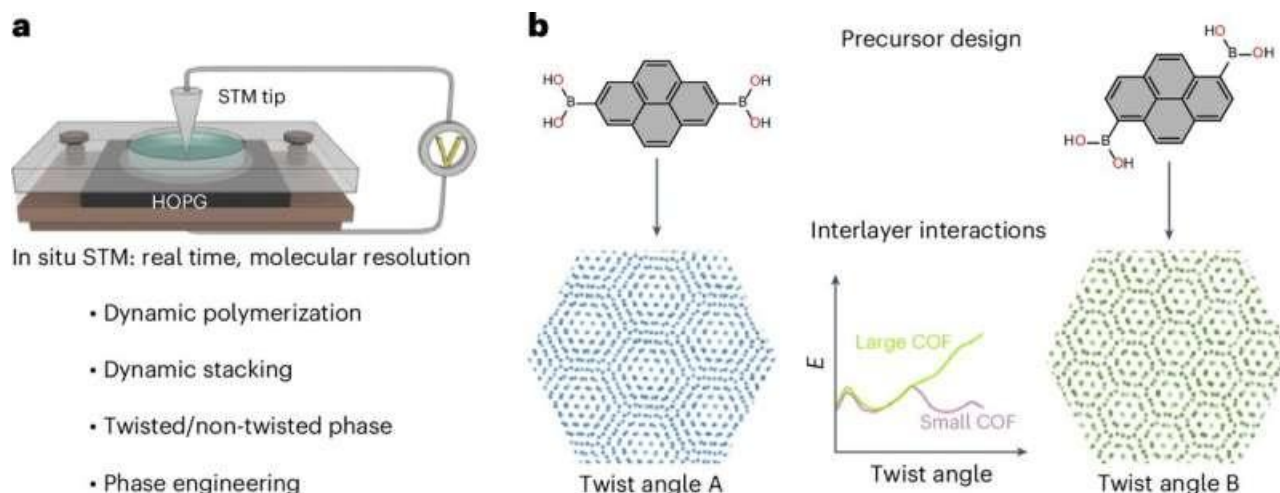
More information: Olli Siltanen et al, Enhancing the Efficiency of Polariton OLEDs in and Beyond the Single-Excitation Subspace, *Advanced Optical Materials* (2025). DOI: [10.1002/adom.202403046](https://doi.org/10.1002/adom.202403046)

Journal information: [Advanced Optical Materials](#)
Provided by [University of Turku](#)

FEBRUARY 24, 2025

Unlocking opportunities to create new designer 2D materials with a twist

by [National University of Singapore](#)



Bilayer 2D COFs monitored in real-time and designable moiré superlattice formation.

Credit: *Nature Chemistry* (2025). DOI: 10.1038/s41557-025-01748-5

Chemists from the National University of Singapore (NUS) have successfully imaged the dynamic assembly of bilayer covalent organic frameworks (COFs) in solution, providing new insights into controlled stacking and moiré superlattice formation.

Moiré superlattices belong to the exciting field of "twistronics," where a new correlated electron phase can be created when one lattice is rotated with respect to another in a stacked structure. In a correlated electron phase, the properties of electrons are significantly influenced by their interactions with each other, rather than behaving as independent particles, and they can give rise to unique forms of superconductivity or ferromagnetism.

While the formation of Moiré superlattices have been seen in pure inorganic materials, it is much rarer to see them in pure organic crystals. One reason is that moiré superlattices have to be ultrathin and highly crystalline to be imaged by conventional microscopy techniques, and these properties are not easy to find in organic materials.

Two-dimensional [covalent organic frameworks](#) (2D COFs) are highly porous organic materials with significant potential in catalysis, energy storage, and gas storage. These frameworks consist of covalently bonded layers, stacked via electrostatic interactions and van der Waals forces. However, the transition from a monolayer to a bilayer remains poorly understood due to the complex interplay of bonding forces, including van der Waals, electrostatic, and hydrogen bonding.

The precise stacking of the second layer is critical, as misalignment can reduce the material's crystallinity. Currently, producing single COF crystals larger than a millimeter is

challenging due to potential errors in bonding in both the horizontal (x–y) and vertical (z) dimensions. Misalignment during stacking often leads to crystallinity issues, particularly from rotational misalignments between layers. Observing the stacking process during growth is essential for understanding the mechanism, but this poses significant experimental challenges, as the process occurs in solution.

Random stacking and bond formation during hydrothermal synthesis contribute to poor crystallinity, often resulting in crystal domains smaller than tens of microns. A deeper understanding of layer stacking could enhance synthesis methods, enabling the fabrication of larger COF crystals.

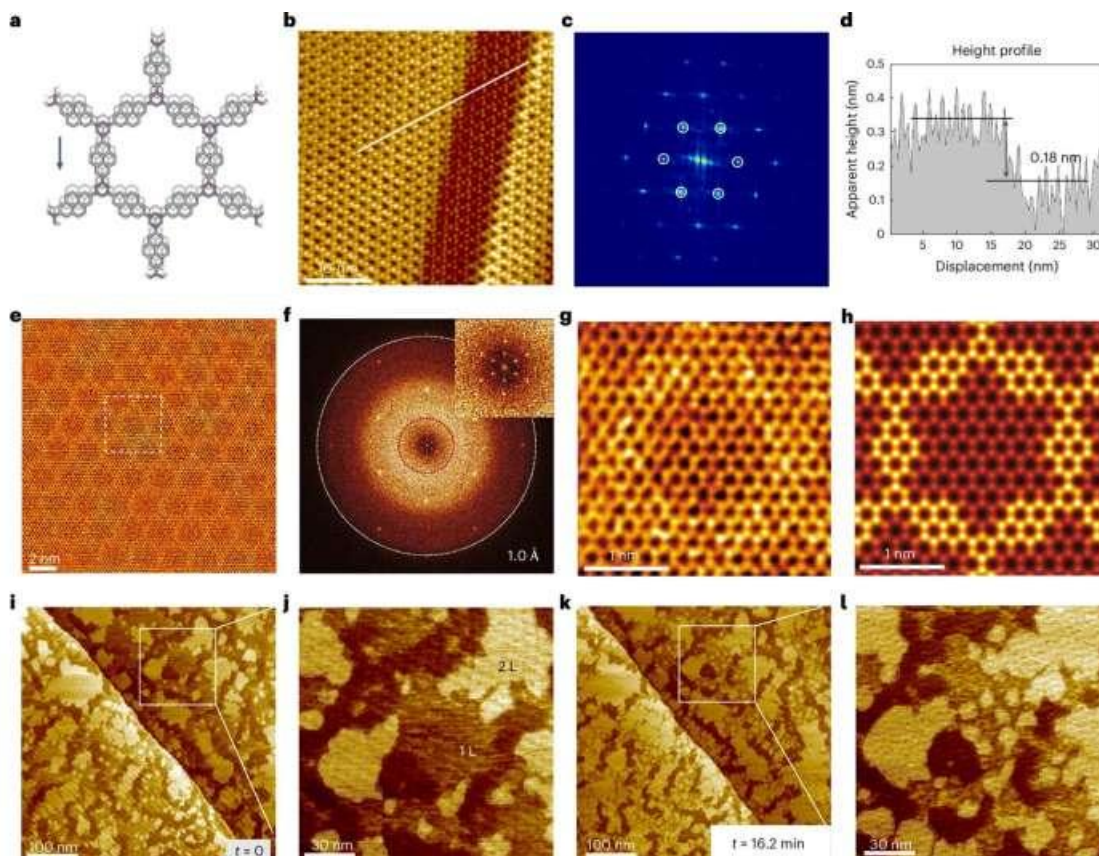
While there has been [substantial progress](#) in synthesizing monolayer 2D polymers (2DP), the development of bilayer 2DP stacks remains limited. This area is particularly promising, as stacking or twisting 2D materials can create new materials with properties distinct from those of the individual layers. In inorganic materials, this field, known as twistrionics, has led to discoveries but remains to be explored in 2D organic materials.

Breakthrough in bilayer COF synthesis and imaging

A team led by Professor Loh Kian Ping from the NUS Department of Chemistry has developed a method for synthesizing large area two-layer 2D COFs at the liquid-substrate interface. This was achieved through the direct condensation of chemical molecules. The research is [published](#) in the journal *Nature Chemistry*.

Using scanning tunneling microscopy (STM) in solution, they successfully imaged the molecular assembly process, capturing the formation of both the monolayer and bilayer. More importantly, they show how molecular structure and solvent mixture influence the bilayer stacking modes, and how, under certain conditions, large-area moiré superlattices emerge from twisted bilayer stacking.

Due to their highly porous and organic nature, COFs present significant challenges for imaging in air or ultra-high vacuum (UHV) conditions using STM. The pores of COFs are typically filled with solvent, and their surfaces may trap residues, complicating atomic-scale imaging. To overcome these difficulties, the team focused on imaging COFs directly in solution, where the surface is cleaner than when exposed to air.



AA eclipsed/shifted stacking and their dynamic stacking processes. Credit: *Nature Chemistry* (2025). DOI: 10.1038/s41557-025-01748-5

Prof. Loh said, "Performing STM in solution allows us to study the dynamic self-assembly process of molecular frameworks in [real-time](#)."

The research team includes Dr. Zhan Gaolei, who was an NUS postdoctoral fellow at the time of the research and is currently a researcher at Suzhou Institute of Nano-tech and Nano-bionics, China, Professor Steven De Feyter from KU Leuven, Belgium, and Professor Zhu Yihan from Zhejiang University of Technology, China.

Moiré superlattices and controlled twist angles

A moiré superlattice is a pattern that emerges when two layers of periodic structures, like 2D materials, are stacked on top of each other but slightly misaligned or at different angles. This misalignment creates a new, larger periodic pattern that is not present in either of the original layers.

In simpler terms, it is like two sets of paper strips. If one set of paper strips is placed over another but rotated slightly, the overlapping area will create a new pattern—similar to the moiré pattern. Moiré superlattices can lead to interesting electronic properties and behaviors that are not found in the individual layers, making them a significant area of research in materials science and condensed matter physics.

The research team demonstrated that by designing specific precursor molecules, they could precisely control the twist angle of the stacked COF layers to form a moiré superlattice. Unlike inorganic 2D materials, where the twist angles are often random and difficult to control, in 2D COFs, the twist angles can be controlled by designing the molecular precursors.

The researchers compared two different monomer isomers: pyrene-2,7-diboronic acid (27-PDBA) and pyrene-1,6-diboronic acid (16-PDBA). With 27-PDBA, the second layer could either be AA-stacked or twisted in relation to the first layer. In contrast, only a moiré superstructure formed with 16-PDBA exhibited a uniform moiré superstructure.

This difference is attributed to the subtle differences in the electrostatic potentials. 27-PDBA exhibits concentrated negative charge lobes on its boroxine rings, which may hinder the formation of twisted phases compared with 16-PDBA, which has a flatter electrostatic potential.

Implications and future directions

This study provides fundamental insights into the controlled synthesis of ultra-thin porous organic films, as thin as two-unit cell layers. Such films with well-controlled channel structures can be used as ultra-thin filtration layers in nanofiltration applications. Furthermore, the ability to tune the twist angle in stacked COFs opens new possibilities for manipulating light propagation, including phase and polarization control.

Looking ahead, the researchers plan to extend the concept to a broader class of molecular precursors with different linkage chemistries. They aim to achieve deterministic control over twist angles in bilayer COF stacking, unlocking further potential applications in filtration and optical materials.

More information: Gaolei Zhan et al, Moiré two-dimensional covalent organic framework superlattices, *Nature Chemistry* (2025). DOI: [10.1038/s41557-025-01748-5](https://doi.org/10.1038/s41557-025-01748-5)

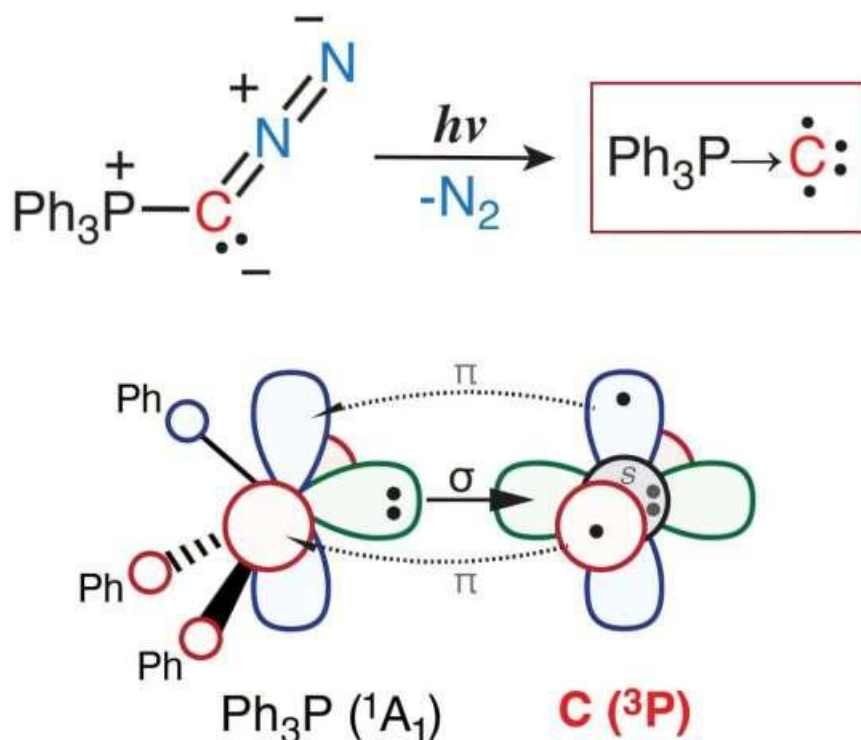
Journal information: [Nature Chemistry](#)

Provided by [National University of Singapore](#)

FEBRUARY 24, 2025

Exotic monovalent carbon compound features single bond with phosphorus group

by [Max Planck Society](#)



Synthesis of monosubstituted $\text{Ph}_3\text{P}\rightarrow\text{C}$ by light-triggered dinitrogen elimination (top) and theoretical description of the bonding (bottom) showing that the carbon exists in its atomic triplet ground state. Credit: Max Planck Society

Carbon, with its myriad compounds, is the backbone of life and the central element of organic chemistry. The number of bonds a carbon atom forms with other elements in a compound determines its chemical structure and behavior.

Normally, a carbon atom shares all four of its [valence electrons](#) to create four bonds with other atoms (tetravalent carbon). When fewer bonds are formed, unusual compounds such as carbenes are obtained, which have [unique properties](#) exploited in various fields of chemistry and catalysis. Rare cases exist of divalent carbon compounds called carbenes, where a central neutral atom in an electronically excited state is stabilized by two bonds with neutral electron-pair donating groups.

Now, another milestone was achieved with the synthesis of an organic compound that contains a singly-bonded (monovalent) carbon atom in its ground state. This is an important step in chemistry as it opens up new possibilities for the development of compounds and reactions.

In a groundbreaking study [published](#) in *Angewandte Chemie*, the research teams of Dimitrios A. Pantazis (MPI für Kohlenforschung, Department of Molecular Theory and Spectroscopy), Müge Kasanmascheff, and Max M. Hansmann (TU Dortmund), report a [chemical compound](#) featuring a single carbon atom bonded to a phosphorus group, $\text{Ph}_3\text{P}\rightarrow\text{C}$. The compound was generated from a diazophosphorus ylide precursor by irradiation with ultraviolet (UV) light at very low temperatures, which led to elimination of N_2 and formation of $\text{Ph}_3\text{P}\rightarrow\text{C}$.

Electron paramagnetic resonance (EPR) and electron–nuclear double resonance (ENDOR) spectroscopies revealed that the compound contains two unpaired electrons with parallel spins (a spin-triplet state). Advanced quantum chemical calculations probed the bonding and spin density distribution of the compound, showing that it represents a new type of carbon-centered diradical with a single dative bond between the phosphorus and the terminal carbon. This is the first known compound where a carbon center persists in the same electronic configuration and spin state as that of an isolated ground-state carbon atom.

