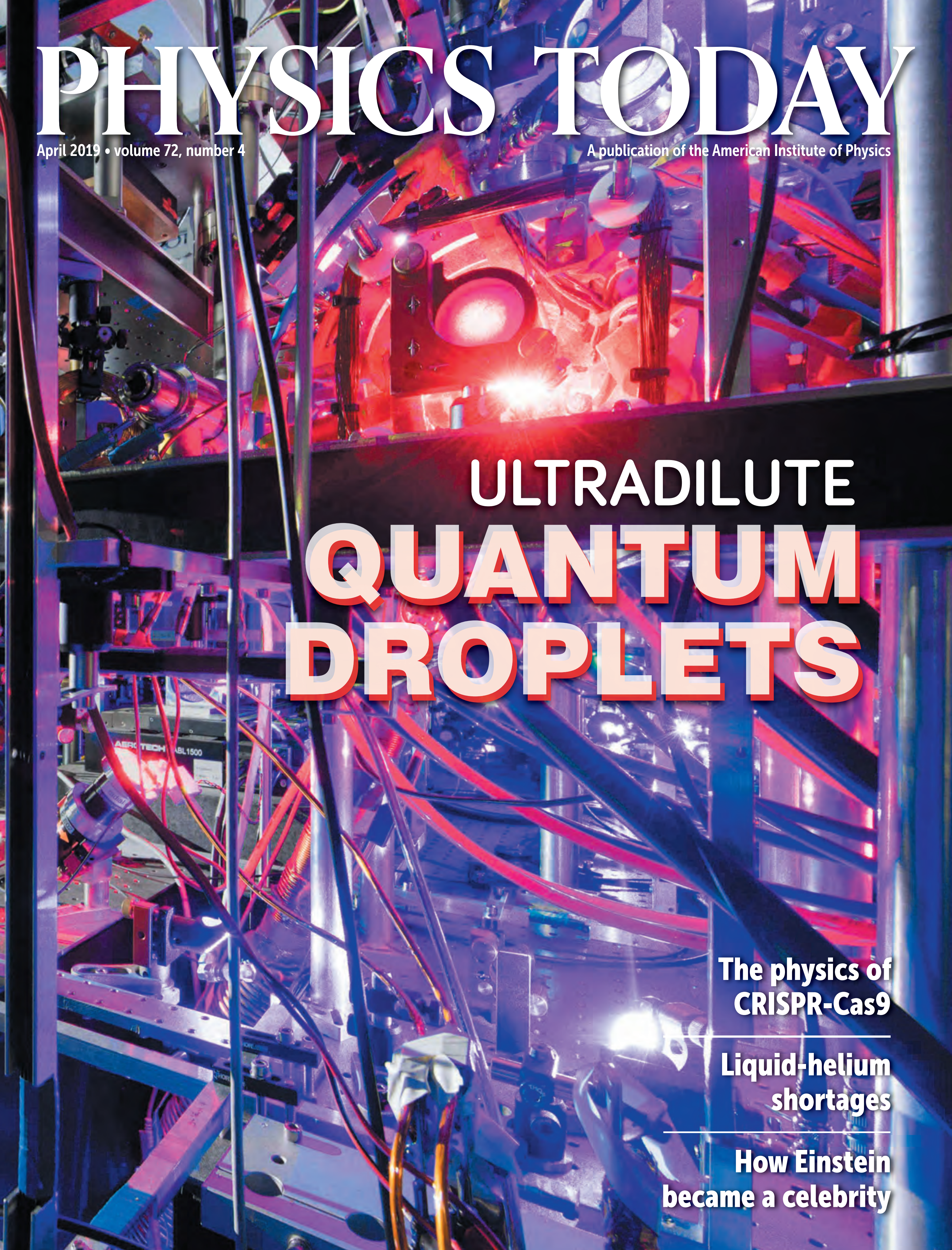
PHYSICS TODAY

April 2019 • volume 72, number 4

A publication of the American Institute of Physics



ULTRADILUTE QUANTUM DROPLETS

The physics of CRISPR-Cas9

Liquid-helium shortages

How Einstein became a celebrity

HINDSIGHT IS 20/20.
READY TO GO BACK?

Buckle up, and make your future self proud.
Apply for ***APSIT Group Term Life Insurance*** *coverage*
today, and there'll be nothing to regret tomorrow.

APSITplans.com/TL-Now

APSIT
INSURANCE FOR SCIENCE PROFESSIONALS

800.272.1637 | APSITplans.com/TL-Now

Voltage Controlled Current Source

Your science. Our tools. SRS.

- Sources/sinks AC & DC current
- Analog voltage control input
- 1 nA/V to 50 mA/V gain
- 200 kHz bandwidth
- ±50 V compliance
- Ultra-low noise design
- RS-232 & optical fiber interfaces

The Model CS580 Voltage Controlled Current Source creates new capabilities for researchers needing an ultra-low noise current source in a flexible, easy to use instrument.

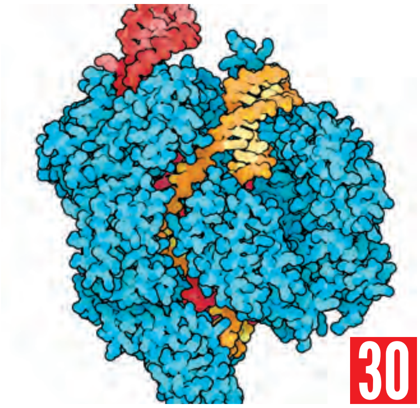
The CS580 is a natural companion to sensitive AC instruments such as lock-in amplifiers, providing a easy way of generating precision current directly from an AC or DC control voltage.

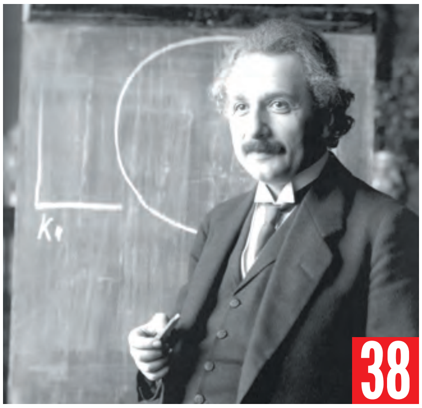
The CS580 is a welcome addition to any research lab studying semiconductors and transport phenomena, superconductivity, or nanotechnology, to name just a few.

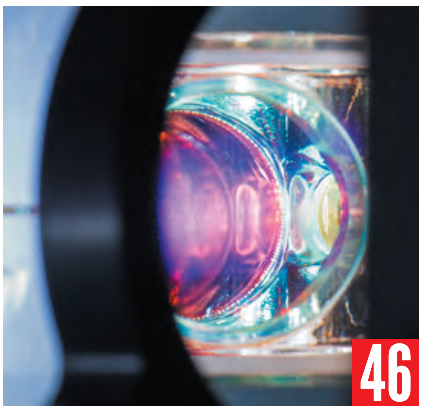
Model CS580 ... $2795 (U.S. list)

Stanford Research Systems
www.thinkSRS.com • Tel: 408-744-9040

www.thinksrs.com/products/cs580.html







PHYSICS TODAY

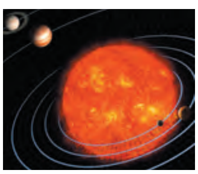
April 2019 | volume 72 number 4

FEATURES

ON THE COVER: In 2016, researchers at the University of Stuttgart in Germany created ultradilute quantum droplets of dysprosium atoms. The red and blue scattered light surrounding their optical table, shown here, comes from the lasers used to cool the atoms. On **page 46**, Igor Ferrier-Barbut explains the mean-field energy correction that led to the droplets' prediction and describes their subsequent realizations. (Photo courtesy of Wolfram Scheible.)

Recently on PHYSICS TODAY ONLINE

www.physicstoday.org



NASA

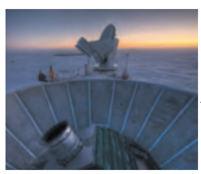
▶ Planet proximity

Venus is often referred to as Earth's nearest planetary neighbor. But although it does get closer to Earth than does any other planet, it's not the closest most frequently or when averaged over time. That honor goes to Mercury. Three researchers do the math and show that Mercury is also the nearest on average to each planet in the solar system.
physicstoday.org/Apr2019a

FASER/CERN

▶ Dark-sector search

A newly approved experiment at CERN's Large Hadron Collider will hunt for low-mass particles that could make up dark matter. The $1 million Forward Search Experiment, or FASER, is expected to begin collecting data in 2021. PHYSICS TODAY's Toni Feder explains how the detector gained fast-track approval.
physicstoday.org/Apr2019b



STEFFEN RICHTER, HARVARD U

▶ Seeking inflation

In 2014 the BICEP2 team claimed detection of a 13.8-billion-year-old signal that on further investigation turned out to be the signature of galactic dust. Five years later PHYSICS TODAY examines the ongoing search for primordial *B* modes and the implications of the results so far for various theories of cosmic inflation.
physicstoday.org/Apr2019c

PHYSICS TODAY (ISSN 0031-9228, coden PHTOAD) volume 72, number 4. Published monthly by the American Institute of Physics, 1305 Walt Whitman Rd, Suite 300, Melville, NY 11747-4300. Periodicals postage paid at Huntington Station, NY, and at additional mailing offices. POSTMASTER: Send address changes to PHYSICS TODAY, American Institute of Physics, 1305 Walt Whitman Rd, Suite 300, Melville, NY 11747-4300. Views expressed in PHYSICS TODAY and on its website are those of the authors and not necessarily those of AIP or any of its member societies.