This fundamental discovery extends the boundaries of carbon chemistry to the extreme bonding situation of a monovalent neutral carbon atom, while paving the way for exploring new organic reactivity with potential implications for synthesis, catalysis, and materials science.

More information: Yury Kutin et al, Ph_3PC – A Monosubstituted C(0) Atom in Its Triplet State, *Angewandte Chemie International Edition* (2025). DOI: [10.1002/anie.202424166](https://doi.org/10.1002/anie.202424166)

Journal information: [Angewandte Chemie International Edition](#) , [Angewandte Chemie](#)
Provided by [Max Planck Society](#)

FEBRUARY 24, 2025

Exploring magnetic molecules for solving geopolitical dependencies

by [University of Oulu](#)

At the University of Oulu, new materials are being developed from available chemical elements. Akseli Mansikkamäki's research group develops molecules that could be used in future technologies. Credit: Mikko Törmänen / Oulun yliopisto

Technologies related to the green transition and digitalization require tremendous amounts of different chemical elements. "We cannot decide which elements we can find from the Earth's crust within the EU. Therefore, we must develop new materials from the elements that are available," senior researcher Akseli Mansikkamäki states.

For example, currently more than 70 different elements—that is more than three quarters of the naturally occurring elements—are needed to manufacture a phone. At least half of these are listed as critical raw materials by the European Union. This makes the EU's industry, defense technology and fight against climate change dependent on foreign countries. Geopolitical instability further aggravates this vulnerability.

Mansikkamäki's research group at the University of Oulu, Finland, is developing molecules that could be used in [future technologies](#). The materials that can be constructed from these kinds of molecules could be used to replace critical raw materials.

In a recent [study](#) published in *Physical Chemistry Chemical Physics*, Mansikkamäki and doctoral researcher Anand Chekkottu Parambil explored how [magnetic molecules](#) could be constructed from the so-called main-group [heavy metals](#). These metals include elements such as tin, lead and bismuth.

They are available in large quantities, but as metals they are not magnetic and they do not have many uses, for example, in microelectronics. But as parts of molecules, they can be used to construct [magnetic materials](#) for future components.

"In other words, we try to make ordinary chemical elements do things we never thought they could do," Mansikkamäki explains.

Designing new materials is basic research at the border between chemistry and physics

The work conducted in Mansikkamäki's research group is basic research that aims to study how the properties necessary for future technologies can be imparted into molecules and materials. The research carried out at the University of Oulu utilizes [high-performance computing](#) and theoretical methods. Practical experiments are conducted in collaboration with Canadian and British research groups.

Mansikkamäki obtained his doctoral degree in chemistry but now he works in theoretical physics.

"Chemistry and theoretical physics is not a very common combination, but as an educational background it is pretty optimal when you want to understand how molecules and [high technology](#) are related," Mansikkamäki says.

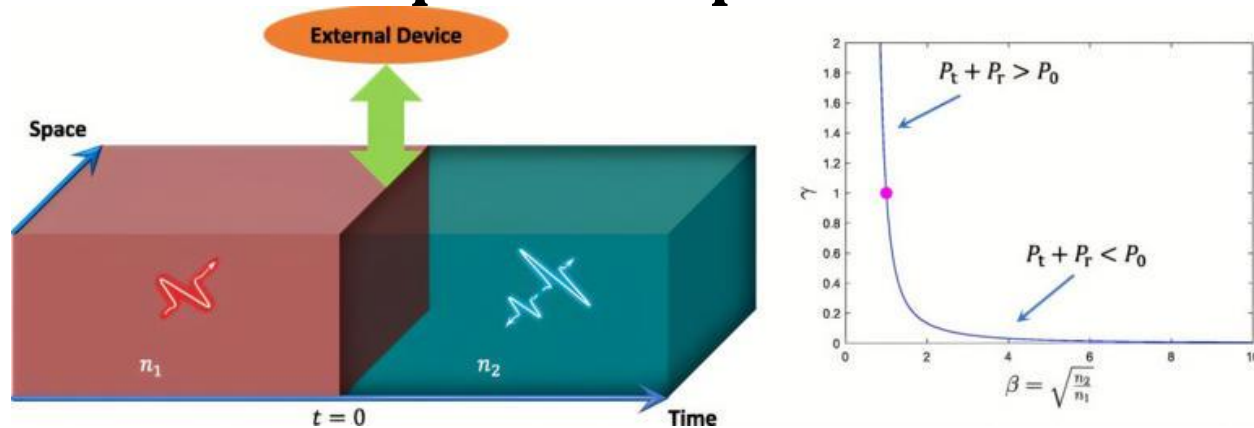
Today, materials based on new types of molecules are still at an early stage of development and practical applications are few. The full potential of these materials in future technologies is still being discovered.

"For the future of our society, it is essential that the scientific foundation for the development of new materials is established today," Mansikkamäki summarizes. "Considering world politics, in the future the transition towards higher development stage materials in the EU is inevitable."

More information: Akseli Mansikkamäki et al, Framework for designing main-group single-molecule magnets, *Physical Chemistry Chemical Physics* (2025). DOI: [10.1039/D4CP04790G](https://doi.org/10.1039/D4CP04790G)

Journal information: [Physical Chemistry Chemical Physics](#)
Provided by [University of Oulu](#)

Time interfaces: The gateway to four-dimensional quantum optics



Time interface in a dielectric medium. Credit: *Physical Review Research* (2025). DOI: [10.1103/PhysRevResearch.7.013120](https://doi.org/10.1103/PhysRevResearch.7.013120)

A new study from the University of Eastern Finland (UEF) explores the behavior of photons, the elementary particles of light, as they encounter boundaries where material properties change rapidly over time. This research uncovers remarkable

quantum optical phenomena that may enhance quantum technology and paves the road for an exciting nascent field: four-dimensional quantum optics.

Four-dimensional optics is a research area investigating light scattering from structures which change in time and space. It holds immense promise for advancing microwave and optical technologies by enabling functionalities such as frequency conversion, amplification, polarization engineering and asymmetric scattering. That is why it has captured the interest of many researchers across the globe.

Previous years have seen significant strides in this area. For instance, a [2024 study](#) published in *Nature Photonics* and also involving UEF highlights how incorporating optical features like resonances can drastically influence the interaction of electromagnetic fields with time-varying two-dimensional structures, opening exotic possibilities to control light.

Now, building on their previous work in classical optics, the researchers at UEF have extended their investigation to quantum optics. The team has conducted a detailed investigation into quantum light interaction with a material whose macroscopic property changes abruptly in time, creating a single temporal interface between two different media (like the interface between air and water, but in time rather than in space). This work is [published](#) in *Physical Review Research*.

Dr. Mirmoosa, the lead researcher in this study, explains, "Four-dimensional quantum optics is the next logical step, allowing us to explore the implications of this area for quantum technology. Our research has taken this initial step and now provides a foundational tool for us to examine complex structures, changing in time and space, for uncovering novel quantum optical effects."

The investigation showed and revealed several intriguing phenomena, including photon-pair creation and annihilation, vacuum state generation and quantum state freezing, all of which may have potential applications in quantum technology.

The researchers acknowledge that this is just the beginning. Four-dimensional quantum optics is an emerging field poised to attract significant attention in the near future. For instance, exploring how quantum light fields interact with

periodically repeating time interfaces, known as photonic time crystals, is particularly exciting.

Dr. Mirmoosa adds, "In our paper, we did not take into account dispersion. Real materials are nonetheless dispersive in nature, meaning that responses have a delay relative to the excitations. To address such an intrinsic feature necessitates the development of a more comprehensive theory.

"Incorporating dispersion may lead to new possibilities for controlling the quantum states of light, and I am very motivated to explore that."

More information: M. S. Mirmoosa et al, Quantum state engineering and photon statistics at electromagnetic time interfaces, *Physical Review Research* (2025). DOI: [10.1103/PhysRevResearch.7.013120](https://doi.org/10.1103/PhysRevResearch.7.013120)

Provided by University of Eastern Finland

Scientists discovered 'secret life' of the universe before the Big Bang



Abstract big bang conceptual image.© iStockphoto by Getty Images

The universe might have had a "secret life" before the [Big Bang](#), a recent study has proposed.

Prior to the Big Bang, researchers say [black holes](#) were created as a result of the universe contracting and this could possibly explain the enigmatic nature of dark matter.

The new study, which was recently published in the Journal of Cosmology and Astroparticle Physics, challenges the traditional belief that the universe originated from the Big Bang which resulted in vast expansion.

Instead, after first contracting, the universe was in an extremely dense state and then began to "bounce" back in an expansion period, and it's this rebound that impacts what we understand about dark matter and black holes.

Density fluctuations may have brought about small black holes in the universe's contraction stage which survived the expansion phase and can so possibly make

up the dark matter that adds up to around 80 per cent of the universe's total matter.

These findings could have major consequences on how we understand the universe, particularly where black holes and dark matter fit in all this.

It could provide a further understanding of the mystery of dark matter as its lack of light interaction has baffled scientists.

"Small primordial black holes can be produced during the very early stages of the universe, and if they are not too small, their decay due to Hawking radiation [a hypothetical phenomenon of black holes emitting particles due to quantum effects] will not be efficient enough to get rid of them, so they would still be around now," said Patrick Peter, director of research at the French National Centre for Scientific Research (CNRS), who was not involved in the study.

In an email, he told [Live Science](#). "Weighing more or less the mass of an asteroid, they could contribute to dark matter, or even solve this issue altogether."

Now, researchers hope to find further evidence to support this cosmology theory with gravitational wave detectors including the Laser Interferometer Space Antenna (LISA) and the Einstein Telescope, to find the waves produced when the primordial black holes were created.

The universe had a secret life before the Big Bang, new study hints

By [Andrey Feldman](#)

published August 31, 2024

The secrets of black holes and dark matter could lie before the Big Bang, a new study of "bouncing" cosmology hints.



An illustration showing various aspects of the early universe, including radiation generated by the Big Bang and ancient black holes (Image credit: ESA)

The [Big Bang](#) may not have been the beginning of the universe, according to a theory of cosmology that suggests the universe can “bounce” between phases of contraction and expansion. If that theory is true, then it could have profound implications about the nature of the cosmos, including two of its most mysterious components: black holes and dark matter.

With this in mind, a recent study suggests that dark matter could be composed of [black holes](#) formed during a transition from the universe's last contraction to the current expansion phase, which occurred before the Big Bang. If this hypothesis holds, the gravitational waves generated during the black hole formation process might be detectable by future gravitational wave observatories, providing a way to confirm this dark matter generation scenario.

Observations of stellar movements in galaxies and the cosmic microwave background — an afterglow of the Big Bang — indicate that about 80% of all matter in the universe is [dark](#)

[matter](#), a substance that doesn't reflect, absorb or emit light. Despite its abundance, scientists have not yet identified what dark matter is made of. In the new study, researchers explored a scenario where dark matter consists of primordial black holes formed from density fluctuations that occurred during the universe's last contraction phase, not long before the period of expansion that we observe now. They published their findings in June in the [Journal of Cosmology and Astroparticle Physics](#).

The bouncing cosmos

The traditional cosmological view of the universe suggests that it started from a singularity, followed by a short period of extremely rapid expansion, called inflation. However, the authors behind the new study analyzed a more exotic theory, known as non-singular matter bouncing cosmology, which posits that the universe first underwent a contraction phase. This phase ended with a rebound due to the increasing density of matter, leading to the Big Bang and the accelerated expansion we observe today.

Related: [The universe could stop expanding 'remarkably soon', study suggests](#)

In this bouncing cosmology, the universe contracted to a size about 50 orders of magnitude smaller than it is today. After the rebound, photons and other particles were born, marking the Big Bang. Near the rebound, the matter density was so high that small black holes formed from quantum fluctuations in the matter's density, making them viable candidates for dark matter.

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"Small [primordial black holes](#) can be produced during the very early stages of the universe, and if they are not too small, their decay due to Hawking radiation [a hypothetical phenomenon of black holes emitting particles due to quantum effects] will not be efficient enough to get rid of them, so they would still be around now," [Patrick Peter](#), director of research at the French National Centre for Scientific Research (CNRS), who was not involved in the study, told Live Science in an email. "Weighing more or less the mass of an [asteroid](#), they could contribute to dark matter, or even solve this issue altogether."

RELATED STORIES

The scientists' calculations show that this universe mode's properties, such as the curvature of space and the microwave background, match current observations, supporting their hypothesis.

To further test their predictions, the researchers hope to make use of next-generation gravitational wave observatories. The scientists calculated the properties of the [gravitational waves](#) produced during black hole formation in their model and found that they could be detected by [upcoming gravitational observatories like the Laser Interferometer Space Antenna \(LISA\)](#) and the [Einstein Telescope](#). These detections could

confirm whether primordial black holes are indeed dark matter; however, it could take more than a decade before either facility sees first light.

"This work is important in the sense that it provides a natural way of forming small yet still present black holes forming dark matter in a framework which is not the usual one based on inflation," Peter said. "Other works currently investigate the behavior of such tiny black holes around stars, potentially leading to a way of detecting them in the future."

Engineers create first flat telescope lens that can capture color while detecting light from faraway stars



Utah researchers demonstrated the capabilities of their flat lens with test images of the sun and moon. Credit: Menon Lab, University of Utah

For centuries, lenses have worked the same way: curved glass or plastic bending light to bring images into focus. But traditional lenses have a major drawback—the more powerful they need to be, the bulkier and heavier they become.

Scientists have long searched for a way to reduce the weight of lenses without sacrificing functionality. And while some slimmer alternatives exist, they tend to be limited in their capacity and are generally challenging and expensive to make.

New research from University of Utah engineering professor Rajesh Menon and colleagues at the Price College of Engineering offers a promising solution applicable to telescopes and astrophotography: a large aperture flat lens that focuses light as effectively as traditional curved lenses while preserving accurate color.

The study, "[Color astrophotography with a 100 mm-diameter f/2 polymer flat lens](#)," appears in *Applied Physics Letters*.

This technology could transform astrophotography imaging systems, especially in applications where space is at a premium, such as on aircraft, satellites and space-based telescopes.

Their study was led by Menon Lab member Apratim Majumder, a research assistant professor in the Department of Electrical & Computer Engineering. Co-authors include fellow Menon Lab members Alexander Ingold and Monjurul Meem, the Department of Physics & Astronomy's Tanner Obray and Paul R. Lenses bend light to make objects appear larger. The thicker and heavier the lens, the more it bends the light, and the stronger the magnification. For everyday cameras and backyard telescopes, lens thickness isn't a huge problem.