PHYSICS TODAY
www.physicstoday.org

DEPARTMENTS

SUBSCRIPTION QUESTIONS? +1 800 344-6902 | +1 516 576-2270 | **ptsubs@aip.org**

Address
American Center for Physics
One Physics Ellipse
College Park, MD 20740-3842
+1 301 209-3100
pteditors@aip.org

PhysicsToday **@physicstoday**

Less physics, more mystery

Charles Day

My wife and I have fully caught up watching two TV dramas that involve travel between alternative realities. In *The Man in the High Castle* (Amazon Studios), Nazi Germany and Imperial Japan occupy, respectively, the eastern and western parts of North America, having prevailed in World War II two decades previously (the show is set in 1962). The other reality, which barely appears on screen, is our own. In *Counterpart* (Starz), the two realities consist of our own and a clone of it that sprang into existence by accident in 1987. The plot unfolds in present-day Berlin (or Berlins, I should say).

How the two shows explain and exploit interdimensional travel differs. For the first two seasons of *The Man in the High Castle*, the travel is evidently an important background element, but most characters are unaware of it. The first hint of another reality comes in the first episode, when one of the main characters, an American named Juliana Crane, comes across what seems like a newsreel that depicts victorious Allied soldiers in Berlin. No actual interdimensional travel is seen on screen until the first season's final episode, when another main character, Japanese trade minister Nobusuke Tagomi, dozes off on a bench in San Francisco's Union Square. When he wakes, he finds himself in a US-run San Francisco devoid of Japanese occupiers. A few instances of interdimensional travel occur in the second season, but it remains in the background.

Things change in the third and latest season, when it emerges that the German Reich has a top-secret research facility in a coal mine in Lackawanna County, Pennsylvania. There, a massive quantum machine, which resembles the ATLAS and CMS detectors at the Large Hadron Collider, has been built to create the physical conditions for interdimensional travel.

Quantum physics is not required for interdimensional travel in *Counterpart*, whose second and final season ended this past February. To cross between the two realities, the few people who know about the worlds—mostly spies and diplomats—simply walk across a heavily guarded passageway that serves as the only border and portal. The drama arises from the fact that the worlds have diverged in the 22 years since the cloning. One world suffered a devastating flu epidemic; the other didn't. That difference, along with the random fluctuations of everyday life, caused people in one world to diverge from their counterparts in the other. On the rare occasions when two counterparts meet, they discover they look similar, but they feel and think differently, despite their identical DNA and their identical, precloning pasts.

Physics, we learn in the flashback episode 6 of the second season, is responsible for forming the cloned world. A synchrotron light source in Berlin malfunctioned and triggered a brief episode of earthquake-like shaking. Perhaps inspired by Hugh Everett's many-worlds interpretation of quantum mechanics, the accident cloned the world.

It's not surprising that the showrunners and screenwriters of both *The Man in the High Castle* and *Counterpart* invoke physics. Physicists study time and space. Teleportation of quantum properties and spooky action at a distance are real. Physics—albeit fanciful and false—bestows authority on science fiction. The Q Continuum of *Star Trek: The Next Generation*, for example, is not explained. But it is described in the language of physics as an "extradimensional plane of existence."

"Explanations, like lies, become less convincing the more elaborate they are."

Watching *The Man in the High Castle* made me wonder whether physics needed to be invoked at all. Until the appearance of the huge quantum machine in season 3, I was prepared to accept the existence of two realities without explanation. The same question of necessity crossed my mind when I watched *Counterpart*. Until that flashback episode, the show was free of physics.

On balance, science fiction should be sparing and judicious when it comes to buttressing plot elements with quasi science. For one thing, explanations, like lies, become less convincing the more elaborate they are. The reader's or viewer's willing disbelief risks being unsuspended, especially if he or she is a scientist. For another, science dispels mystery and imagination. The Force in *Star Wars* lost some of its power to enthrall when, in the first of the regrettable prequels, *The Phantom Menace*, it was ascribed to microscopic, symbiotic bugs. PT

Commentary

Making my way in physics

While I was in high school in New York City, I had a naive view of science. I thought of it as a collection of facts that only existed in textbooks. Still, after physics class piqued my interest, I explored my attraction to science by interning at the American Museum of Natural History. At AMNH, I engaged visitors by performing hands-on experiments in the museum's halls—building tinfoil penny boats to teach about buoyancy and bending light through prisms to demonstrate how telescope lenses work. I was swept away by the spark of excitement I saw in the visitors' faces, so I decided to follow my teachers' examples and set my sights on becoming a physics educator.

In fall 2014 I entered Hunter College, part of the City University of New York (CUNY), as a physics major. That same year I set a foot on the path to research and became a fellow in the astronomy program AstroCom NYC. My continuing internship experiences developed my understanding of the physics community and my place in it and helped me figure out what I wanted to do post-undergrad.

As part of my AstroCom NYC fellowship, the summer after my freshman year I returned to the AMNH to be a part of Brown Dwarfs in New York City (BDNYC), a collaboration between the museum, Hunter College, and CUNY College of Staten Island. I discovered that I enjoy the day-to-day tasks of research. I savored the relief of finally getting my code to run after hours of fighting bugs, the rush of giving a scientific talk, and the stop-and-go pace of remote observations, my first being on NASA's Infrared Telescope Facility. I started to see science as a living body of knowledge and as a field populated by curious individuals.

VICTORIA DiTOMASSO, author of this commentary, took an atypical route to her current position at the Leibniz Institute for Astrophysics Potsdam in Germany, where she studies stars under a Fulbright grant. She stands here in front of the Reichstag building, home of the German parliament.

Although I felt welcomed by the BDNYC researchers, with whom I still collaborate today, I found them somewhat intimidating. They were overwhelmingly brilliant, incredibly independent, and focused on their investigations in a way I felt I was not. I had expected that first summer to transform me into a research scientist, but I had some way to go before I could see myself as a valuable member of the group.

During sophomore year, I continued my research with BDNYC but also became involved with BridgeUp: STEM, a program for high school girls interested in learning coding for science, technology, engineering, and mathematics. My role was to mentor two students in their programming-based projects related to the work being done by BDNYC. My mentees used Python and SQL to analyze brown dwarf data and produce visualizations; at the end of the year, they presented a scientific poster. Guiding the students helped change my thinking that I was less than a scientist. In their eyes, I was the expert, a view that certainly built my confidence. As the liaison between the students and my own mentor from BDNYC, I got an inside look at what goes into designing a student's project. As I learned more about brown dwarfs, built coding techniques, went on more observing runs, and gave more presentations, I shared my journey with the students so we could grow together.

Although working with the students helped me feel like a scientist, it ultimately made me reconsider going into education. The summer after my sophomore year I pursued an internship of a different type: I became a Society of Physics Students (SPS) history intern at the American Institute of Physics (which publishes PHYSICS TODAY). I wrote teaching guides about the history of women and minorities in the physical sciences. For what seemed like the first time, I read about physicists other than Isaac Newton and Albert Einstein. I found plenty of evidence that collaboration among scientists with diverse backgrounds and identities, as opposed to the singular genius of a few male luminaries, has pushed the field forward throughout history. I became emboldened to believe that I could be in those history books someday.

During my SPS internship I also learned about science careers beyond research and academia, particularly in science policy. I and the other interns attended a briefing by NASA and the Planetary Society on Capitol Hill, participated in a STEM fair put on by Women's Policy Inc (now the Women's Congressional Policy Institute), and spoke with the Democratic chief of staff for the House Committee on Science, Space, and Technology. Meeting scientists in a government setting opened my eyes to how a STEM education and career could enable me to have influence beyond my field.

Next, as a representative of the American Astronomical Society, I participated in a STEM Congressional Visits Day. I received further training from the society on how the government functions and how I, a scientist and citizen, can affect it. My experiences that summer made me realize that continuing in research beyond my college years could open doors to other careers, including in education and science policy.

Over the following two years I continued to do research at the AMNH and the University of Michigan, through their Summer Research Opportunities Program. I purposefully balanced my efforts in fundamental research and nonresearch activities. I wrote articles for national

CONTACT PHYSICS TODAY

Letters and commentary are encouraged and should be sent by email to **ptletters@aip.org** (using your surname as the Subject line), or by standard mail to Letters, PHYSICS TODAY, American Center for Physics, One Physics Ellipse, College Park, MD 20740-3842. Please include your name, work affiliation, mailing address, email address, and daytime phone number on your letter and attachments. You can also contact us online at **http://contact.physicstoday.org**. We reserve the right to edit submissions.

physics undergraduate publications; helped revive Hunter College's physics and astronomy club and served as its vice president; served on AMNH's Youth and Alumni Committee, where I helped run student events and promoted education programs; and organized a coding "hack day" for CUNY women in STEM. The "soft" skills that I developed in those nonresearch pursuits served me well in giving presentations, participating in discipline-specific workshops, and collaborating with scientists.

During my last year as an undergraduate, I applied to PhD programs in astronomy and astrophysics and for postbaccalaureate positions. In my application, I highlighted the multiple ways in which I had participated in science throughout my college years. I came to appreciate the early and long-standing investment that my mentors at BDNYC, AstroCom NYC, and the University of Michigan had made in me as they supported my research and allowed me time and freedom to identify and follow my own path. Because of those experiences I can envision making a contribution to the field, and I see it arising from my passion for education, communication, and collaboration and from my varied experience. I consider myself fortunate that admissions committees seem to have seen value in the skills I gained outside the lab.

The days of scientists all having the same personal and professional background are slowly coming to an end. My story here may be a bit uncommon, but I don't think it should be. Varied internship experiences have shaped my idea of physics as a field into that of one I can see myself working in long term. They have also helped me gain skills that will ultimately form my contributions to the field, and those skills are not mathematical genius or the ability to answer a hundred physics questions in three hours. I have gone from planning to be a high school physics teacher to receiving a Fulbright grant for 2018–19 to study the lowest mass stars at the Leibniz Institute for Astrophysics Potsdam in Germany. And now I have plans to enroll this fall in Harvard University's astronomy department to pursue a PhD.

Especially for students who do not fit the scientist stereotype, having the opportunities and time to explore a field and find their place in it is essential. The scientific community would do well to make various opportunities accessible to students with different socioeconomic, racial, and educational backgrounds; gender identities; sexual orientations; and physical abilities. Science directly benefits from a diverse set of thinkers with diverse skills.

Victoria DiTomasso
(victoriaditomasso@gmail.com)
Potsdam, Germany

LETTERS

Challenges facing high-field tokamaks

David Kramer wrote an interesting report on high-magnetic-field fusion devices for the August 2018 issue of Physics Today (page 25). The high magnetic field certainly does shrink the device's plasma volume, but high magnetic field is a double-edged sword. It has significant disadvantages. The story points out only one: the increased pressure on the field coils.

Another disadvantage is that as one shrinks the device, the neutron wall loading increases. Take SPARC, the tokamak being developed by Commonwealth Fusion Systems (CFS). It has 1/70 the volume of ITER, the international prototype fusion energy reactor, but 10 times the power density. Whereas ITER hopes to achieve 500 MW of neutron power, SPARC hopes to achieve about 70 MW. If one assumes surface area scales as the 2/3 power of volume, SPARC's surface area is about 1/17 of ITER's. Hence SPARC, a small experimental device, will have about 2.5 times ITER's wall loading of about 1 MW/m^2! The problem will only get worse as CFS moves to devices like the ARC (affordable, robust, compact) reactor, which will produce commercially interesting amounts of power. Wall loading is a big issue, not a minor detail, in fusion physics.

In addition, whereas the plasma scales to smaller size with increasing magnetic field, the fusion blanket does not. No matter what the magnetic field, the blanket has to prevent leakage of uncharged neutrons out the other end. The minimum blanket thickness I have seen is about one and a half meters thick. The blanket alone dictates some minimum size for a power-producing fusion device. It is difficult to see how shrinking the minor radius to below a meter buys you very much if the blanket thickness is one and a half meters. That could be a problem especially for the Tokamak Energy device, a spherical tokamak, which relies on a thin center post that must remain superconducting in the presence of an intense neutron flux.

To me, the most important advantage of using high-temperature superconductors (HTS), whether at 5 T or 10 T, is a point Kramer mentions in passing at the end. Namely, the magnets could be disassembled and reassembled rather easily. Since I first heard of tokamaks a half century ago, the story has always been that because of the interlocking coil arrangement, one could not do maintenance on them. The new HTS magnets, in one fell swoop, may have solved that issue. To me, that is the really big deal.

Wallace Manheimer
(wallymanheimer@yahoo.com)
Allendale, New Jersey PT


IDEA

Neutron-rich magnesium undergoes unexpected transitions

The structure of an exotic isotope near the edge of stability strays from that of its lower-mass counterparts.

The first model of the nucleus envisioned it as a structureless liquid drop of protons and neutrons. In 1949 Maria Goeppert Mayer and Hans Jensen upended that picture by introducing the nuclear shell model: Like electrons in a nuclear potential, protons and neutrons too experience a central potential generated by the other nucleons and therefore, as quantum particles, must exist in discrete energy levels.[1] For their discovery, Goeppert Mayer and Jensen shared half of the 1963 Nobel Prize in Physics (see PHYSICS TODAY, December 1963, page 21).

Today researchers can use heavy-ion accelerators to study much more exotic nuclides than the more easily accessible ones that inspired the nuclear shell model. Experiments have shown that low-atomic-number nuclei with nearly equal numbers of protons and neutrons are well described by the model. As proton–neutron asymmetry increases, however, the model's mean-field approximation breaks down, and corrections to the nuclear potential change the shell structure and its energy levels.

With 12 protons and 28 neutrons, magnesium-40 exists at the edge of nuclear stability. In a new study of the nuclide's nuclear excitations, a multi-institute team of researchers using the Radioactive Isotope Beam Factory (RIBF) at the RIKEN Nishina Center in Wako, Japan, has found that the nuclear structure of ^{40}Mg does not follow the trends established by lighter Mg nuclides.[2] Gamma-ray spectroscopic measurements of the first two excited states of ^{40}Mg uncovered energies much lower than those predicted by current models and experimental trends. The researchers tentatively attribute the discrepancy to weak binding of the outermost neutrons, but it is not yet clear whether accounting for that in theoretical calculations will reproduce the observed transition energies.

FIGURE 1. THE RADIOACTIVE ISOTOPE projectile separator BigRIPS enabled researchers to isolate enough magnesium-40 for gamma-ray spectroscopy. The separator was part of the upgrade to RIKEN's facility in 2007 and is used to separate the isotopes produced by the primary beam's breakup into secondary beams. BigRIPS allows for higher-intensity beams than its predecessor, RIPS, because of its larger apertures and two-stage separation scheme. (Photo courtesy of RIKEN Nishina Center.)

The outer limit

The shell model predicts that particular so-called magic numbers—2, 8, 20, 28, 50, 82, or 126—of neutrons (N) or protons (Z) make for especially stable nuclei because they have a filled outer shell. Because of the energy gap between shells, the first excitation in a nucleus with a

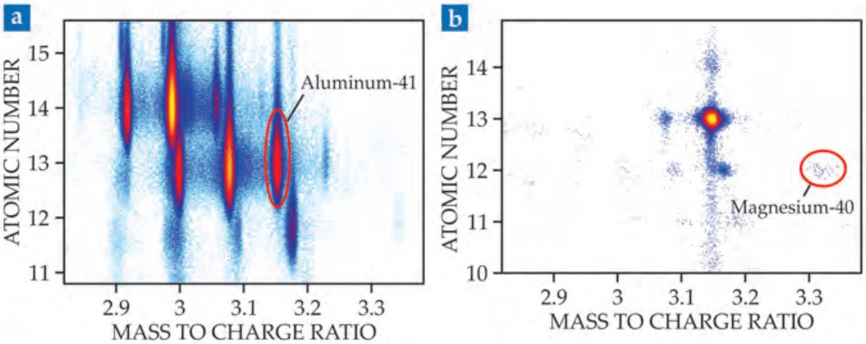


FIGURE 2. THE RADIOACTIVE ISOTOPE BEAM FACTORY AT RIKEN uses a high-intensity calcium-48 beam to generate exotic isotopes. **(a)** A beam of aluminum-41 nuclei (circled in red) can be clearly identified after the breakup of the primary ^{48}Ca beam on a beryllium target. **(b)** A small number of nuclei from the ^{41}Al beam lose a proton after interacting with a reaction target and become magnesium-40. As excited states in those nuclei quickly transition to the ground state, they emit gamma rays whose energies provide insight into the nuclear structure. (Adapted from ref. 2.)

magic number of protons or neutrons requires more energy than in a nonmagic nucleus. (The experimental observation of that feature was crucial to Goeppert Mayer and Jensen's insight regarding the nuclear structure.)

But magic numbers are not always so magic. As the number of nucleons strays from the most stable configurations, correlations between them become important and the mean-field nuclear potential changes. Correlation effects lead to so-called islands of inversion, where having a magic number of nucleons no longer means that the ground state has a filled outer shell.[3] Instead, the shells overlap and nucleons begin to fill the next shell before the previous one is complete. The large gap between the ground state and the first excitation disappears.