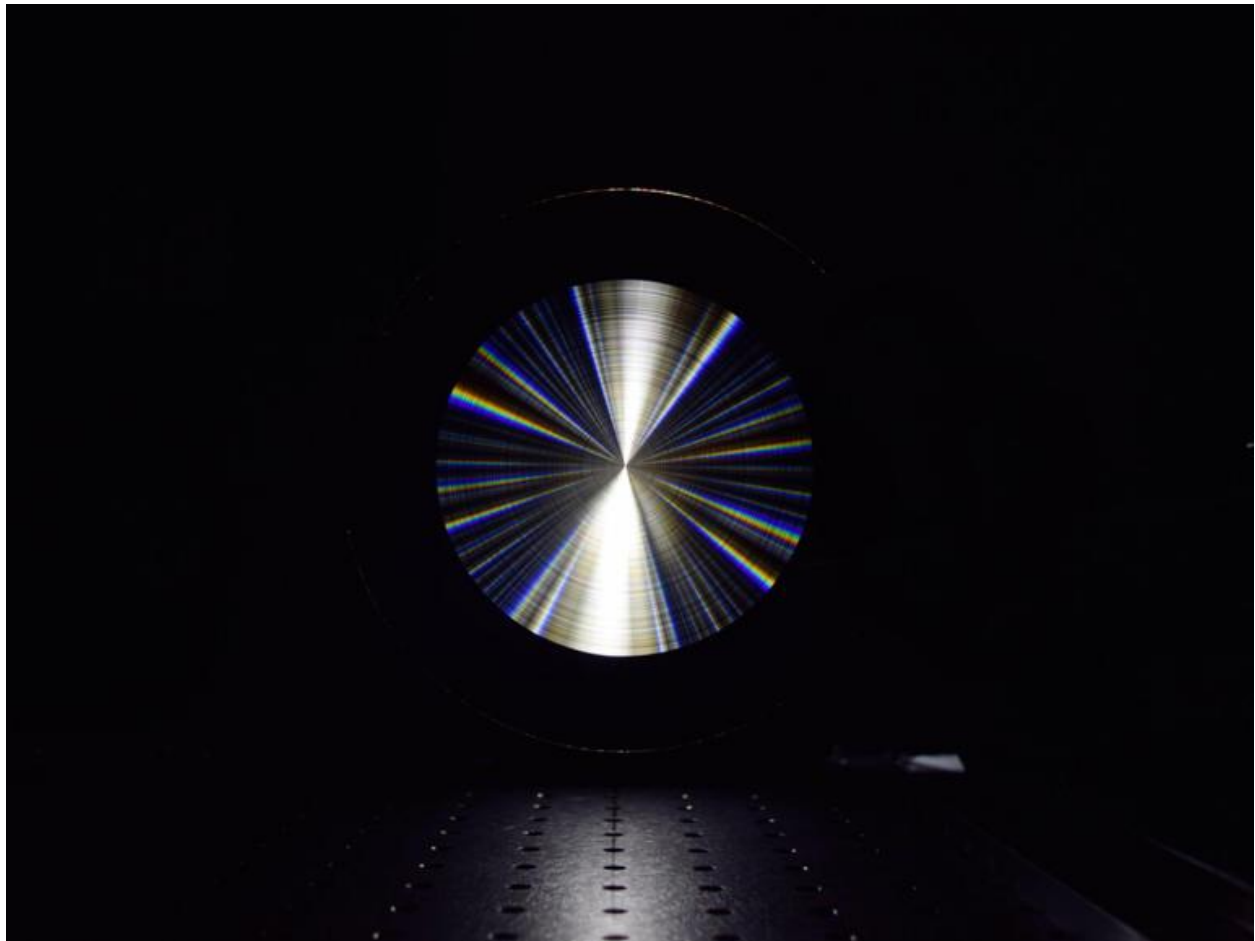
But when telescopes must focus light from galaxies millions of light-years away, the bulk of their lenses become impractical. That's why observatory and space-based telescopes rely on massive, curved mirrors instead to achieve the same light-bending effect, since they can be made much thinner and lighter than lenses. Scientists have also tried to solve the bulkiness problem by designing flat lenses, which manipulate light in a different way.

One existing type, called a Fresnel zone plate (FZP), uses concentric ridges to focus light, rather than a thick, curved surface. While this method does create a lightweight and compact lens, it comes with a tradeoff: it can't produce true

colors. Rather than bending all of the wavelengths of visible light at the same angle, the ridges of an FZP diffract them at different angles, resulting in an image with chromatic aberrations, or color distortions.

Enter Rajesh Menon and his team at the U. Their new flat lens offers the same light-bending power as traditional curved lenses while avoiding the color distortions of FZPs.

"Our computational techniques suggested we could design multi-level diffractive flat lenses with large apertures that could focus light across the visible spectrum and we have the resources in the Utah Nanofab to actually make them," said Menon, who directs the U's Laboratory for Optical Nanotechnologies.



The concentric rings of microscopic indentations on the researchers' flat lens are optimized to bring all wavelengths of light into focus at the same time. Credit: Menon Lab, University of Utah

The key innovation lies in the microscopically small concentric rings that the researchers can pattern on the substrate. Unlike the ridges of FZPs, which are optimized for a single wavelength, the size and spacing of the flat lens' indentations keep the diffracted wavelengths of light close enough together to produce a full-color, in-focus image.

"Simulating the performance of these lenses over a very large bandwidth, from visible to near-infrared, involved solving complex computational problems involving very large datasets," Majumder said.

"Once we optimized the design of the lens' microstructures, the manufacturing process involved required very stringent process control and environmental stability."

A large, flat, color-accurate lens could have massive implications across industries, but its most immediate application is in astronomy. The researchers demonstrated the capabilities of their flat lens with test images of the sun and moon.

"Our demonstration is a stepping stone towards creating very large aperture lightweight flat lenses with the capability of capturing full-color images for use in air-and-space-based telescopes," Majumder said.

More information: Apratim Majumder et al, Color astrophotography with a 100 mm-diameter f/2 polymer flat lens, *Applied Physics Letters* (2025). DOI: [10.1063/5.0242208](https://doi.org/10.1063/5.0242208)

Provided by University of Utah

FEBRUARY 28, 2025

Inspired by Maxwell's demon, heat flow acts as a witness to quantum properties

by Tejasri Gururaj , Phys.org

The heat-based witness setup for detecting quantum entanglement. Credit: Dr. Alexssandre de Oliveira Junior.

In a [new study](#) published in *Physical Review Letters*, scientists have discovered a novel approach to detecting the quantum properties of a system by simply using heat as a witness, requiring no direct measurement of the quantum system itself.

The study proposes connecting thermodynamics with [quantum information theory](#), drawing inspiration from the concept of Maxwell's demon.

The concept proposed in the 19th century involves an imaginary entity, Maxwell's demon, that can sort gas molecules by their velocities inside a closed box, seemingly violating the second law of thermodynamics.

Phys.org spoke to the authors of the study, Dr. Alexssandre de Oliveira Junior and Prof. Jonatan Bohr Brask from the Technical University of Denmark, and Prof. Patryk Lipka-Bartosik from Jagiellonian University in Poland.

"Inspired by Maxwell's demon, a famous thought experiment in physics, we explored what happens when classical memory is replaced with a quantum one," explained Dr. Oliveira Junior.

"This led us to uncover a fundamental connection between heat flow and uniquely quantum properties. We found that [quantum systems](#) reveal their special traits simply by exchanging heat with their surroundings."

Measuring quantum properties

Traditional methods for observing the quantum properties of a system, like entanglement and coherence, rely on specific measurements that collapse the quantum state of the system.

This method destroys the quantum information stored in the system. Traditional methods also introduce noise into the system since they require external input to make the measurements.

The new approach offers an alternative.

Prof. Brask explains, "What makes our approach exciting is that it doesn't rely on any specific model or system. "Instead, we can explore fundamental constraints on heat exchange in a quantum process simply by measuring a thermal ancilla, or heat bath, acting as the environment."

The fundamental idea is that coherence influences [energy transfer](#) in ways that classical systems cannot replicate, allowing for indirect detection.

Therefore, the quantum properties of the system can be detected by observing the heat signatures when it interacts with the environment or heat bath.

How it works

The researchers developed a theoretical framework where a main quantum system interacts with a thermal environment.

A quantum memory acts as a catalyst for this interaction without exchanging energy. Instead, it affects the dynamics of how heat flows between the system and environment by holding quantum information.

The researchers explained the process using an intuitive example.

Alice and Bob want to determine if their shared quantum state is entangled. They use two extra systems—one acting as a heat bath and another as a quantum memory, with no restrictions on their size.

First, they measure the thermal ancilla to check its initial energy. Then, they apply a unitary operation that connects all three systems and lets them evolve.

The quantum memory plays a crucial role here. Because it's quantum in nature, it can form quantum connections with the system, which a classical memory can't.

These quantum connections allow heat to flow between the system and bath in unique ways that depend on whether the original system has quantum properties like entanglement. In other words, it opens pathways for heat flow that only exist when quantum properties are present.

After the interaction, they measure the thermal ancilla again to see how much its energy has changed. By comparing this energy difference to our theoretical bounds, they can check if the result falls outside the expected range. If it does, that's a clear sign that their state is entangled.

This range was derived using a mathematical framework developed by the researchers based on optimal heat exchange.

Applications and the broader impact

The researchers demonstrated their heat-based witness approach with two examples—entanglement detection and coherence certification.

They also highlight its implementation in current experimental platforms.

Prof. Lipka-Bartosik said, "Our approach can be implemented in state-of-the-art experimental setups. For instance, [nuclear magnetic resonance](#) (NMR) and cavity-QED with [superconducting qubits](#) have been used to realize energy-preserving unitary processes, a fundamental building block of our framework. Additionally, both techniques can implement a quantum memory."

The team also suggests that other platforms, such as single-electron devices and trapped ions, could verify their results, having previously been used to test related ideas.

By establishing a relationship between thermodynamics and quantum information theory, the research opens new avenues for studying quantum properties.

Speaking of future directions, the researchers highlight generalizing the approach to certify and quantify multipartite quantum correlations.

"It is well known that measuring such correlations typically comes with an exponential cost. This naturally raises the question of whether it is possible to construct witnesses that enable a practical measure of multipartite quantum correlations based on differences in heat exchange," explained Dr. Oliveira Junior.

With advances in quantum technologies, this approach could play a crucial role in developing practical quantum applications.

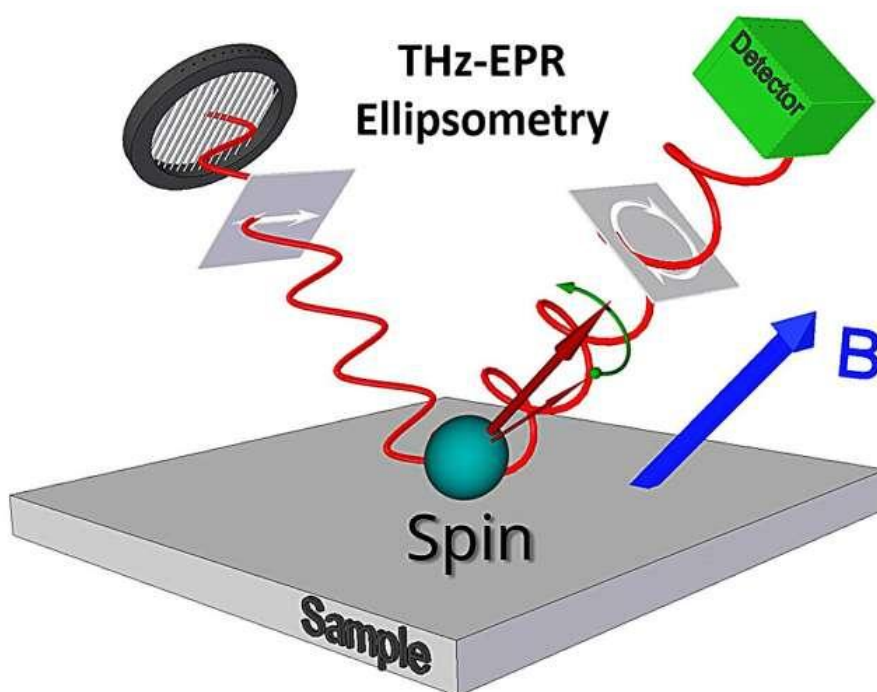
More information: A. de Oliveira Junior et al, Heat as a Witness of Quantum Properties, *Physical Review Letters* (2025). DOI: [10.1103/PhysRevLett.134.050401](https://doi.org/10.1103/PhysRevLett.134.050401).
On *arXiv*: DOI: [10.48550/arxiv.2408.06418](https://doi.org/10.48550/arxiv.2408.06418)
Journal information: [Physical Review Letters](#) , [arXiv](#)

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MARCH 3, 2025

Researchers discover magnetic equivalent of the Lyddane-Sachs-Teller relation

by Ingrid Fadelli , Phys.org



Schematic illustration of the principle of terahertz EPR ellipsometry. Terahertz light with a defined polarization is directed onto and reflected off a sample. In a strong magnetic field, the unpaired spins of the system precess and interact with the magnetic field component of the incident light. The frequency-dependent interaction provides insight into the sample's static (DC) response under an applied magnetic field, by using the magnetic LST. Credit: Rindert et al

Materials are known to interact with electromagnetic fields in different ways, which reflect their structures and underlying properties. The Lyddane-Sachs-Teller relation is a physics construct that describes the relationship between a material's static and dynamic dielectric constant (i.e., values indicating a system's behavior in the presence or absence of an external electric field, respectively) and the vibrational modes of the material's crystal lattice (i.e., resonance frequencies).

This construct, first introduced by physicists Lyddanne, Sachs and Teller in 1941, has since been widely used to conduct solid-state physics research and materials science studies.

Ultimately, it has helped better explain and delineate the properties of various materials, which were then used to create new electronic devices.

Researchers at Lund University recently extended the Lyddane-Sachs-Teller relation to magnetism, showing that a similar relation links a material's static permeability (i.e., its non-oscillatory response to a [magnetic field](#)) to the frequencies at which it exhibits a [magnetic resonance](#). Their [paper](#), published in *Physical Review Letters*, opens new exciting possibilities for the study of magnetic materials.

"This study was inspired by my supervisor, Prof. Mathias Schubert, who previously explored how electric fields interact with phonons and suspected a similar relationship could exist for magnetic fields and materials," Viktor Rindert, first author of the paper, told Phys.org.

"The opportunity to investigate this came with our development of a terahertz ellipsometer capable of capturing the polarization response. With this tool, we rigorously tested whether such a relation exists, leading to the discovery of the Magnetic Lyddane-Sachs-Teller relation."

The Magnetic Lyddane-Sachs-Teller relation, the new relation unveiled by Rindert and his colleagues, is essentially a magnetic parallel of the construct devised by Lyddane, Sachs and Teller. Instead of applying the responses of materials to an external electric field, it links the static (DC) and dynamic (AC) responses of a material following its interaction with magnetic fields.

"Specifically, this relation connects the material's magnetic [resonance frequencies](#) to its static permeability," explained Rindert. "We validated this relation by measuring the magnetic resonance frequencies using our newly developed method, THz-EPR-GSE, and comparing our results to those obtained using SQUID magnetometry, a well-established and precise technique."

To demonstrate the existence of this relation, the researchers used an advanced optical technique developed in their lab, called THz-EPR-GSE, to measure the magnetic resonance frequencies of an iron-doped gallium nitride (GaN) semiconductor. Their measurements and analyses ultimately confirmed the existence of the predicted Magnetic Lyddane-Sachs-Teller relation.

The new relation uncovered by Rindert and his colleagues could be a valuable tool for gathering new insights into the magnetic excitations of semiconductors and other materials with magnetic properties. In the future, it could contribute to the advancement of various electronic devices and their underlying components.

"Our study provides a new fundamental relation in magneto-optics, particularly relevant for researchers working on antiferromagnetic and altermagnetic materials," added Rindert. "While the exact direction is still evolving, our immediate focus is on applying the THz-GSE-EPR technique to study paramagnetic point defects in ultrawide band gap semiconductors."

"This research is particularly relevant for power electronics applications, where such materials are critical in enhancing performance and efficiency."

More information: Viktor Rindert et al, Magnetic Lyddane-Sachs-Teller Relation, *Physical Review Letters* (2025). DOI: [10.1103/PhysRevLett.134.086703](https://doi.org/10.1103/PhysRevLett.134.086703).

Journal information: [Physical Review Letters](#)

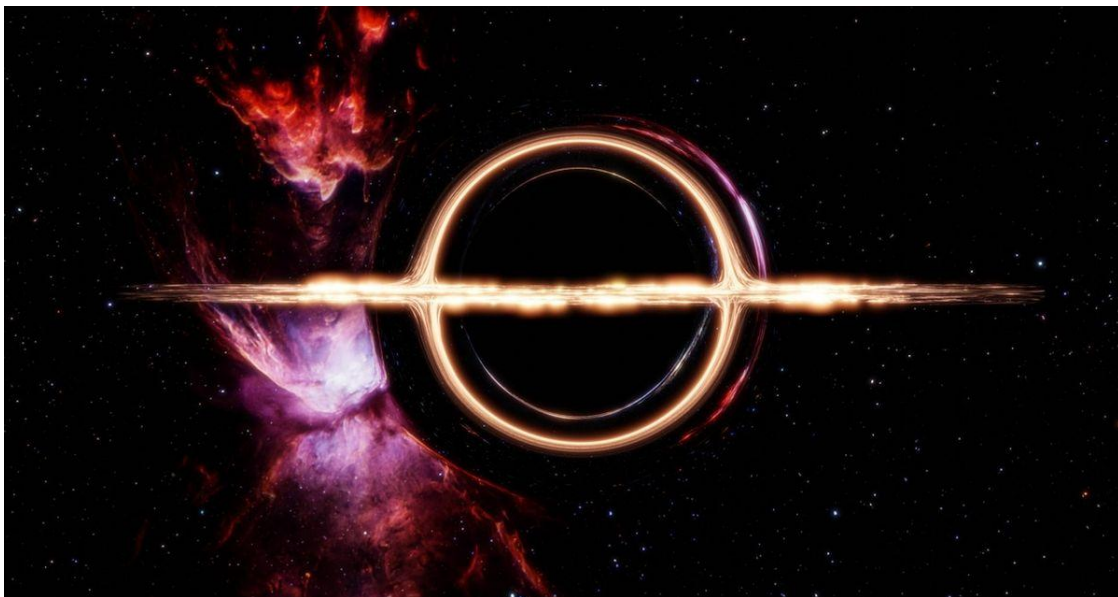
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'Einstein's equations need to be refined': Tweaks to general relativity could finally explain what lies at the heart of a black hole

By [Andrey Feldman](#)

published 23 hours ago

Black hole singularities should not exist, according to theories of quantum mechanics. New tweaks to Einstein's equations of general relativity could finally do away with them, and explain what truly lies at the heart of a black hole.



Black hole singularities — theoretical points of infinite density at the centers of the cosmic monsters — defy physics. New tweaks proposed to Einstein's relativity may do away with them at last. (Image credit: Adis Resic via Pixabay)

Theoretical physicists have proposed a potential solution to one of the most puzzling problems in modern physics: the [black hole](#) singularity paradox. By modifying Einstein's theory of general [relativity](#), the center of a black hole with infinite curvature could be replaced by a highly curved but regular region of space-time, the researchers suggest in a new study.

"Singularities are regions of the universe where space, time and matter are crushed and stretched into nonexistence," study co-author [Robie Hennigar](#), a postdoctoral researcher at Durham University in the U.K., told Live Science via email. "This is a very serious problem, as if singularities were to really exist in our universe, it would be catastrophic for science. "We could no longer use the equations of [physics](#) to predict the future from the past and present," he continued. "For these reasons, most practising scientists expect that

singularities are not physical, but are telling us that general relativity must be replaced by a more complete theory to describe the universe near singularities."

Correcting Einstein

Since its introduction in 1915, general relativity has been remarkably successful in explaining astrophysical and cosmological phenomena, including the formation of black holes, the structure of neutron stars, and the [large-scale structure](#) and evolution of the universe.

However, the theory has fundamental limitations. It is incompatible with [quantum mechanics](#), which governs the behavior of particles at the smallest scales, and it predicts singularities — points of infinite density — at the centers of black holes and at the [Big Bang](#).

To address this issue, the researchers used a concept known as quantum gravity, which is commonly applied in attempts to unify Einstein's general relativity with quantum mechanics, which predicts continuous particle creation and annihilation in empty space, along with perpetual fluctuations in all fields, including gravity. Their study, published in February in the journal [Physics Letters B](#), suggests that at extremely high energies or incredibly small distances, general relativity should be modified by an infinite series of additional terms in its equations.

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"In [quantum gravity](#), one considers all corrections to the equations relating the energy and momentum of a system with the spacetime curvature that are consistent with known physical principles," Hennigar said. "Different approaches to quantum gravity will place different importance on different terms in the equations, but they all suggest that Einstein's equations need to be refined."

By incorporating these modifications into their calculations, the researchers examined how black holes would behave under this revised framework. Their results showed that when an infinite number of new terms are included, the singularity vanishes. Instead of an infinitely dense point, the black hole's core becomes a highly curved but regular region of space-time.

Testing the theory

Although the new model resolves the singularity problem mathematically, scientific theories must ultimately be tested through observation. The researchers acknowledged that directly confirming their idea presents a significant challenge.

"The absence of singularities itself is hard to test experimentally, because it would occur inside a black hole, or at the very beginning of the universe," [Pablo Cano](#), a postdoctoral researcher at the University of Barcelona and another co-author of the study, told Live Science in an email. "However, we can look for signatures of the theories that lead to singularity resolution.

"The modifications of general relativity that we consider become larger in stronger gravitational fields, but are very small otherwise," Cano added. "This means that, for instance, gravitational waves coming from collisions of black holes — where gravitational fields are much stronger than in the [solar system](#) — provide a way of searching for these effects."

Another promising avenue is the study of the early universe. If the effects of this modified gravity theory influenced cosmic inflation — the rapid expansion that followed the Big Bang — evidence of these changes might be imprinted in primordial gravitational waves. Future experiments targeting these signals could help test the validity of the theory.

In addition, further theoretical work is needed to determine whether singularity-free black holes can form naturally through gravitational collapse and whether the team's approach can address other types of singularities, such as those associated with the Big Bang.

"We have recently shown that the collapse of a certain type of matter gives rise, within this framework, to the formation of these regular black holes," said [Pablo Bueno](#), a research fellow at the University of Barcelona and a co-author of the study. "We would like to test this under more general assumptions. This may give rise to intriguing features in other areas, such as explicit models of [bouncing cosmologies](#) in which the usual Big Bang scenario is replaced by a never ending series of expansive and contracting phases."

Tweak to Schrödinger's cat equation could unite Einstein's relativity and quantum mechanics, study hints

published April 26, 2024

Physicists have proposed modifications to the infamous Schrödinger's cat paradox that could help explain why quantum particles can exist in more than one state simultaneously, while large objects (like the universe) seemingly cannot.



The universe's largest structures appear to follow the rules of Einstein's relativity, while the smallest objects obey quantum mechanics. Can proposed changes to the infamous Schrödinger's cat equations help unite the two theories? (Image credit: TheDigitalArtist / Pixabay)

Theoretical physicists have proposed a new solution to the [Schrödinger's cat paradox](#), which may allow the theories of quantum mechanics and Einstein's relativity to live in better harmony.

The bizarre laws of [quantum physics](#) postulate that physical objects can exist in a combination of multiple states, like being in two places at once or possessing various velocities simultaneously. According to this theory, a system remains in such a "superposition" until it interacts with a measuring device, only acquiring definite values as a result of the measurement. Such an abrupt change in the state of the system is called a collapse.

Physicist Erwin Schrödinger summarized this theory in 1935 with his famous feline paradox — using the metaphor of a cat in a sealed box being simultaneously dead and alive until the box is opened, thus collapsing the cat's state and revealing its fate.

However, applying these rules to real-world scenarios faces challenges — and that's where the true paradox arises. While quantum laws hold true for the realm of [elementary particles](#), larger objects behave in accordance with classical physics as predicted by Einstein's [theory of general relativity](#), and are never observed in a superposition of states. Describing the entire universe using quantum principles poses even greater hurdles, as the cosmos appears entirely classical and lacks any external observer to serve as a measuring device for its state.

"The question is can the Universe, which does not have a surrounding environment, be in such a superposition?" lead author [Matteo Carlesso](#), a theoretical physicist at the University of Trieste in Italy, told Live Science in an email. "Observations say no: everything goes along the classical predictions of General Relativity. Then, what is breaking such a superposition?"

To tackle this question, Carlesso and his colleagues proposed modifications to the Schrödinger equation, which governs how all states, including those in superposition, evolve over time.

"Specific modifications of the Schrödinger equation can solve the problem," Carlesso said. In particular, the team added terms to the equation that captured how the system interacts with itself, as well as adding some other specific terms. This in turn leads to superposition breaking down.

"Such effects are stronger the larger the system," Carlesso added.

Crucially, these modifications have little impact on microscopic quantum systems, such as atoms and molecules, but allow larger systems — like the universe itself — to collapse at frequent intervals, giving them definite values that fit with our observations of the cosmos. The team described their modified Schrödinger equation in February in the [Journal of High Energy Physics](#).

Taking the cat out of purgatory



An illustration of an atom (Image credit: Getty Images)

In their tweaked version of quantum physics, the researchers eliminated the distinction between objects subject to measurement and measuring devices. Instead, they proposed that each system's state undergoes spontaneous collapse at regular intervals, leading to the acquisition of definite values for some of their attributes.

For large systems, spontaneous collapse occurs frequently, rendering them classical in appearance. Subatomic objects interacting with these systems become part of them, leading to rapid collapse of their state and the acquisition of definite coordinates, akin to measurement.

"With no action from external entities, any system localizes (or collapses) spontaneously in a particular state. In place of having a cat being dead AND alive, one finds it dead OR alive," Carlesso said.

The new model may explain why our universe's [space-time](#) geometry doesn't exist in a superposition of states and obeys the classical equations of [Einstein's](#) relativity.

"Our model describes a quantum Universe, which eventually collapsed thus becoming effectively classical," Carlesso said. "We show that spontaneous collapse models can explain the emergence of a classical Universe from a quantum superposition of Universes, where each of these Universes has a different space-time geometry."

While this theory may explain why the universe seems to be governed by classical laws of physics, it doesn't make new predictions about large-scale physical processes.

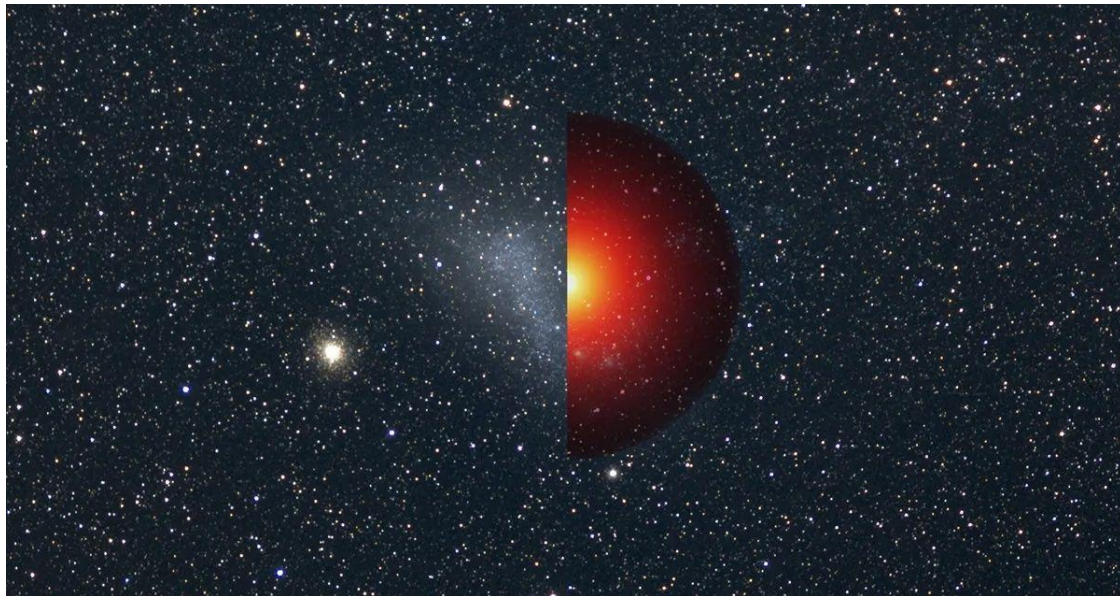
However, it does make predictions about how atoms and molecules will behave, albeit with minimal deviations from conventional quantum mechanics.

As a result, testing their modified quantum model won't be so simple. Future work will be aimed at coming up with such tests.

"Together with experimental collaborators, we are trying to test the effects of the collapse modifications or derive bounds on their parameters. This is completely equivalent to testing the limits of quantum theory."

published January 26, 2025

Because we haven't found anything yet, we've started to wonder if dark matter might be lighter or heavier than we thought.



Invisible dark matter makes up most of the mass in the universe, far outweighing the amount of matter we can see. (Image credit: Dark matter, R. Caputo et al. 2016; background, Axel Mellinger, Central Michigan University)

Dark matter can't be too heavy or it might break our best model of the universe, new research suggests.

We have an abundance of evidence that something fishy is happening in the universe. Stars orbit within galaxies far too quickly. Galaxies move around inside clusters much too fast. Structures grow and evolve too rapidly. If we count only the matter we can see, there simply isn't enough [gravity](#) to explain all of these behaviors.

The vast majority of cosmologists believe all of these phenomena can be explained through the presence of [dark matter](#), a hypothetical form of matter that is massive, electrically neutral and hardly, if ever, interacts with normal matter. This dark matter makes up most of the mass in the universe, far outweighing the amount of luminous matter.

The identity of dark matter remains a mystery, as experiments designed to detect a stray, rare collision have failed to turn up anything. But these experiments have focused on targeting a specific mass range: roughly 10 to 1,000 giga-electron volts (GeV). (A GeV is equivalent to 1 billion electron volts.) That's in the range of the heaviest known particles, like the W boson and the top quark. For decades, theorists favored this mass range because several simple extensions of the [Standard Model](#) of particle physics predicted the existence of such particles.

Because we haven't found anything yet, though, we've started to wonder if dark matter might be lighter or heavier than we thought. But heavier dark matter runs into some serious issues, according to a new [paper](#) published to the preprint database arXiv. The problem is that [dark matter does sometimes interact with normal matter](#), if only rarely. But in the early universe, when the cosmos was much hotter and denser, these interactions were much more frequent. Eventually, as the universe expanded and cooled, these interactions slowed and then stopped, leading the dark matter to "freeze out" and remain silent in the background.

While there are many, many models of potential dark matter candidates, many interact with regular particles through exchanges involving the [Higgs boson](#) — a fundamental particle that interacts with almost all other particles and, through those interactions, imbues those particles with mass.

We know the mass of the Higgs boson: around 125 GeV. The researchers found that this mass puts a fundamental upper limit on the possible mass of most dark matter candidates.

The problem is that all interactions in physics are two-way streets. The Higgs talks to both dark matter and regular matter and, in many models, mediates interactions between them. But both kinds of matter also talk back to the Higgs. These interactions appear as slight modifications to the Higgs boson's mass.

For Standard Model particles, we can calculate these corrections and feedback interactions, which is how theorists predicted the mass of the Higgs boson well before it was detected.

The researchers found that if the dark matter particle had a mass greater than a few thousand GeV, its contribution to the Higgs mass would be incredibly important, driving it

away from its observed value. And because the Higgs is so central to determining many other fundamental physics, it would essentially shut down particle interactions altogether.

There are possibilities to get around this restriction, however. Dark matter might not interact with regular particles at all, or the interaction might happen through some exotic mechanism that doesn't involve the Higgs. But those models are few and far between and require a lot of fine-tuning and extra steps.

Or it could be that dark matter is lighter than we thought. If we don't think heavy dark matter is a viable candidate, then as we continue to learn about this mysterious component of the universe, we can instead focus our efforts in the other direction. There has already been a surge of interest in axions, ultralight particles that are predicted in some particle physics models and might be a viable dark matter candidate.

On the experimental side, if this result is confirmed and holds to be a widespread restriction on dark matter particle mass, we can refine and redesign our experiments to search for low-mass, instead of high-mass, particles.

Originally posted on [Space.com](https://www.space.com).