Magnesium needs eight more neutrons than protons to reach what was thought to be its first magic number, $N = 20$. But it turns out that 20 is not a magic number for Mg, because ^{32}Mg is on an island of inversion. That change in the energy levels accompanies a change in the nuclear shape from a sphere to a prolate, or elongated, spheroid. Spectra of nuclides from ^{32}Mg to ^{38}Mg indicate that the nucleus retains its prolate shape as more neutrons are added.

Neutrons can't be added indefinitely. Beyond a certain threshold, known as the drip line, the nuclear potential is not strong enough to bind another neutron, even in a metastable state (see the article by David Dean, PHYSICS TODAY, November 2007, page 48). Scientists were unclear whether they had reached the drip line with ^{38}Mg; the lighter ^{37}Mg showed extremely weak binding, and what would be the outermost neutron in ^{39}Mg is actually unbound. But nucleon pairing is energetically favorable, so an isotope with even N can be bound even if its lighter odd-N neighbor is not. When ^{40}Mg was finally observed as a bound state[4] in 2007, it showed itself to be an even more neutron-rich Mg nuclide for studying the effects of weak binding on the nuclear structure.

Piling on neutrons

The ^{40}Mg experiment at RIBF was conducted in December 2016. Products from the breakup of a calcium-48 beam, which is popular for nuclear experiments because it has a magic number of protons and neutrons and a large neutron-to-proton ratio (see PHYSICS TODAY, June 2010, page 11), were directed to a two-stage projectile fragment separator, BigRIPS, shown in figure 1. The separator isolated an aluminum-41 beam from the products. After hitting a reaction target, most of that secondary beam reached the spectrometer at the end of BigRIPS unchanged; however, a small population of the ^{41}Al nuclei lost a proton and became ^{40}Mg. As shown in figure 2, only a tiny fraction of the intense primary beam actually ends up forming that neutron-rich species.

Such exotic, heavy nuclei are now easier to create since RIKEN's 2007–08 facilities upgrade. The researchers knew that they needed an intense primary ^{48}Ca beam to produce enough ^{40}Mg downstream for gamma-ray spectroscopy.

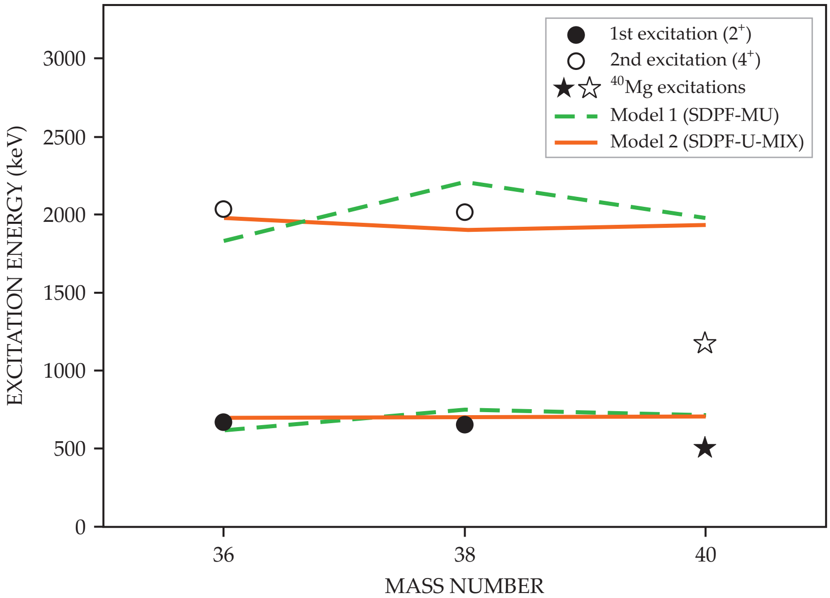


FIGURE 3. THE FIRST TWO EXCITATIONS in magnesium-36 and magnesium-38 (circles) agree with theoretical calculations predicting a prolate nuclear shape (green and orange lines). The same shape is expected to persist in ^{40}Mg, but measurements of the nuclide's first two excitations (stars) deviate far from both the trends of lighter nuclei and theoretical predictions. (Adapted from ref. 2.)

"Everything about measuring a gamma-ray spectrum depends on statistics," the paper's lead author, Heather Crawford of Lawrence Berkeley National Laboratory (LBNL), pointed out. "The only place where this is currently possible is RIBF."

The LBNL team initially attempted to do gamma-ray spectroscopy on ^{40}Mg in 2010, but that run was cut short due to problems with RIBF's cyclotron. A second scheduled experiment in 2014 was ultimately canceled. Everything finally fell into place in 2016: "We had an amazing beam intensity and stability at RIBF, and nature was kind to us with two populated excited states in ^{40}Mg," said Crawford. "It was really about patience in waiting for the measurement to happen."

As a calibration, the researchers first remeasured the energies associated with the first two excited states in ^{36}Mg and ^{38}Mg. The values matched both previous experiments and theoretical calculations of the excited state energies, as shown in figure 3. But the energies from ^{40}Mg, shown as stars in the figure, deviated far from predictions: At about 500 keV, the first transition, which was tentatively ascribed to the first excited state decaying to the ground state, was 20% lower than expected. The second transition, about 670 keV higher, was nearly 50% lower than expected and so far from any theoretical predictions that it is unclear which excited state could have generated it.

Mysterious transitions

A nuclear shape change could explain the deviation from predictions: If the ^{40}Mg nucleus was an oblate spheroid or had triaxial deformation, its expected energy levels would shift. However, in their truncated 2010 experiment,[5] the same researchers measured the two-proton removal cross section from silicon-42 to generate ^{40}Mg. The production yield supported the idea that, like lighter nuclides, ^{40}Mg should be a prolate spheroid.

In the absence of such a dramatic nuclear shape change between ^{38}Mg and ^{40}Mg, the discrepancy could also stem from the coupling of outer neutrons to the rest of the nucleus. The weakly bound outer neutrons in near-drip-line nuclei can generate a long tail known as a halo in the distribution of nuclear material. First observed in lithium-11, the extended structures have since been observed in other nuclei. But as Crawford points out, not all weakly bound nucleons form halos; they must also be in a low-angular-momentum, single-particle orbital that allows them to spend time away from the core. "This is part of why these nuclei are interesting," she says. "Halos have been observed, but how they modify other aspects of structure is not so clear."

Most halo studies have been restricted to smaller nuclei with fewer than 20 neutrons. With 28 neutrons—more than twice the number of protons—^{40}Mg is the most neutron-rich nucleus with that many neutrons to be studied. It is also the heaviest isotope with such weakly bound nucleons to be probed using gamma-ray spectroscopy.

With two weakly bound neutrons, ^{40}Mg could be viewed as a ^{38}Mg nucleus surrounded by a two-neutron halo. If that picture is correct, how do those halo neutrons couple to the rest of the nucleus? Experiments and theory agree that for lighter nuclei the first excitation is the 2^+ state with positive parity and overall spin $J = 2$, followed by a second excitation to the 4^+ state with $J = 4$. In those nuclei, the 4^+ state emits a gamma ray as it decays into the 2^+ state, which then subsequently decays into the 0^+ ground state with the emission of a second gamma ray. But as Crawford notes, the 4^+ state may no longer be the second excitation in ^{40}Mg: "It's possible that the weak binding may push the second 2^+ state down in energy, as we speculate in the paper, but honestly we don't know for sure the nature of the second state."

Whatever their cause, the unexpectedly low excitation energies in ^{40}Mg show that the current models fail to accurately describe nuclear structures as the nuclei become heavier and further from stability. Improvements like those at RIKEN's RIBF are enabling researchers to perform measurements on increasingly exotic nuclei, which will help them understand how collective effects can change the nuclear shape and energy levels far from stability. A better understanding of neutron binding may also elucidate the rapid neutron capture that forms heavy isotopes in stars.

Christine Middleton

References

1. M. Goeppert Mayer, *Phys. Rev. Lett.* **75**, 1969 (1949).
2. H. L. Crawford et al., *Phys. Rev. Lett.* **122**, 052501 (2019).
3. A. Poves, J. Retamosa, *Phys. Lett. B* **184**, 311 (1987).
4. T. Baumann et al., *Nature* **449**, 1022 (2007).
5. H. L. Crawford et al., *Phys. Rev. C* **89**, 041303 (2014).

Circular polarization is made to order in the extreme UV

Concepts from conventional optics underlie a flexible technique that uses high-energy photons to probe chiral effects.

Birefringent materials, characterized by their direction-dependent indices of refraction, are powerful tools for manipulating light's polarization. Held one way, a birefringent crystal serves as a polarization analyzer that separates a light beam into orthogonally polarized components—or puts those components back together again. Held another way, the crystal becomes a wave plate that retards one polarization component with respect to the other. As figure 1 shows, the sum of two suitably phased linearly polarized waves is circularly polarized. So with the right arrangement of birefringent components, one can engineer light with linear or circular polarization or any of the continuum of elliptical polarization states in between.