'A frankly embarrassing result': We still know hardly anything about 95% of the universe

published January 22, 2025

"As yet, nobody has managed to understand what gives rise to this strange phenomenon, and explaining dark energy remains one of the most formidable challenges of modern science."



The discovery of dark energy nearly 30 years ago was a surprise — and it's still baffling scientists to this day. (Image credit: Javier Zayas Photography/Getty Images)

In this excerpt from "[Matter: The Magnificent Illusion](#)" (Polity, 2025, translated by Edward Williams), author and physicist Guido Tonelli delves into the discovery of dark energy, and the multiple attempts to explain this strange phenomenon that appears to be driving the ever increasing expansion of the universe.

The discovery of [dark energy](#) was a real surprise for everyone, including those working on it. When it happened, in 1998, the astronomers who were the first to find themselves in the presence of such surprising data, couldn't believe their eyes. And yet the results left no doubt.

The velocity at which the universe had expanded was not constant; on the contrary, for quite some time now it had been increasing significantly. Everything was moving away from everything at an increasingly frenetic rhythm.

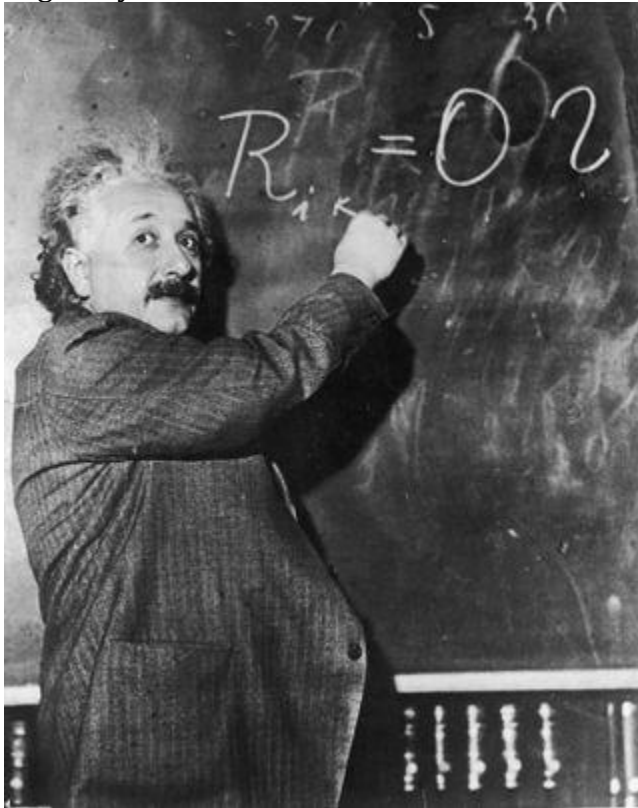
What scientists were seeing contradicted what they were expecting; the idea of the accelerated expansion of the universe was counterintuitive. Everyone expected that the attraction exerted by gravity would slowly reduce the expansion velocity of space-time, whereas the exact opposite was happening.'

For many years, different teams of scientists tried to understand whether what the data was pointing to was real or whether, on the other hand, errors had been made in the measurements. In the end, they gave in to the evidence. There was no doubt that a new natural phenomenon was being observed, however completely unexpected it was. In the end even the Royal Swedish Academy of Sciences in Stockholm recognized the importance of the work of [Saul Perlmutter](#), [Brian Schmidt](#) and [Adam Riess](#), the three astronomers who had carried out the early research, rewarding their discovery with the 2011 [Nobel Prize](#).

Right from the earliest moments, in an attempt to explain this strange phenomenon, the expression dark energy was coined, indicating the complete ignorance of the mechanism that produced it: an absolutely unknown form of energy seemingly pushing everything away from everything else and growing as the dimensions of the universe grow.

Some imagined a kind of anti-gravity, an extremely strange behaviour of gravity which from being attractive, as we know it, becomes repulsive over great distances. Others imagined a kind of vacuum energy, a positive energy, which creates a kind of negative pressure, thereby pushing everything towards dilation.

The idea that the void contains positive energy which makes it expand goes back many years. And [Albert Einstein](#) was the first to come up with it. To make the universe static, that is to counterbalance the effect of gravity, which, acting alone, would sooner or later make everything collapse into one point, Einstein added a positive constant, called the "[cosmological constant](#)" into his equations by hand, that is to say arbitrarily. This classification served to build a balance; making the universe expand countered the effects of gravity and made it stable.



Einstein proposed the idea of a "cosmological constant" to his theory of general relativity to counteract gravity and create a static universe. (Image credit: Keystone-France/Getty Images)

Later, when it was discovered that everything had had a turbulent beginning and that galaxies were still moving apart from one another, Einstein regretted this choice, to the extent of referring to it as one of the worst blunders of his life. In fact, with a universe arising from an ultra-dense and super-incandescent singularity, there was no need for this further impetus to expansion to produce a condition of equilibrium. The curious thing is

that nobody, least of all Einstein, could predict that by the end of the 20th-century, the discoveries made by Perlmutter, Schmidt and Riess would bring his cosmological constant back into vogue. And so, it seems as if nature will always end up proving Einstein right, even when the great scientist is convinced that he's clearly wrong.

In this case, too, precious information about the presence and distribution of dark energy can be extracted by analyzing the tiniest inhomogeneity in cosmic background radiation and the gravitational lens effects produced by galaxies and clusters. It's curious to discover that it is still light which allows us to take a look at this shady side of the cosmos.

The distribution of dark energy in the cosmos is very homogeneous. It behaves quite differently from matter, whether ordinary matter or [dark matter](#). These latter material substances have reticular distributions with high- density nodes and filaments alternating with broad empty spaces. On the contrary, dark energy is distributed uniformly throughout space and seems to occupy the entire volume of the universe quite happily, exerting a repulsive force on everything.

In an attempt to understand the origin of this mysterious form of energy, scientists have ascertained whether the expansion velocity is the same, over a given period, for all the different regions of the universe. They also realized that this phenomenon has only become dominant in the last billions of years. For a long period, the universe expanded following a very different rhythm from the current one.

Various hypotheses have been tested, including the idea that we are dealing with a new fundamental force or an anomalous behaviour of gravity or even the presence in the fabric of spacetime of very particular structures, similar to defects in its regular pattern. But, as yet, nobody has managed to understand what gives rise to this strange phenomenon, and explaining dark energy remains one of the most formidable challenges of modern science.

While the mystery surrounding its origins remains, the precise measurements taken of the effects of dark energy on the geometry of the universe and on the spatial fluctuations in the density of matter have made it possible to quantify the weight of this component in the material composition of the universe.

The result is sensational; dark energy contributes around 68% of the total mass. Around two-thirds of the universe is made up of this most mysterious of components. Totalling up the contribution of dark energy, we obtain a frankly embarrassing result. Despite the great progress made by contemporary science, we are forced to admit that we don't know anything about 95% of everything that surrounds us.

Otherworldly 'time crystal' made inside Google quantum computer could change physics forever

published September 14, 2021

The crystal is able to forever cycle between states without losing energy.



The time crystal was created inside Google's Sycamore chip, which is kept cool inside their quantum cryostat. (Image credit: Eric Lucero/Google, Inc.)

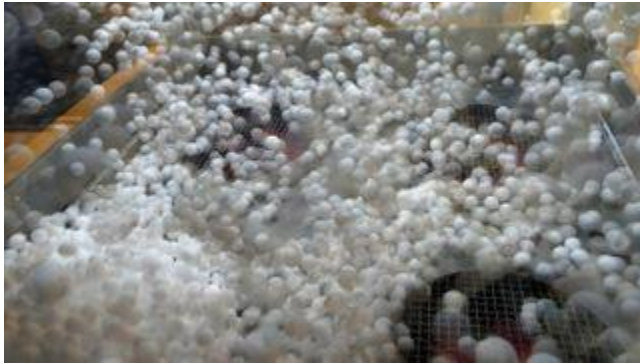
Researchers working in partnership with Google may have just used the tech giant's quantum computer to create a completely new [phase of matter](#) — a time crystal. With the ability to forever cycle between two states without ever losing energy, time crystals dodge one of the most important laws of physics — the [second law of thermodynamics](#), which states that the disorder, or entropy, of an isolated system must always increase. These bizarre time crystals remain stable, resisting any dissolution into randomness, despite existing in a constant state of flux. According to a research article posted July 28 to the preprint database [arXiv](#), scientists were able to create the time crystal for roughly 100 seconds using qubits (quantum computing's version of the traditional computer bit) inside the core of Google's Sycamore quantum processor.

The existence of this weird new matter phase, and the entirely new realm of physical behaviors it reveals, is incredibly exciting to physicists, especially as time crystals were only first predicted to exist just nine years ago.

"This was a big surprise," Curt von Keyserlingk, a physicist at the University of Birmingham in the U.K. who was not involved in the study, told Live Science. "If you asked someone 30, 20 or maybe even 10 years ago, they would not have expected this."

Time crystals are fascinating objects to physicists because they essentially sidestep the second law of thermodynamics, one of the most ironclad laws in physics. It states that entropy (a rough analog for the amount of disorder in a system) always increases. If you want to make something more ordered, you need to put more energy into it.

This tendency for disorder to grow explains a lot of things, such as why it's easier to stir ingredients into a mixture than it is to separate them out again, or why headphone cords get so tangled in pants' pockets. It also sets the arrow of time, with the past universe always more ordered than the present; watching a video in reverse, for instance, is likely to look strange to you primarily because you're witnessing the counterintuitive reversal of this entropic flow.



The second law of thermodynamics says that all systems evolve toward a state of more disorder, where energy is shared out evenly across the system. (Image credit: Universal History Archive/Universal Images Group via Getty Images) Time crystals don't follow this rule. Instead of slowly approaching thermal equilibrium — "thermalizing" so that their energy or temperature is equally distributed throughout their surroundings, they get stuck between two energy states above that equilibrium state, cycling back and forth between them indefinitely.

To explain how deeply unusual this behavior is, von Keyserlingk said to picture a sealed box filled with coins before being shaken a million times. As the coins ricochet from, and bounce around, each other, they "become more and more chaotic, exploring all of the sorts of configurations that they can explore" until the shaking stops, and the box is opened to reveal the coins in a random configuration, with roughly half of the coins facing up and half facing down. We can expect to see this random, half-up, half-down endpoint regardless of the way we first arranged the coins in the box.

Inside the "box" of Google's Sycamore, we can view the quantum processor's qubits much like we would our coins. In the same way that the coins can be either heads or tails, qubits can be either a 1 or a 0 — the two possible positions in a two-state system — or a weird mix of the probabilities of both states called a superposition. What's weird about time

crystals, von Keyserlingk says, is that no amount of shaking, or zapping from one state to another, can move the time crystal's qubits into the lowest energy state, which is a random configuration; they can only flip it from its starting state to its second state, then back again.

"It just sort of flip-flops," von Keyserlingk said. "It doesn't end up looking random, it just gets jammed stuck. It's like it remembers what it looked like initially, and it repeats that pattern over time."

In this sense, a time crystal is like a pendulum that never stops swinging.

"Even if you totally physically isolate a pendulum from the universe, so there's no friction and no air resistance, it will eventually stop. And that's because of the second law of thermodynamics," Achilleas Lazarides, a physicist at the University of Loughborough in the U.K. who was among the scientists to first discover the theoretical possibility of the new phase in 2015, told Live Science. "Energy starts out concentrated in the pendulum's center of mass, but there's all of these internal degrees of freedom — like the ways the [atoms](#) can vibrate inside the rod — that it will eventually be transferred into."

In fact, there's no way for a large-scale object to behave like a time crystal without sounding absurd, because the only rules that enable time crystals to exist are the spooky and surreal rules that govern the world of the very small — [quantum mechanics](#).

In the quantum world, objects behave both like point particles and little waves at the same time, with the magnitude of these waves in any given region of space representing the probability of finding a particle at that location. But randomness (such as random defects in a crystal's structure or a programmed randomness in the interaction strengths between qubits) can cause a particle's probability wave to cancel itself out everywhere apart from one very small region. Rooted in place, unable to move, change states or thermalize with its surroundings, the particle becomes localized.

The researchers used this localization process as the foundation of their experiment. Using 20 strips of superconducting [aluminum](#) for their qubits, the scientists programmed each one into one of two possible states. Then, by blasting a microwave beam over the strips, they were able to drive their qubits to flip states; the researchers repeated the experiment for tens of thousands of runs and stopped at different points to record the states their qubits were in. What they found was that their collection of qubits was flipping back and forth between only two configurations, and the qubits weren't absorbing heat from the microwave beam either — they had made a time crystal.

They also saw a key clue that their time crystal was a phase of matter. For something to be considered a phase, it usually has to be very stable in the face of fluctuations. Solids will not melt if the [temperatures](#) around them vary slightly; neither will slight fluctuations cause liquids to evaporate or freeze suddenly. In the same way, if the microwave beam used to flip the qubits between states was adjusted to be close to but slightly off from the exact 180 degrees needed for a perfect flip, the qubits still nonetheless flipped to the other state.

"It's not the case that if you're not exactly at the 180 degrees you will scramble them," Lazarides said. "It [the time crystal] magically will always tip a bit in, even if you're making slight mistakes."

Another hallmark of moving from one phase to another is the breaking of physical symmetries, the idea that the laws of physics are the same for an object at any point in time or space. As a liquid, the molecules in water follow the same physical laws at every point in space and in every direction, but cool water down enough so that it transforms into ice and its molecules will pick regular points along a crystal structure — or lattice — to arrange themselves across. Suddenly, the water molecules have preferred points in space to occupy, and they leave the other points empty — the spatial symmetry of the water has been spontaneously broken.

In much the same way that ice becomes a crystal in space by breaking with spatial symmetry, time crystals become crystals in time by breaking with time symmetry. At first, before their transformation into the time crystal phase, the row of qubits will experience a continuous symmetry between all moments in time. But the periodic cycle of the microwave beam chops the constant conditions experienced by the qubits down into discrete packets (making the symmetry imposed by the beam a discrete time-translation symmetry). Then, by flipping back and forth at twice the period of the wavelength of the beam, the qubits break with the discrete time-translation symmetry imposed by the laser. They are the first objects we know of that are able to do this.

All of this weirdness makes time crystals rich in new physics, and the control that Sycamore provides researchers beyond other experimental setups could make it an ideal platform for further investigation. That's not to say it cannot be improved, however. Like all quantum systems, Google's quantum computer needs to be perfectly isolated from its environment to prevent its qubits from undergoing a process called decoherence, which eventually breaks down the quantum localization effects, destroying the time crystal. The researchers are working on ways to better isolate their processor and mitigate the impact of decoherence, but it's unlikely they will eliminate the effect for good.

Despite this, Google's experiment is likely to remain the best way to study time crystals for the foreseeable future. Though numerous other projects have succeeded in making what convincingly appear to be time crystals in other ways — with diamonds, helium-3 superfluids, quasiparticles called magnons and with [Bose-Einstein condensates](#) — for the most part the crystals produced in these setups dissipate too quickly for detailed study. The theoretical newness of the crystals is in some ways a double-edged sword, as physicists currently struggle to find clear applications for them, although von Keyserlingk has suggested that they could be used as highly accurate sensors. Other proposals include using the crystals for better memory storage or for developing quantum computers with even faster processing power.

But in another sense, the greatest application of time crystals may already be here: They allow scientists to probe the boundaries of quantum mechanics.