Circularly polarized light is important because of its capacity to distinguish between the mirror-image forms of molecules that are asymmetric, or chiral—a category that includes almost all biomolecules and many of the substances that interact with them (see PHYSICS TODAY, July 2018, page 14). Chiral materials absorb right- and left-circularly polarized light in different amounts. By measuring that differential absorption, or circular dichroism, one can infer, among other things, which chiral form is present and in what quantity.

Now Nirit Dudovich of the Weizmann Institute of Science in Israel, her graduate student Doron Azoury, and their colleagues have demonstrated a new scheme for achieving full polarization control in the extreme UV (XUV),[1] the electromagnetic regime with photon energies between 10 eV and about 100 eV. Circular polarization in the XUV, and in the next higher frequency band of soft x rays (photon energies up to 1 keV), can be used to study the magnetic structure of materials. But until recently, the requisite polarization control has been available only at large synchrotron facilities (see the article by Neville Smith, PHYSICS TODAY, January 2001, page 29). Dudovich and colleagues' tabletop scheme produces XUV pulses that are attoseconds in duration, so they have the potential to probe not only the structures of chiral materials but also their ultrafast dynamics (see PHYSICS TODAY, January 2018, page 18, and June 2018, page 20).

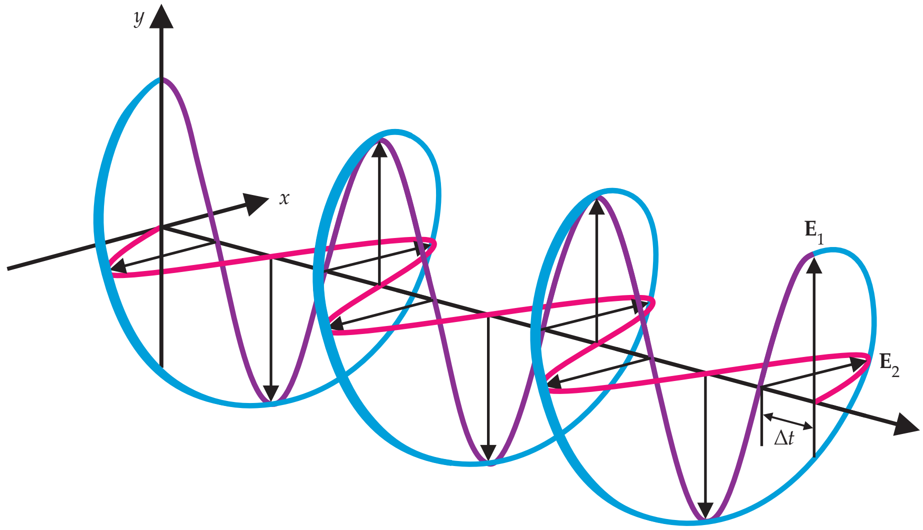


FIGURE 1. BUILDING CIRCULAR POLARIZATION. Two linearly polarized waves shown in purple and pink, with electric field vectors $\mathbf{E}_1$ and $\mathbf{E}_2$, combine to form the right-circularly polarized wave shown in blue. Changing the time delay Δt between the two waves changes the polarization of the combination wave.

Not so impossible

Researchers who work in the attosecond regime generate their ultrashort XUV pulses using a process called recollision. (See the article by Henry Kapteyn, Margaret Murnane, and Ivan Christov, PHYSICS TODAY, March 2005, page 39.) An intense, linearly polarized IR pulse, with a photon energy of 1.6 eV or less, is focused on a target gas. As the electric field reaches peak value, it pulls electrons away from their parent atoms; the electrons then slam back into the atoms and produce a short burst of linearly polarized XUV photons. Each swing of the IR electric field produces a new burst; converted to frequency space, the train of XUV pulses corresponds to a ladder of high harmonics of the IR frequency.

But using a circularly polarized IR input doesn't yield circularly polarized harmonics, or indeed any XUV emission at all: The electrons and parent atoms are driven apart and never recollide. It's possible, it turns out, to produce circularly polarized high harmonics in the XUV and soft-x-ray regimes by superposing circularly polarized IR and visible light so that the net electric field oscillates in a trefoil pattern.[2] But the polarization depends on the harmonic number, and the strong-field nature of the interaction makes the output polarization difficult to fully tune.

Dudovich and her colleagues use a different approach to polarization control that's similar to the conventional birefringent-crystal scheme. With different portions of a single IR starting wave, they generate two copropagating linearly polarized XUV pulse trains. By independently controlling the electric field vectors $\mathbf{E}_1$ and $\mathbf{E}_2$ and the time delay Δt between the two waves, they can straightforwardly dial up any XUV polarization state.

The experimental setup is depicted in figure 2. An IR pulse, focused in the first of two XUV source gases, generates an XUV pulse train with electric field vector $\mathbf{E}_1$. But not all of the incoming light has its frequency upconverted; much of it, especially around the edges of the beam where the intensity is lower, passes through the first source unchanged. That remaining IR radiation, focused into another XUV source, generates a second pulse train with electric field vector $\mathbf{E}_2$.

The optics components between the two XUV sources enable the researchers to control the properties of the two pulse trains. First, a filter blocks any residual IR from the center of the beam and allows the XUV pulse train in the middle to be manipulated separately from the IR in the outer annulus. A concentric two-segment mirror introduces a time delay Δt between the two components. An iris provides a way to control the magnitude of $\mathbf{E}_2$ by trimming away the edges of the IR beam. And a half-wave plate, with a hole drilled in the middle to let the XUV pulses pass through, rotates the polarization of the IR beam and thus controls the direction of $\mathbf{E}_2$.

Because XUV wavelengths are so short, getting the two XUV pulse trains to combine coherently into the desired elliptical polarization requires the whole setup to be extraordinarily stable. "Even with the core idea in hand, it isn't at all obvious that the experiment is actually feasible," says Emilio Pisanty of the Institute of Photonic Sciences in Barcelona, Spain. "If anyone had suggested this idea 10 years ago, they would have been laughed out of court for suggesting the impossible."

Dudovich and colleagues got their first inkling that it might be possible two years ago, when during a routine calibration of an unrelated experiment they observed a hint of interference between XUV waves with a photon energy of 15 eV. "Motivated by our accidental discovery, we introduced substantial stability upgrades," explains Azoury, "and finally were able to demonstrate interferometric optical control up to a photon energy of 60 eV." Higher energies than that—the range of greatest interest for magnetism studies—will require greater stabilization than Dudovich's group has so far achieved.

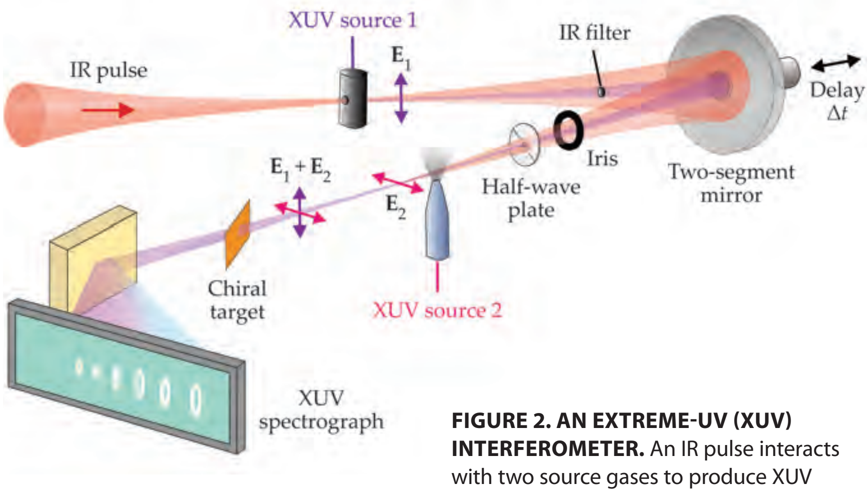


FIGURE 2. AN EXTREME-UV (XUV) INTERFEROMETER. An IR pulse interacts with two source gases to produce XUV pulse trains with electric field vectors $\mathbf{E}_1$ and $\mathbf{E}_2$. A two-segment mirror, iris, and half-wave plate offer control over the relative phase, amplitude, and linear polarization of the two trains and thus the polarization state of their sum. An XUV spectrograph records the frequency-dependent transmission through a chiral target material. (Adapted from ref. 1.)

Locked in

The simplest approach to measuring circular dichroism entails separately quantifying the absorption of right- and left-circularly polarized light and then subtracting. It doesn't always work in practice. Chiral effects in real-life samples are often small, and small differences between large measured quantities are prone to large uncertainties. A more sensitive detection method is to modulate the incident light's polarization and look for a signal oscillation at the same frequency. Dudovich and colleagues' new scheme makes that approach possible in the XUV: Modulating the polarization is as simple as scanning Δt by moving the center mirror a short distance at a controlled speed.

The advantages don't end there. The scheme offers control over a degree of freedom that's less easily accessible with

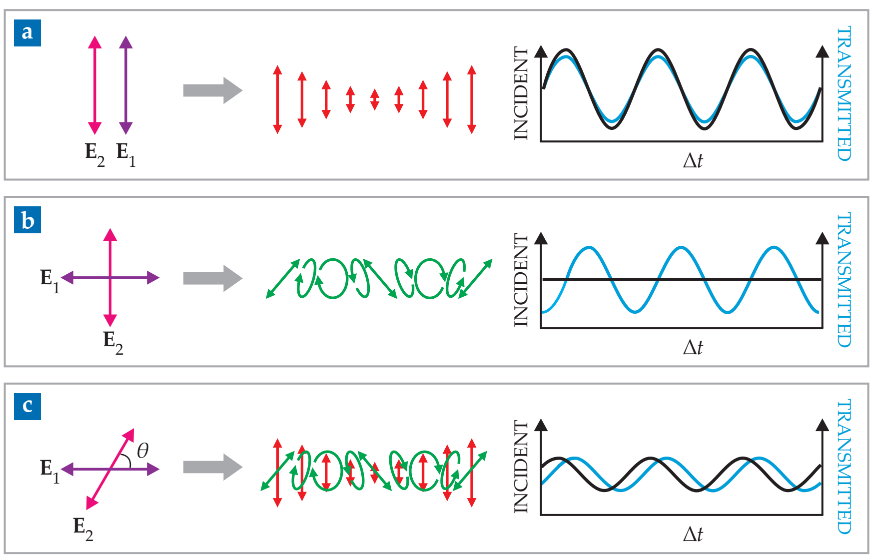


FIGURE 3. LOCK-IN MEASUREMENT of a chiral signal. **(a)** When the electric field vectors $\mathbf{E}_1$ and $\mathbf{E}_2$ of two linearly polarized waves are parallel, their linearly polarized sum (red) provides no information about the chiral structure of a target, no matter how the time delay Δt between the waves is modulated. **(b)** When $\mathbf{E}_1$ and $\mathbf{E}_2$ are perpendicular, the chiral signal appears as the amplitude of the oscillation of the intensity transmitted through the target as a function of Δt. **(c)** But when the angle between the vectors is set at an intermediate value θ, the chiral signal appears in the more easily measured phase difference between the incident and transmitted intensities. (Adapted from ref. 1.)

real birefringent crystals: the angle between $\mathbf{E}_1$ and $\mathbf{E}_2$. In the setup shown in figure 2, the half-wave plate is positioned with its axis at a 45° angle to $\mathbf{E}_1$; the IR polarization is thus rotated by twice that angle, or 90°, and $\mathbf{E}_1$ and $\mathbf{E}_2$ are orthogonal. By reorienting the half-wave plate, one can set the angle θ between the polarization vectors to any desired value.

That flexibility facilitates the lock-in detection of chiral signals. Figure 3 illustrates how it works. In panel 3a, $\mathbf{E}_1$ and $\mathbf{E}_2$ are parallel. Their sum always has the same linear polarization but varies in intensity with Δt as the components constructively and destructively interfere. The transmission through a chiral target is proportional to the incident intensity but gives no information about the target's chiral structure.

Panel 3b shows the case of $\theta = 90°$. Scanning Δt leaves the intensity of the combined wave unchanged but modulates its polarization. Transmission through a chiral target also oscillates, and the magnitude of the chiral effect can be inferred from the oscillation amplitude. Panel 3c, which shows an intermediate θ, is effectively a superposition of panels 3a and 3b. Both the incident and transmitted intensities oscillate with Δt, and the chiral signal is encoded in the phase shift between them. Phases are less sensitive than amplitudes to intensity fluctuations in the incident wave, so they can be more accurately measured.

Because the scheme works in the time domain, it's possible, at least in principle, to isolate a single circularly polarized attosecond pulse, whose frequencies span a broad XUV continuum. In contrast, the previous approach using a trefoil-evolving electric field is inherently limited to a series of discrete harmonics: Each pulse in isolation is linearly polarized, and only when a long train of pulses are taken together are the harmonics circularly polarized. Chiral effects in many materials manifest in spectral features as narrow as a fraction of an eV, so full spectral coverage is important.[3]

"Most experiments to date have been looking at toy systems where the features are extremely broad and the exact wavelength is irrelevant," says Allan Johnson of the Institute of Photonic Sciences. "This is probably the first time I've felt that circularly polarized harmonics could seriously make it out of attosecond labs and be taken up as a general tool."

Johanna Miller

References

1. D. Azoury et al., *Nat. Photon.* **13**, 198 (2019).
2. A. Fleischer et al., *Nat. Photon.* **8**, 543 (2014); O. Kfir et al., *Nat. Photon.* **9**, 99 (2015); T. Fan et al., *Proc. Natl. Acad. Sci. USA* **112**, 14206 (2015).
3. J. Simmendinger et al., *Phys. Rev. B* **97**, 134515 (2018); L. Vidas et al., *Nano Lett.* **18**, 3449 (2018).

Atlantic water carried northward sinks farther east of previous estimates

The first set of continuous observations in the subpolar North Atlantic challenges the long-held view that the Labrador Sea dominates ocean-circulation variability.

Climate models predict that the Atlantic Ocean's overturning circulation should slow down over the next few decades.[1] If they're right, northern Europe could experience colder winters, and the global cycling of nutrients that feeds biological systems may be disrupted. The regularly functioning meridional overturning circulation (MOC) moves warm surface water from the tropical Atlantic to higher latitudes where it loses heat to the atmosphere. Once the cold, salty, and consequently dense water reaches the northern Atlantic and Arctic, it sinks, or overturns, to a depth of 1–5 kilometers and becomes what's known as deep water. It then travels southward back to the tropics as part of a global ocean circulation (see the article by J. Robert Toggweiler, PHYSICS TODAY, November 1994, page 45).

Simulations are the only way to evaluate the future state of the MOC, and direct measurements are needed to test

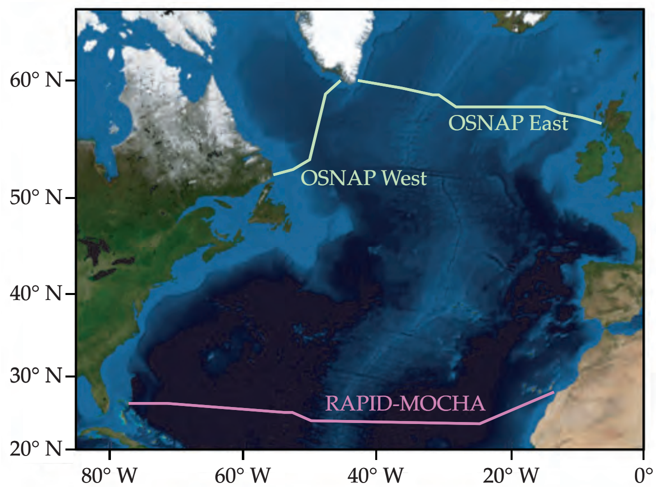


FIGURE 1. THE OVERTURNING IN THE SUBPOLAR NORTH ATLANTIC PROGRAM (OSNAP) is the first array to continuously measure temperature, salinity, and velocity at regular depth intervals in the northern Atlantic and Arctic Oceans. OSNAP West crosses the Labrador Sea between northeastern Canada and southwestern Greenland. OSNAP East stretches across the basins to the east of Greenland and ends at the western coast of Scotland. The first measurement array in the Atlantic, RAPID-MOCHA, is an international partnership between the UK-based Rapid Climate Change program and the US-based Meridional Overturning Circulation and Heatflux Array.