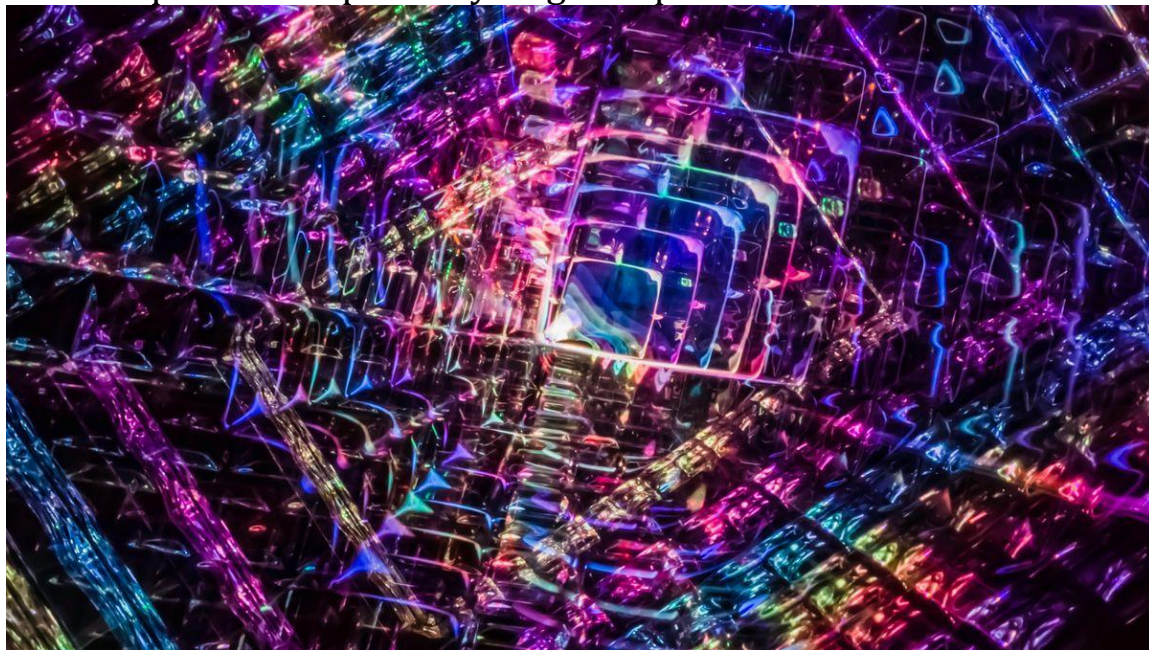
"It allows you to not just study what shows up in nature, but to actually design it and look at what quantum mechanics lets you do and doesn't let you do," Lazarides said. "If you don't find something in nature then it doesn't mean it can't exist — we just created one of those things."

Originally published on Live Science.

China claims fastest quantum computer in the world

published December 7, 2020

China's quantum supremacy reigns supreme.



(Image credit: Alamy)

A team of Chinese scientists has developed the most powerful [quantum](#) computer in the world, capable of performing at least one task 100 trillion times faster than the world's fastest supercomputers.

In 2019, Google said it had built the first machine to achieve "quantum supremacy," the first to outperform the world's best supercomputers at quantum calculation, [Live Science previously reported](#). (IBM disputed Google's claim at the time.) The Chinese team, based primarily at the University of Science and Technology of [China](#) in Hefei, reported their quantum computer, named Jiuzhang, is 10 billion times faster than Google's. A description of Jiuzhang and its feat of calculation was published Dec. 3 in the journal [Science](#). Assuming

both claims hold up, Jiuzhang would be the second quantum computer to achieve quantum supremacy anywhere in the world.
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PLAY SOUND

China has invested heavily in quantum computing, with Xi Jinping's government spending \$10 billion on the country's National Laboratory for Quantum Information Sciences, [NDTV](#) reported. The country is also a world leader in quantum networking, where data encoded using quantum mechanics is transmitted across great distances, as Quantum computers can exploit the unusual [mathematics](#) governing the quantum world to outperform classical computers on certain tasks, [as Live Science reported](#). Where classical computers perform calculations using bits, which can have one of two states (typically represented by a 1 or a 0), quantum bits, or qubits, can exist in many states simultaneously. This allows them to solve problems more quickly than classical computers. But while the theories predicting that quantum computing would beat classical computing have been around for decades, building practical quantum computers has proved much more challenging.

The Chinese computer makes its calculations (limited to particular questions about the behavior of light particles) using optical circuits. Google's device, Sycamore, uses superconducting materials on a chip and more nearly resembles the basic structure of classical computers. Neither would be particularly useful on its own as a computer, and the Chinese device was built to solve just one type of problem.

To test Jiuzhang, the researchers assigned it a "Gaussian boson sampling" (GBS) task, where the computer calculates the output of a complex circuit that uses light. That output is expressed as a list of numbers. (Light is made of particles known as photons, which belongs to a category of particles known as bosons.)

Success is measured in terms of number of photons detected. Jiuzhang, which itself is an optical circuit, detected a maximum of 76 photons in one test and an average of 43 across several tests. Its calculation time to produce the list of numbers for each experimental run was about 200 seconds, while the fastest Chinese supercomputer, TaihuLight, would have taken 2.5 billion years to arrive at the same result. That suggests the quantum computer can do GBS 100 trillion times faster than a classical supercomputer.

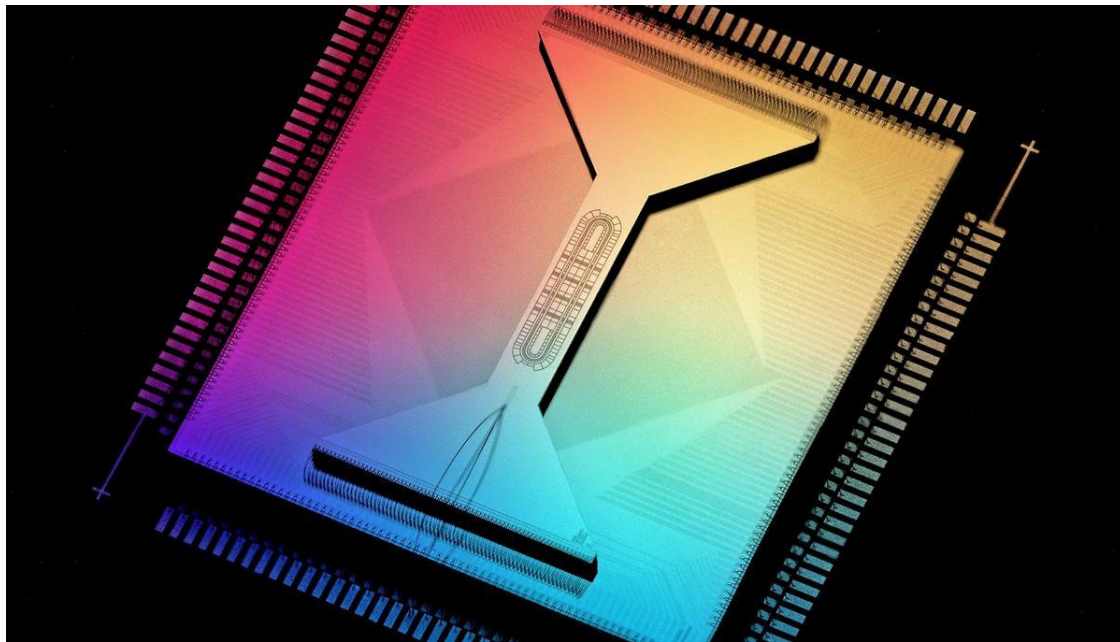
This doesn't mean that China has a fully practical quantum computer yet, according to Xinhua. China's device is specialized, and mostly useful as a tool for doing GBS. But it's a major milestone on the way there.

Originally published on Live Science.

Bizarre particle that can remember its own past created inside quantum computer

published August 1, 2023

Non abelian-anyons' recollection of their past has enabled physicists to weave them into complex entangled designs with new behaviors.



Quantinuum's H2 quantum processor, on which the non-abelian anyons were created. (Image credit: Quantinuum)

A weirdo particle that can remember its own past has been created inside a [quantum computer](#), and scientists think it could be used to probe even deeper into quantum phenomena.

The quasiparticles, called non-abelian anyons, maintain records of their previous location when swapped with each other — enabling physicists to weave them together into complex entangled designs with new and weird behaviors.

To get a picture of how most subatomic particles behave, imagine the old street game where a ball is hidden under one of three identical cups, then shuffled around. Just like in this shell game, if you swap three perfectly identical particles around any number of times without tracking their movements, you'll have no way of guessing which is which by the time the cups have stopped moving. In quantum physics jargon, we say that particles are abelian: the order we observe them in doesn't matter because they are indistinguishable. Yet for non-abelian anyons, the opposite is the case. First proposed by the theoretical physicist Frank Wilczek in 1982, each change to the positions of the bizarre particles causes them to become more entangled with each other, altering their quantum

vibrations to form an ever-more-complex braid that remains visible even after they have been swapped.

For physicists designing quantum computers, this gives non-abelian anyons some very alluring properties. Quantum bits, or qubits, can easily be exposed to noise and scrambled, meaning that scientists often try to encode information in quantum systems not in the bits themselves, but in how the bits are arranged relative to each other.

For an analogy, imagine a book “where every page is empty, but if you look at all the pages at once, the information slowly adds up,” [Henrik Dryer](#), a theoretical physicist at the quantum computing firm Quantinuum, which created the particle, told Live Science. “Even if you scratch out one page, it doesn't matter, because the information is in the correlation between the pages.”

Dryer explained that until now, physicists working on quantum computers have connected the pages using abelian particles, or ones that are completely interchangeable. This is an effective method to account for noise, but because abelian particles are indistinguishable from each other, it requires computationally intense workarounds to prevent the qubits from getting mixed up.

To find a way around this, Dryer and his colleagues developed a new quantum computer, named H2, that trapped ions of barium and ytterbium inside powerful magnetic fields, before tuning the ions with lasers to transform them into qubits.

By entangling these qubits with each other into a complex braid-like arrangement, the researchers found they had given the qubits properties exactly like those predicted for non-abelian anyons — a result which they say is equivalent to having created the elusive particles.

“It's not simulated, it's the real thing. And that is just the mathematical definition,” Dryer said. “Let's take water ice: if you make a crystal that has the same properties as ice, but without H₂O, then you could say it was a simulation, right?” But in this case, the definition of a non-abelian anyon is only about entanglement.

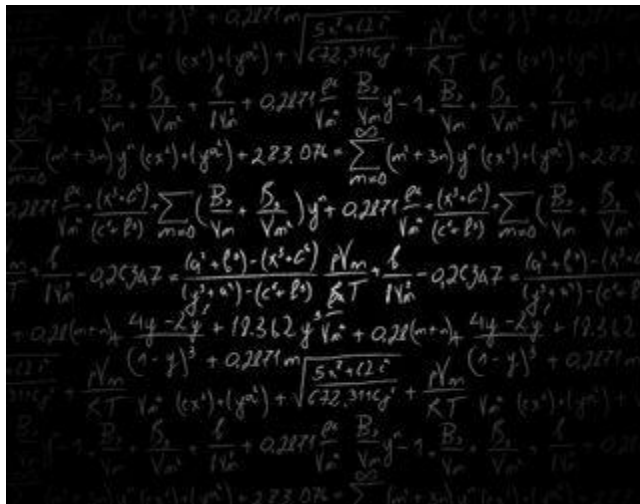
Besides helping build more robust quantum systems, the scientists say that non-abelian anyons will help them to design more advanced experiments to probe even deeper into weird quantum effects that emerge from large-scale entanglement.

“I think the most exciting thing that comes out of this is using these kinds of states, not for computational purposes, but just for asking research questions,” Dryer said. “This could provide some value to people as a science tool by performing new experiments that you couldn't with a classical computer.”

Images: The World's Most Beautiful Equations

published January 29, 2013

Numerical beauty

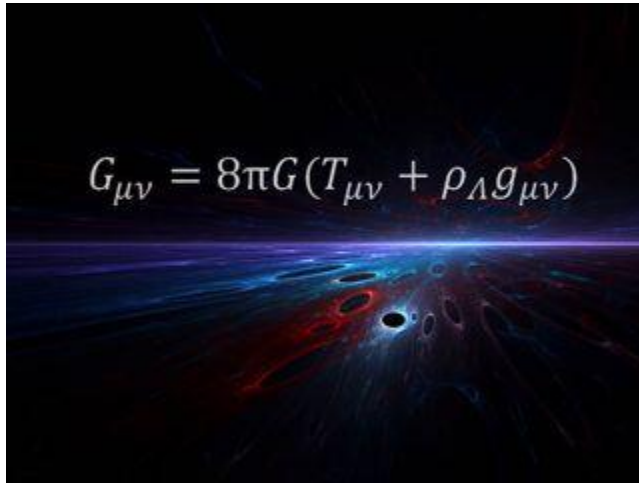
A blackboard filled with complex mathematical equations, including the Schrödinger equation and various summations and integrals. The equations are written in white chalk on a dark background. The top part of the board shows the Schrödinger equation:
$$\frac{\partial \psi}{\partial t} = \frac{\hbar}{4\pi m} \nabla^2 \psi + \sqrt{\frac{5\pi^2 + 12\pi}{c^2 32, 311 c^2}} + \frac{\hbar}{4\pi m} \nabla^2 \psi + \dots$$
 Below this, there are several lines of equations involving summations and integrals, such as
$$\sum_{m=0}^{\infty} (m^2 + 3m) y^m (x^m) + 2.23, 074 = \sum_{m=0}^{\infty} (m^2 + 3m) y^m (x^m) + 2.23, 074$$
 and
$$\frac{1}{T} \frac{1}{V_m} - 0.25347 = \frac{(q^2 + q^2) - (x^2 + c^2)}{(y^2 + q^2) - (c^2 + p^2)} \frac{\hbar}{4\pi m} - 0.25347 = \frac{(q^2 + q^2) - (x^2 + c^2)}{(y^2 + q^2) - (c^2 + p^2)} \frac{\hbar}{4\pi m}$$

(Image credit: Shutterstock/[Fedorov Oleksiy](#))

Mathematical equations aren't just useful — many are quite beautiful. And many scientists admit they are often fond of particular formulas not just for their function, but for their form, and the simple, poetic truths they contain.

While certain famous equations, such as Albert Einstein's $E = mc^2$, hog most of the public glory, many less familiar formulas have their champions among scientists. LiveScience asked physicists, astronomers and mathematicians for their favorite equations; here's what we found:

General relativity



(Image credit: Shutterstock/[R.T. Wohlstadter](#))

The equation above was formulated by [Einstein](#) as part of his groundbreaking [general theory of relativity](#) in 1915. The theory revolutionized how scientists understood gravity by describing the force as a warping of the fabric of space and time.

"It is still amazing to me that one such mathematical equation can describe what space-time is all about," said Space Telescope Science Institute astrophysicist Mario Livio, who nominated the equation as his favorite. "All of Einstein's true genius is embodied in this equation." [[Einstein Quiz: Test Your Knowledge of the Genius](#)]

"The right-hand side of this equation describes the energy contents of our universe (including the 'dark energy' that propels the current cosmic acceleration)," Livio explained. "The left-hand side describes the geometry of space-time. The equality reflects the fact that in Einstein's general relativity, mass and energy determine the geometry, and concomitantly the curvature, which is a manifestation of what we call gravity." [[6 Weird Facts About Gravity](#)]

"It's a very elegant equation," said Kyle Cranmer, a physicist at New York University, adding that the equation reveals the relationship between space-time and matter and energy.

"This equation tells you how they are related — how the presence of the sun warps space-time so that the Earth moves around it in orbit, etc. It also tells you how the universe evolved since [the Big Bang](#) and predicts that there should be black holes."