ISABELA LE BRAS, UNIVERSITY OF CALIFORNIA, SAN DIEGO

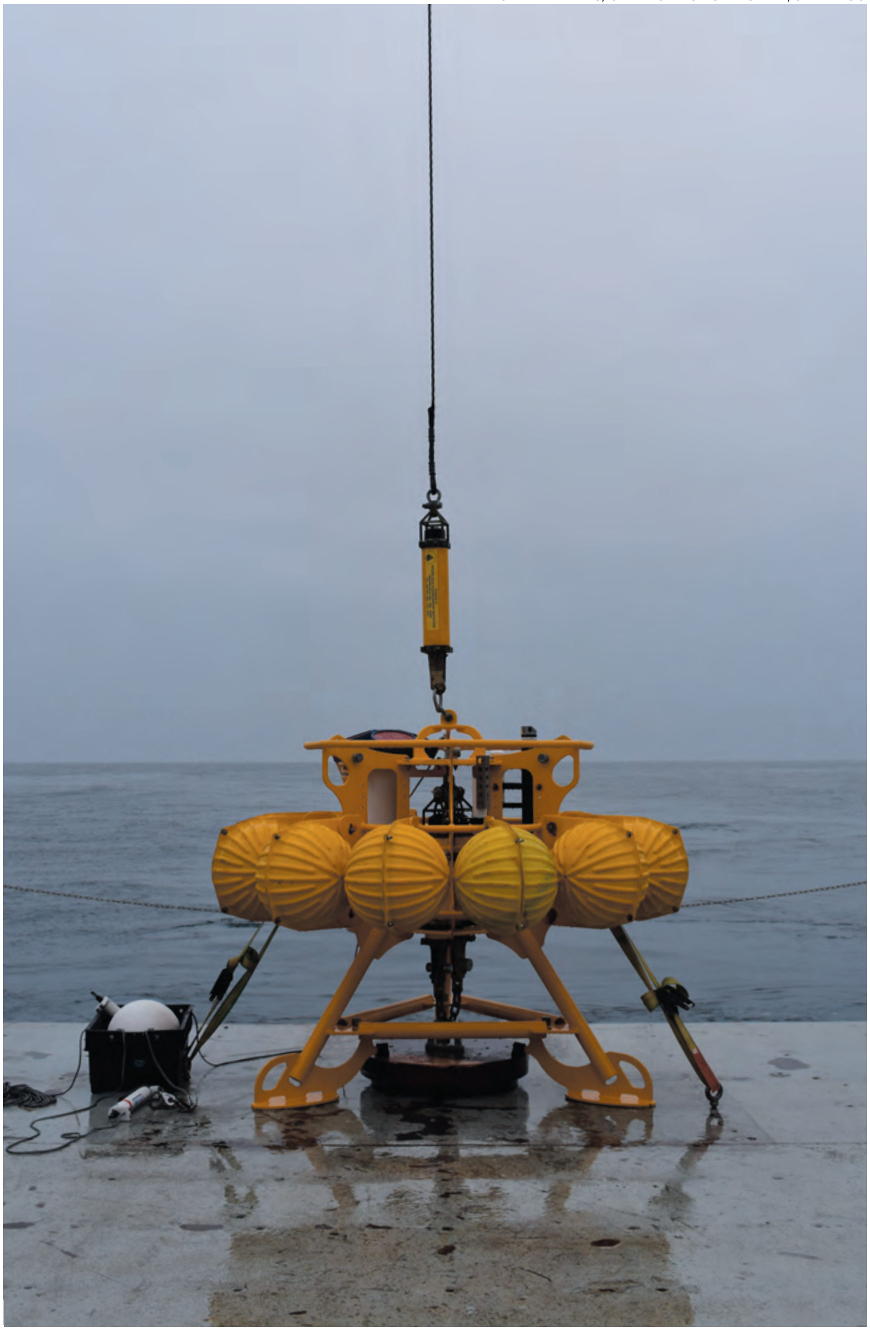


FIGURE 2. THE MOORING SHOWN HERE will sit on Greenland's continental shelf 200 m below the surface. While the yellow portion anchors the mooring to the seafloor, the instruments in the black box to the left float above it and collect continuous measurements of temperature, salinity, and velocity at multiple depths.

and evaluate models. For decades, physical oceanographers who study the MOC have hitched their wagons to hydrographic research cruises to collect those observations. Temperature, salinity, velocity, and other properties of seawater have been measured at many depths and locations when cruises pass through the North Atlantic. The cruises are expensive, though, and usually happen a year to a few years apart. Researchers can't rely on such infrequent sampling to gauge long-term MOC trends.

Data-gathering efforts expanded substantially in 2004 when RAPID-MOCHA, an international partnership between the UK-based Rapid Climate Change program and the US-based Meridional Overturning Circulation and Heatflux Array, deployed the first set of ocean sensors to collect continuous measurements and at many depths in the Atlantic. Rather than choosing the subpolar North Atlantic for the array, researchers chose the subtropics because it's home to fewer, less-complicated flows. In examining the historical data from the hydrographic cruises and one year of measurements from the array, oceanographers were stunned to learn that the month-to-month variations of the MOC could be as large as 10 Sv (1 sverdrup equals 1 million cubic meters per second), or about half of the MOC's average annual transport.[2] Many researchers thought that such large variations were only possible on decadal to multidecadal time scales.

To better understand the entire spectrum of MOC variability, Susan Lozier of Duke University and international colleagues have deployed the first array of ocean sensors to continuously collect measurements in the subpolar North Atlantic.[3] Known as the Overturning in the Subpolar North Atlantic Program (OSNAP), the array collects data across the region at multiple depths. When the researchers analyzed the initial 21 months of data, they found that the eastern North Atlantic overturned seven times as much water as the western region.

Years in the making

Research since RAPID-MOCHA was first deployed has revealed that the MOC in the subpolar Atlantic can vary independently from the subtropics. A 2010 study that combined observations with a numerical model concluded that overturning in the subtropics from 1950 to 2000 had slightly weakened while the subpolar overturning had strengthened.[4] Another study from 2014 that reanalyzed historical data from 1965 to 2000 found that variability in the storage of heat in the subtropical Atlantic differed from the subpolar Atlantic basin.[5] Meanwhile, most simulations suggested that overturning in the subpolar North Atlantic should be dominated by density-driven flows primarily in the Labrador Sea to the west of Greenland, with some contribution from the Nordic Seas. Even before those studies were published, an international team of oceanographers began planning another array.

"We met over the course of three days at Duke in 2010," says Lozier, "and the design came together." It took another five years before OSNAP—a collaboration between Canada, China, Germany, the Netherlands, the UK, and the US—deployed the trans-basin array. As shown in figure 1, the array consists of two sections of moorings. OSNAP West crosses the Labrador Sea from northeastern Canada to southwestern Greenland; OSNAP East stretches across the ocean basins east of Greenland before terminating at the western coast of Scotland.

Each mooring, one of which is shown in figure 2, sits on the ocean floor while the attached sensors float above it collecting daily measurements. The technology is essentially the same as that used in 2004 by RAPID-MOCHA in the subtropical Atlantic. A part of the OSNAP team participated in several cruises to retrieve the initial measurements, which were taken from August 2014 through April 2016. The system continues to collect data. Lozier says it has been "a long road indeed, but it can hardly be any other way with a program of this scope and size."

Overturning expectations

The discovery, shown in figure 3, that the overturning across the OSNAP East array is seven times as much as that of OSNAP West, surprised researchers. It also clashes with most climate models, which predict substantial overturning in the Labrador Sea. The result is even more startling given that the Labrador Sea experienced exceptionally strong convection, a condition that usually drives more overturning, during the winters of 2014–15 and 2015–16.

Because OSNAP is positioned at the gateway through which heat enters the Arctic, the new data will also help uncover how heat moves through the North Atlantic. To that end, the researchers partitioned the water into a uniform-density flow and a density-varying MOC flow. The results revealed that 73% of the average heat transported was attributable to the MOC. Because the Labrador Sea experienced far less overturning than expected, the newly observed eastern pathway for heat to the Arctic challenges previous expectations too.

In contrast to the overturning's strong effect on heat transport, overturning had less of an effect on the transport of fresh water that comes either from glacier melt or excess precipitation over the ocean.

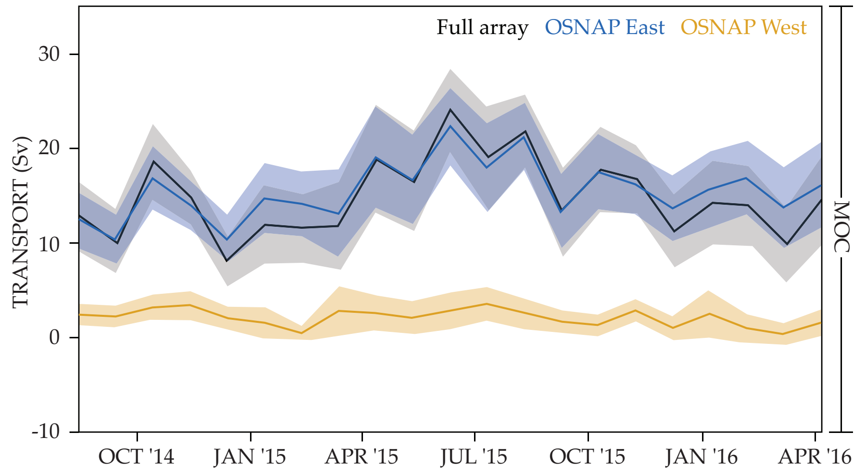


FIGURE 3. SEVEN TIMES AS MUCH WATER OVERTURNED across the eastern array (blue) compared to the western array (yellow) of the Overturning in the Subpolar North Atlantic Program (OSNAP). (1 sverdrup, Sv, equals 1 million cubic meters per second.) The shading denotes the uncertainty in the 30-day averaged transport.

More fresh water was moved in the west, which had a weaker MOC than the east, from July through November of 2015. The water crossing OSNAP West consists mostly of a uniform-density flow. However, the water in the east has flows of uniform density that nearly match the density-varying MOC flow. Lozier and her colleagues hypothesize that the flow imbalances in the west and strong salinity differences across the Labrador basin spur a stronger flux of freshwater transport.

A new mental model

Jochem Marotzke, an oceanographer from the Max Planck Institute for Meteorology, who helped initiate the RAPID-MOCHA program, says the first OSNAP results "confirm what a small minority of us have been saying based on modeling studies: The connection between deepwater formation and the sinking branch of the MOC is way more complicated than that held by prevailing beliefs."