Standard model

$$\begin{aligned}
 \mathcal{L}_{SM} = & \underbrace{\frac{1}{4} W_{\mu\nu}^a \cdot W^{\mu\nu a} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} G_{\mu\nu}^a G^{\mu\nu a}}_{\text{kinetic energies and self-interactions of the gauge bosons}} \\
 & + \underbrace{\bar{L} \gamma^\mu (i\partial_\mu - \frac{1}{2} g \tau \cdot \mathbf{W}_\mu - \frac{1}{2} g' Y B_\mu) L + \bar{R} \gamma^\mu (i\partial_\mu - \frac{1}{2} g' Y B_\mu) R}_{\text{kinetic energies and electroweak interactions of fermions}} \\
 & + \underbrace{\frac{1}{2} |(i\partial_\mu - \frac{1}{2} g \tau \cdot \mathbf{W}_\mu - \frac{1}{2} g' Y B_\mu) \phi|^2 - V(\phi)}_{\text{W, Z, } \gamma \text{ and Higgs masses and couplings}} \\
 & + \underbrace{g'' (\bar{q} \gamma^\mu T_a q) G_\mu^a}_{\text{interaction between quarks and gluons}} + \underbrace{(G_1 \bar{L} \phi R + G_2 \bar{L} \phi_c R + h.c.)}_{\text{fermion masses and couplings to Higgs}}
 \end{aligned}$$

(Image credit: Shutterstock/[R.T. Wohlstadter](#))

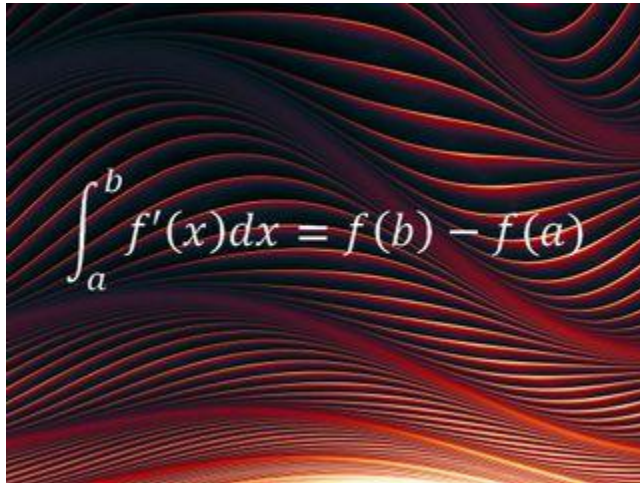
Another of physics' reigning theories, the [standard model](#) describes the collection of fundamental particles currently thought to make up our universe.

The theory can be encapsulated in a main equation called the standard model Lagrangian (named after the 18th-century French mathematician and astronomer Joseph Louis Lagrange), which was chosen by theoretical physicist Lance Dixon of the SLAC National Accelerator Laboratory in California as his favorite formula.

"It has successfully described all elementary particles and forces that we've observed in the laboratory to date — except gravity," Dixon told LiveScience. "That includes, of course, the recently discovered Higgs(like) boson, phi in the formula. It is fully self-consistent with quantum mechanics and special relativity."

The standard model theory has not yet, however, been united with general relativity, which is why it cannot describe gravity. [[Infographic: The Standard Model Explained](#)]

Calculus


$$\int_a^b f'(x)dx = f(b) - f(a)$$

(Image credit: Shutterstock/[agsandrew](#))

While the first two equations describe particular aspects of our universe, another favorite equation can be applied to all manner of situations. The fundamental theorem of calculus forms the backbone of the mathematical method known as calculus, and links its two main ideas, the concept of the integral and the concept of the derivative.

"In simple words, [it] says that the net change of a smooth and continuous quantity, such as a distance travelled, over a given time interval (i.e. the difference in the values of the quantity at the end points of the time interval) is equal to the integral of the rate of change of that quantity, i.e. the integral of the velocity," said Melkana Brakalova-Trevithick, chair of the math department at Fordham University, who chose this equation as her favorite. "The fundamental theorem of calculus (FTC) allows us to determine the net change over an interval based on the rate of change over the entire interval."

The seeds of calculus began in ancient times, but much of it was put together in the 17th century by [Isaac Newton](#), who used calculus to describe the motions of the planets around the sun.

Pythagorean theorem



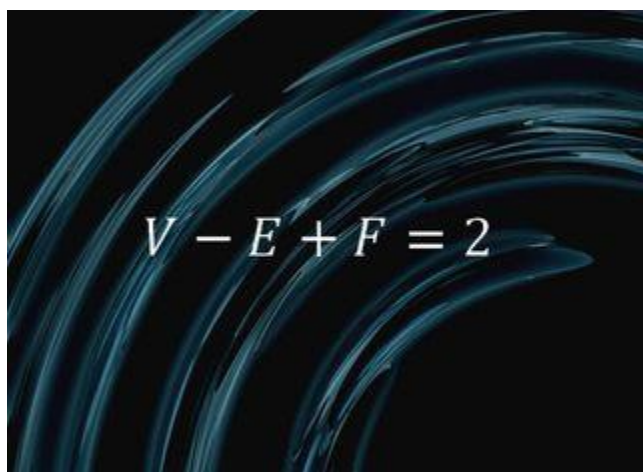
(Image credit: Shutterstock/ [igor.stevanovic](#))

An "oldie but goodie" equation is the famous Pythagorean theorem, which every beginning geometry student learns.

This formula describes how, for any right-angled triangle, the square of the length of the hypotenuse (the longest side of a right triangle) equals the sum of the squares of the lengths of the other two sides.

"The very first mathematical fact that amazed me was Pythagorean theorem," said mathematician Daina Taimina of Cornell University. "I was a child then and it seemed to me so amazing that it works in geometry and it works with numbers!" [[5 Seriously Mind-Boggling Math Facts](#)]

Euler's equation



(Image credit: Shutterstock/ [Jezper](#))

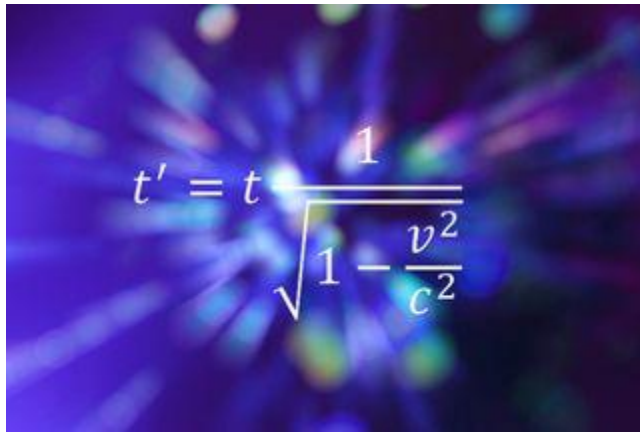
This simple formula encapsulates something pure about the nature of spheres:

"It says that if you cut the surface of a sphere up into faces, edges and vertices, and let F be the number of faces, E the number of edges and V the number of vertices, you will always get $V - E + F = 2$," said Colin Adams, a mathematician at Williams College in Massachusetts.

"So, for example, take a tetrahedron, consisting of four triangles, six edges and four vertices," Adams explained. "If you blew hard into a tetrahedron with flexible faces, you could round it off into a sphere, so in that sense, a sphere can be cut into four faces, six edges and four vertices. And we see that $V - E + F = 2$. Same holds for a pyramid with five faces — four triangular, and one square — eight edges and five vertices," and any other combination of faces, edges and vertices.

"A very cool fact! The combinatorics of the vertices, edges and faces is capturing something very fundamental about the shape of a sphere," Adams said.

Special relativity


$$t' = t \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

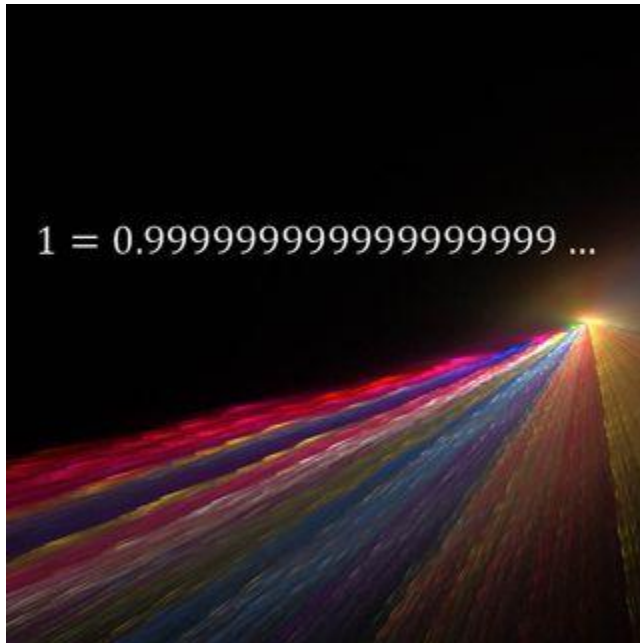
(Image credit: Shutterstock/[optimarc](#))

Einstein makes the list again with his formulas for [special relativity](#), which describes how time and space aren't absolute concepts, but rather are relative depending on the speed of the observer. The equation above shows how time dilates, or slows down, the faster a person is moving in any direction.

"The point is it's really very simple," said Bill Murray, a particle physicist at the CERN laboratory in Geneva. "There is nothing there an A-level student cannot do, no complex derivatives and trace algebras. But what it embodies is a whole new way of looking at the world, a whole attitude to reality and our relationship to it. Suddenly, the rigid unchanging cosmos is swept away and replaced with a personal world, related to what you observe. You move from being outside the universe, looking down, to one of the components inside it. But the concepts and the maths can be grasped by anyone that wants to."

Murray said he preferred the special relativity equations to the more complicated formulas in Einstein's later theory. "I could never follow the maths of general relativity," he said.

$$1 = 0.999999999 \dots$$

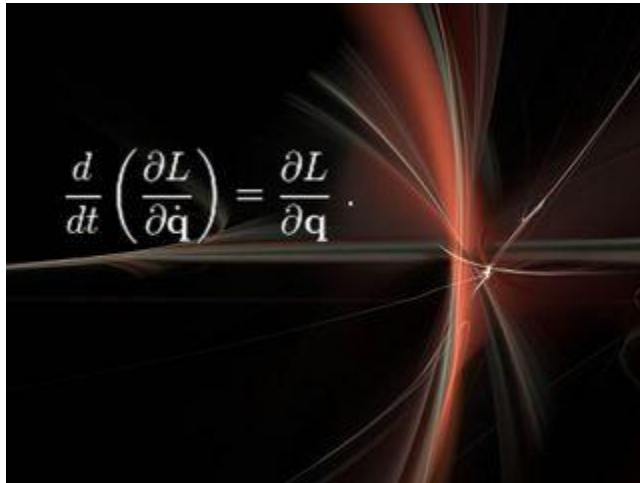


(Image credit: Shutterstock/[Tursunbaev Ruslan](#))

This simple equation, which states that the quantity 0.999, followed by an infinite string of nines, is equivalent to one, is the favorite of mathematician Steven Strogatz of Cornell University.

"I love how simple it is — everyone understands what it says — yet how provocative it is," Strogatz said. "Many people don't believe it could be true. It's also beautifully balanced. The left side represents the beginning of mathematics; the right side represents the mysteries of infinity."

Euler-Lagrange equations and Noether's theorem

An abstract, artistic representation of the Euler-Lagrange equation. The equation $\frac{d}{dt} \left(\frac{\partial L}{\partial \dot{\mathbf{q}}} \right) = \frac{\partial L}{\partial \mathbf{q}}$ is displayed in white text on a dark background. The background features a complex, glowing pattern of red and orange lines that appear to be trajectories or paths in a high-dimensional space, possibly representing the configuration space of a physical system. The lines are concentrated in the center and spread out towards the edges, creating a sense of dynamic movement and complexity.

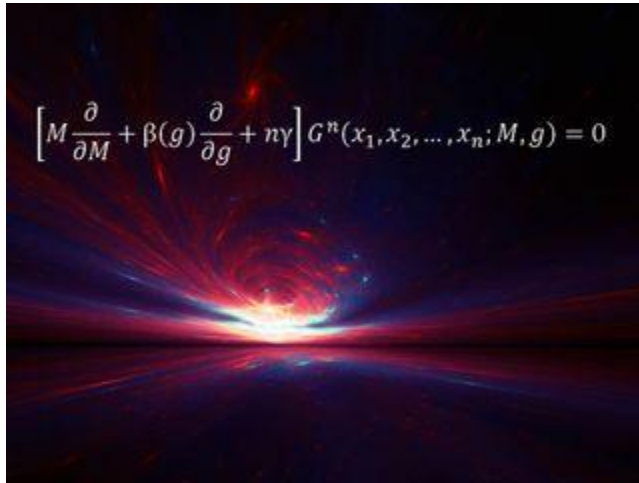
(Image credit: Shutterstock/[Marc Pinter](#))

"These are pretty abstract, but amazingly powerful," NYU's Cranmer said. "The cool thing is that this way of thinking about physics has survived some major revolutions in physics, like quantum mechanics, relativity, etc."

Here, L stands for the Lagrangian, which is a measure of energy in a physical system, such as springs, or levers or fundamental particles. "Solving this equation tells you how the system will evolve with time," Cranmer said.

A spinoff of the Lagrangian equation is called Noether's theorem, after the 20th-century German mathematician Emmy Noether. "This theorem is really fundamental to physics and the role of symmetry," Cranmer said. "Informally, the theorem is that if your system has a [symmetry](#), then there is a corresponding conservation law. For example, the idea that the fundamental laws of physics are the same today as tomorrow (time symmetry) implies that energy is conserved. The idea that the laws of physics are the same here as they are in outer space implies that momentum is conserved. Symmetry is perhaps the driving concept in fundamental physics, primarily due to [Noether's] contribution."

Callan-Symanzik Equation


$$\left[M \frac{\partial}{\partial M} + \beta(g) \frac{\partial}{\partial g} + n\gamma \right] G^n(x_1, x_2, \dots, x_n; M, g) = 0$$

(Image credit: Shutterstock/[R.T. Wohlstadter](#))

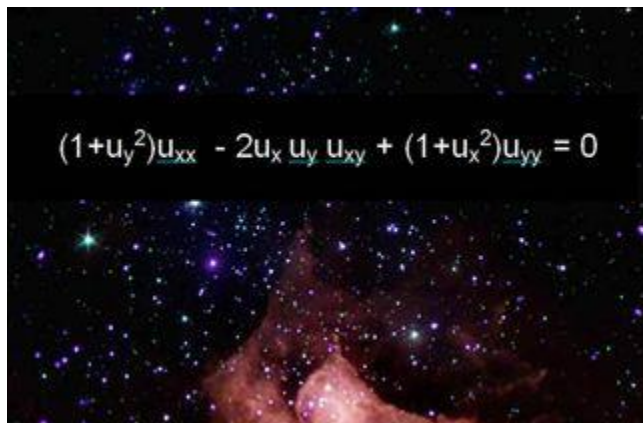
"The Callan-Symanzik equation is a vital first-principles equation from 1970, essential for describing how naive expectations will fail in a [quantum world](#)," said theoretical physicist Matt Strassler of Rutgers University.

The equation has numerous applications, including allowing physicists to estimate the mass and size of the proton and neutron, which make up the nuclei of atoms.

Basic physics tells us that the gravitational force, and the electrical force, between two objects is proportional to the inverse of the distance between them squared. On a simple level, the same is true for the strong nuclear force that binds protons and neutrons together to form the nuclei of atoms, and that binds quarks together to form protons and neutrons. However, tiny quantum fluctuations can slightly alter a force's dependence on distance, which has dramatic consequences for the strong nuclear force.

"It prevents this force from decreasing at long distances, and causes it to trap quarks and to combine them to form the protons and neutrons of our world," Strassler said. "What the Callan-Symanzik equation does is relate this dramatic and difficult-to-calculate effect, important when [the distance] is roughly the size of a proton, to more subtle but easier-to-calculate effects that can be measured when [the distance] is much smaller than a proton."

The minimal surface equation



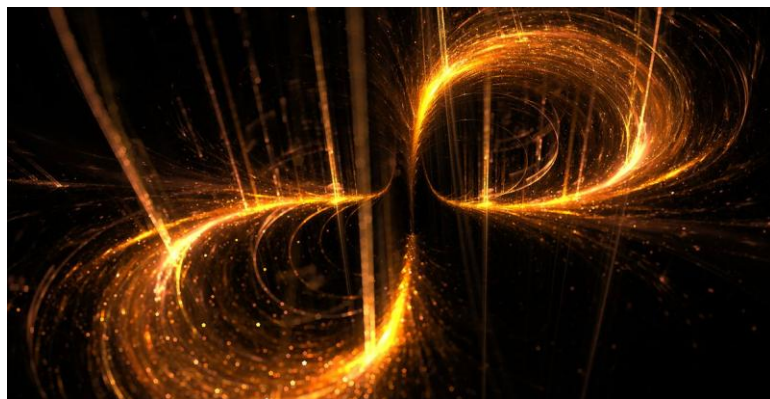
(Image credit: Hubble)

"The minimal surface equation somehow encodes the [beautiful soap films](#) that form on wire boundaries when you dip them in soapy water," said mathematician Frank Morgan of Williams College. "The fact that the equation is 'nonlinear,' involving powers and products of derivatives, is the coded mathematical hint for the surprising behavior of soap films. This is in contrast with more familiar linear partial differential equations, such as the heat equation, the wave equation, and the Schrödinger equation of quantum physics."

The 9 most massive numbers in existence

last updated October 23, 2024

From the humble trillion to Graham's number, here are some of the most massive numbers ever conceived by humans.

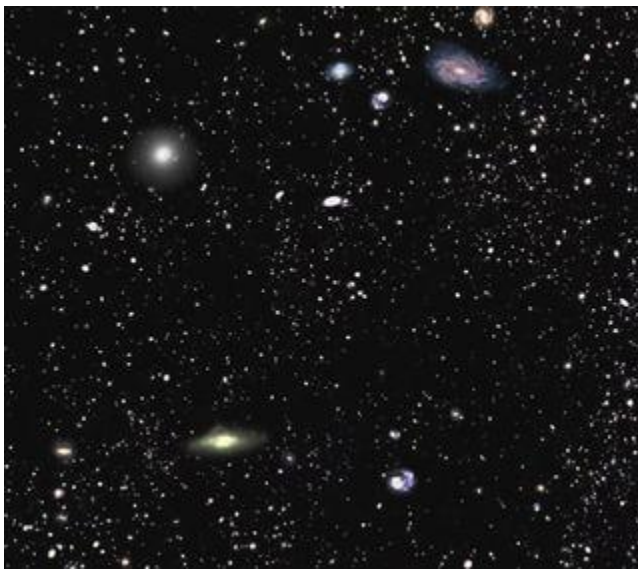


There are infinitely many large numbers, but some of the biggest non-infinite numbers are still so big they can't be represented by standard mathematical notation. (Image credit: Shutterstock)

Big numbers are everywhere, from the cells in the human body to the size of the universe. But once numbers edge past the realm of the physical, the human mind can struggle to grasp the sheer awesome scale of these numbers. Even infinity can seem easier to understand in comparison — it just goes on and on. And once numbers start to get large enough, everything starts to blur together, the late [Jon Borwein](#), who was an applied mathematician at the University of Newcastle in Australia, told Live Science in 2013. "We don't understand numbers on this scale," Borwein said.

From the humble trillion to Graham's number, here are some of the most mind-boggling numbers there are.

Big is relative



This still from an animated fly-through of the new universe map created by the Sloan Digital Sky Survey-III shows the positions of galaxies mapped in 3D space. (Image credit: Miguel A. Aragón (Johns Hopkins University), Mark SubbaRao (Adler Planetarium), Alex Szalay (Johns Hopkins University), Yushu Yao (Lawrence Berkeley National Laboratory, NERSC), and the SDSS-III Collaboration)

When thinking about a personal budget, a [\\$31.4 trillion debt ceiling](#) is pretty inconceivable. But on the scale of the atoms in the universe, it looks absolutely paltry in comparison, Scott Aaronson, a computer scientist formerly at MIT and now at the University of Texas at Austin, told Live Science in 2013.

To try to understand huge numbers, most people rely on analogies of scale. For instance, Carl Sagan famously likened the age of the universe to a calendar year, with humans only showing up in the last few hours of New Year's Eve.

Riemann hypothesis

$$\zeta(s) = \sum_{n=1}^{\infty} \frac{1}{n^s}$$

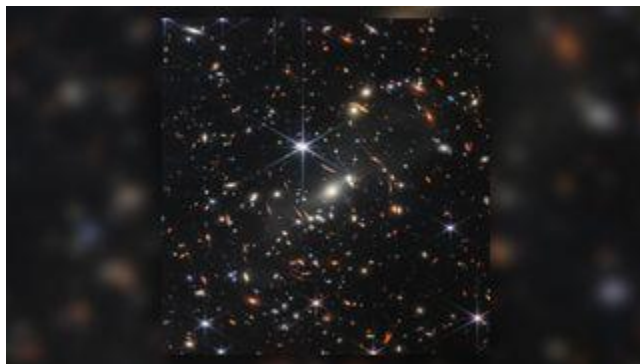
The Riemann zeta function. Anyone who solves the Riemann hypothesis, which states that any non-trivial zero of this equation is $1/2$, will win a \$1 million prize. (Image credit: Furfur)

First stated in 1859, [the Riemann hypothesis](#) is one of the greatest unsolved conjectures of mathematics, and whoever solves it will nab a \$1 million prize. The hypothesis is that the real part of every non-trivial zero of a specific function, aptly named the Riemann zeta function, is $1/2$.

"This is the biggest open question in mathematics, the one that will guarantee your name is known in 10,000 years," Borwein said.

The hypothesis, if true, has important implications for the distribution of prime numbers, which aren't divisible by anything other than themselves or one. To test the hypothesis, mathematicians look for extremely large primes — those bigger than about 10 raised to the power of 30, he said. That may sound abstract, but it has many real-world implications, Borwein said. "Primes are embedded in everything we use for encryption," he said. "That all relies on stuff where the algorithms are designed using properties of primes that we think are true but don't know."

The universe



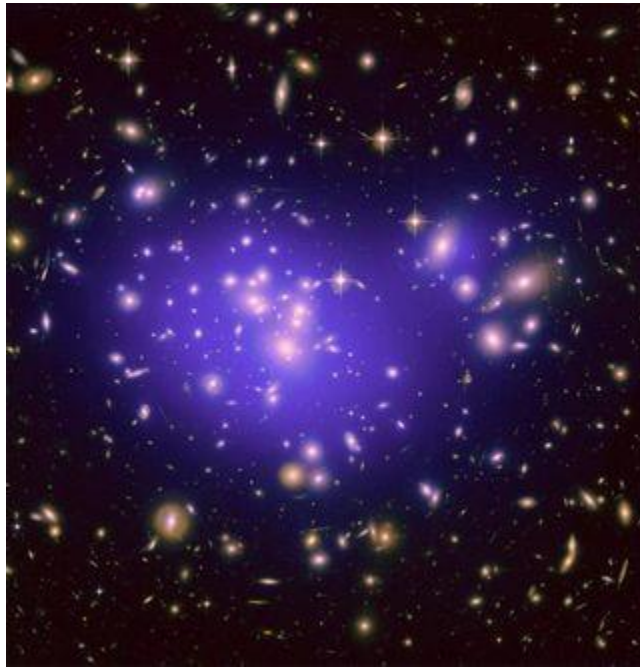
NASA's James Webb Space Telescope has produced the deepest and sharpest infrared image of the distant universe to date. The universe is thought to contain 10^{82} atoms, research suggests. (Image credit: NASA, ESA, CSA, and STScI)

As far back as Archimedes, philosophers have wondered how many tiny particles could fit in [the universe](#). Archimedes estimated that about 10 to the power of 63 grains of sand could fill the universe. He used a series of extremely rough estimates — the poppy seeds

that make a grain of sand, the grains of sand that would cover the length of a stadium, and the stadia lengths between Earth and the sun, said [Henry Mendell](#), a classical historian at California State University, Los Angeles.

Despite his crude measures, he wasn't too far off. Current estimates put the total number of atoms in the universe at about [10 to the 82](#).

Cosmological fudge factor



The galaxy cluster Abell 1689. A study of Abell 1689 reveals something about how dark energy shapes the universe, a key element of the cosmological constant discrepancy. (Image credit: NASA, ESA, E. Jullo (JPL/LAM), P. Natarajan (Yale) and J-P. Kneib (LAM))

When Einstein conceived of his equations of [relativity](#), he included a small constant, called the [cosmological constant](#), to account for the fact that the universe is stationary. Though he later scrapped the constant when he learned the universe is expanding, it turns out the genius may have been on to something: Scientists believe the cosmological constant, which amounts to just 10 raised to the minus 122 power, reveals clues to the dark energy that is mysteriously accelerating the universe, Aaronson told Live Science in 2013.

The cosmological constant has been a huge headache for scientists because predictions differ from measurements of the constant by 120 orders of magnitude, and over the years, physicists have tried to explain away this discrepancy by tweaking other elements, such as how particle mass changes over time, [Live Science previously reported](#).

Hercules and the Hydra

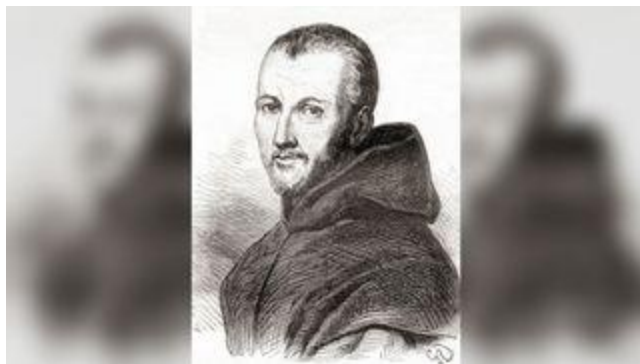


A 19th-century illustration of Hercules slaying the hydra. This myth inspired a riddle about how quickly the number of Hydra heads will grow if multiple sprout every time Hercules cuts off one. (Image credit: Getty Images)

Sometimes things have to get big before they get small. In 1982, mathematicians Jeff Paris and Laurie Kirby [posed a riddle](#): Imagine Hercules fighting a Hydra that grows heads like a tree. If he cuts off one head, the mythic monster simply grows back a certain number of heads governed by a few rules. Amazingly, Hercules will always prevail against the Hydra eventually and chop off all of the Hydra's heads.

But even if Hercules is clever and chooses the most efficient strategy, the Hydra will first grow more than a googolplex of heads (or 10 raised to the power of 10 raised to the 100 power).

Mersenne primes



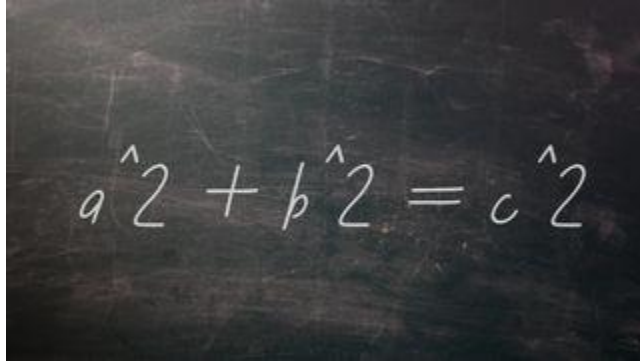
Marine Mersenne was a 17th century monk and polymath who is perhaps best known for describing a sequence of prime numbers, now named after him. (Image credit: ilbusca/Getty Images)

The Mersenne Primes are a class of numbers that get big in a hurry. These prime numbers are equal to 2 raised to the power of a prime number minus 1. While the first few start out small — 3, 7, 31 — they blow up to become incredibly large extremely quickly. Until about 1951, only 12 of these primes were known, but by this year (2024), 52 were known.

To power through these gigantic numbers, scientists use the Great Internet Mersenne Primes Search (GIMPS), which uses the computing power of thousands of Internet users to search for the elusive prime numbers. The [largest known prime number](#) was discovered in October 2024 by amateur researcher and former Nvidia employee Luke Durant. The

number, $2^{136,279,841} - 1$, possesses a whopping 41,024,320 digits, more than 16 million digits more than the previous record holder, which was also discovered by GIMPS six years earlier.

A trillion triangles



Right triangles in which the sides are all integers or fractions are known as congruent triangles, and the area of said triangles are known as congruent numbers. These numbers can get huge very, very quickly. (Image credit: Background: Eskay Lim / EyeEm via Getty Images)

Around 1000 years ago, [Persian mathematician Al Karaji](#) first asked how many congruent numbers existed. But just what are congruent numbers? The numbers are the area of right-angle triangles with integer or fraction length sides. So a triangle with sides of length of 3, 4 and 5 would have an area of $\frac{1}{2} * 3 * 4 = 6$, making 6 a congruent number.

It took another millennia before the first hundred congruent numbers were discovered. By 2009, however supercomputers had discovered the first 3,148,379,694 congruent numbers. Some of these numbers are so enormous that if their digits were written out in decimal form, they would stretch to the moon and back. Gigantic numbers have interesting implications in data storage, because they are so huge that a stray gamma ray could disrupt the bits in these numbers and make them wrong, Borwein said.

Graham's number



This illustration shows a black hole emitting jets of fast-moving plasma above and below it, as matter swirls around in an orbiting disk. (Image credit: NASA/JPL-Caltech)

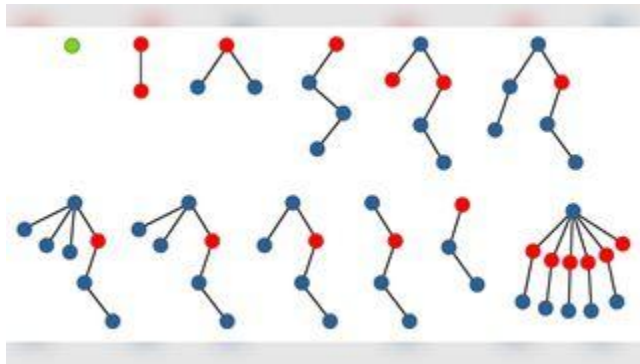
All these numbers pale in comparison to Graham's number, a number so large that simply trying to remember all the digits would turn your head into a black hole. The number, which at one point was the largest number to ever be used in a math proof, arose in

response to a simple riddle about how to allocate people to a certain set of committees with a few constraints.

While mathematicians are confident that at least 13 people are needed to solve the problem, in the 1970s mathematician and juggler Ronald Graham deduced that the number of people had to be lower than Graham's number. Simply computing the number would take 64 steps, and involves multiplying an insanely huge number of 3s.

There is no way to write the number out using scientific notation, and instead it must be written with a series of up-arrows that denote towers of exponents. Later on, Graham showed that the upper bound to for this riddle is much much smaller than Graham's number, but still huge.

TREE(3)



A sequence of rooted trees with three labels (red, green and blue). The n th tree in the sequence contains at most n vertices, and no tree is inf-embeddable within any later tree in the sequence. TREE(3) is defined to be the longest possible length of such a sequence. (Image credit: LightbulbMEOW; Wikimedia Commons; [CC BY-SA 4.0](#))

While Graham's number was one of the largest numbers proposed for a specific math proof, mathematicians have gone even bigger since then. In 1998 the logician [Harvey Friedman](#) of The Ohio State University [proposed a riddle](#) asking how long a sequence of letters needs to be given certain parameters of repeating stretches of letters. While the answer isn't infinite, it's absolutely massive.

The number Friedman derived, TREE(3), is calculated by creating increasingly massive towers of twos raised to the power of two using something called Ackerman functions. To give a sense of the scale, the fourth Ackerman functions involves raising two to the power of 65,536 twos. But TREE(3) is massively, massively larger than that — so massive that it makes Graham's number look like the tiniest fleck of dust in comparison.

"These higher levels of largeness blur, where one is unable to sense one level of largeness from another," Friedman wrote in his paper.