Many simulations predict that climate change will weaken the MOC. OSNAP is still in its early days; confirming those predictions will require measurements over a longer time. And resolving the MOC's basin-scale differences by comparing the OSNAP results with those from RAPID-MOCHA could benefit from more measurements.

A short record, though, can still improve climate models. "We can test whether the models show the same relationship between deepwater formation and MOC as in the measurements," says Marotzke. That verification will help determine the skill of models in simulating the MOC in a future climate. The ocean also moderates climate by acting as a carbon sink (see the article by Jorge L. Sarmiento and Nicolas Gruber, PHYSICS TODAY, August 2002, page 30). Therefore, improved observations of the MOC will help modelers develop more realistic simulations of the ocean's uptake and storage of carbon.

Though limited, the data may also help open researchers' minds to new ideas. "Even the short measurements rattle beliefs long held by many," says Marotzke. Yet such shifts in thinking are routine in science. "Even though the final word cannot be said," says Marotzke, "the measurements prepare us for having to revise our mental models of how the ocean works."

Alex Lopatka

References

1. T. F. Stocker et al., eds., *Climate Change 2013: The Physical Science Basis—Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge U. Press (2013).
2. S. A. Cunningham et al., *Science* **317**, 935 (2007).
3. M. S. Lozier et al., *Science* **363**, 516 (2019).
4. M. S. Lozier et al., *Nat. Geosci.* **3**, 728 (2010).
5. R. G. Williams et al., *J. Clim.* **27**, 698 (2014).

PT

A physics master's degree opens doors to myriad careers

If you want to improve your options in industry or consider a career in teaching, a master's in physics may be for you.

In the US—unlike in many other countries—academics in physics and some other fields commonly treat the master's degree as an ugly stepchild. At PhD-granting institutions, leaving with a physics master's degree may even be accompanied by undertones of failure. So is a master's degree in physics a consolation prize or an aspirational degree?

For many people, a master's is a step toward earning a PhD. And in society at large, and among employers, a physics master's degree is a respected qualification that can lead to interesting, well-paying careers in industry, government, education, and not-for-profit sectors.

Physics master's programs vary widely in what they offer and require, whom they attract, what their graduates go on to do, what tuition they charge, and what financial support they provide. Despite those differences, they all share a sense of purpose. As David Kieda, an astronomer and dean of the graduate school at the University of Utah, says, "Our job is not to make the students bend to our experiences, but to bend to the needs of our students."

Alternative career paths

Over the past few years, California State University Long Beach (CSULB) has consistently conferred among the most physics master's degrees of any institution in the country, with 15–20 a year, up from just 3–5 annually a decade or so ago. The three main career paths for master's recipients are teaching, industry, or the PhD, says CSULB physicist Andreas Bill. A master's is the highest physics degree available at the school.

Master's programs variously require students to do a project, thesis, or internship, or to pass comprehensive exams. Challenging and interesting jobs in industry increasingly demand more knowledge than a bachelor's recipient typically has. For many industry positions nowadays, says Bill, "new hires need to know quantum mechanics and statistical physics." At CSULB, he says, "students learn graduate physics and techniques that are useful in industry—maybe they write code to solve a theoretical problem or learn to make thin films or to use a scanning electron microscope." Students gain confidence from struggling with and solving real-world research problems, he adds.

Programs attract students who are unprepared for the PhD or are unsure that's what they want to do, according to Bill and others. For some, the PhD seems like too long a commitment. "The master's can be a path for students in difficult socioeconomic conditions and underrepresented minorities," Bill says. "It's an important channel to increase diversity among highly educated persons."

Some choose to pursue a master's first because "they woke up late," says Bill. "They realize they want to do a PhD, but their grade point average is low." Or as Jeff Wilkes, who runs a master's program in physics at the University of Washington, Seattle, puts it, "students who want to do a master's often say, 'I drank too much beer, and now I realize I should have paid more attention.' They drifted through college and now are stuck in a boring job." It's easier to gain admission into a master's program than a PhD program; some schools accept students with less-than-stellar grade point averages, contingent on performance. The master's gives them a chance to earn better grades and see if they like research. "We catch some excellent students that way," Bill says.

About half of CSULB physics master's recipients continue to the PhD, Bill says. Each year a few enter through the American Physical Society (APS) Bridge Program, which aims to help students from underrepresented groups get their physics PhDs (see the article by Ted Hodapp and Kathryne Woodle in PHYSICS TODAY, February 2017, page 50). A year after receiving their exiting physics master's degree at a master's- or PhD-granting department, 30% of US students and 50% of international students from the combined classes of 2014, 2015, and 2016 were enrolled in a physics PhD program at a different institution, according to the Statistical Research Center at the American Institute of Physics (AIP; publisher of PHYSICS TODAY). The rest were in other graduate programs (9% of citizens and 15% of noncitizens), had left the country (4% and 17%), had entered the workforce (50% and 14%), or were unemployed (7% and 4%).

MARIAH BIRCHARD

AFTER EARNING HER MASTER'S DEGREE IN ENGINEERING PHYSICS last year at Appalachian State University in Boone, North Carolina, Mariah Birchard took a job working on instrumentation and automation of telescopes at Gemini South in Chile.

Jesús Pando, who heads the physics master's program at DePaul University in Chicago, says that students "who are ready for and can get accepted to a PhD institution should always do that," especially if they plan to continue to the PhD. "They will get the lay of the land and form support systems with other students—everything that is necessary but is not strictly academics." But, he says, for students who want a more personalized experience, a master's-focused institution can be a good fit.

Changing life paths

Some master's programs in physics cater to particular needs. Since the 1980s Harold Metcalf has run a small program at Stony Brook University that specializes in scientific instrumentation. "There are students who struggle with math or concepts, but they are golden in the lab, they are so good with their hands. Those are the kids for whom this program is designed," he says. Students take courses at the undergraduate and graduate levels and complete two hands-on projects. Typically about five people are enrolled at any given time; graduates have gone on to work on telescopes, music synthesizers, the Brookhaven accelerator test facility, and other things. "I view this as a professional degree, which confers on the students the notion that they are physicists," Metcalf says.

The physics master's degree offered by the University of Washington was started in the 1970s with local companies, Boeing in particular, in mind. By taking a master's degree, employees could further their education and potentially gain a promotion. The program remains evenings and online only, but the student base has widened to include high school teachers, military personnel, employees at a broad range of companies, and some fresh bachelor's recipients, says Wilkes. About 15 people enter each year, and about 60 are enrolled at any given time. "This program is intended to help people change their life path," he says. Students take courses and do a research project.

Originally, notes Wilkes, the Washington program was supported by the state. But about 10 years ago it was forced to become self-sustaining. Students pay about \$26 000 to complete the degree. Sometimes businesses foot the bill to train their employees. Stony Brook students also pay tuition, but many run undergraduate physics labs to help cover costs. At CSULB and other schools where the master's is the highest degree available, students may work as teaching assistants.

As with many programs, the master's in physics at the University of Massachusetts Dartmouth feeds into local industry. "Graduates are snapped up by defense contractors," says Gaurav Khanna, the gravitational physicist who runs the program. "If you want to go into industry or teaching, a master's is a good degree," says Gary Forrester, who earned his master's in the program in 2012. "It's pretty applicable in most technical fields."

Forrester began a PhD with Khanna, but was increasingly drawn to teaching. One Thursday in 2014, he responded to an ad for a high school teacher, and by the following Monday he was in the classroom. Forrester says his physics background makes him a better teacher. "Every day kids ask me, What happens at the edge of a black hole? What was the Big Bang? They ask about quantum mechanics. Because of my background, I can tell them about cutting-edge research."

Professional degrees

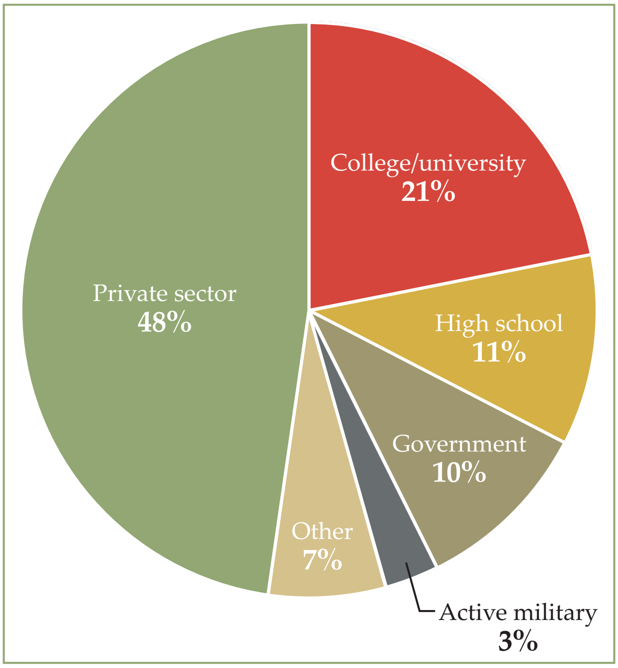
In the 1990s a dip in openings for academic positions led many students and early-career scientists to leave the sciences.

It also led to the Alfred P. Sloan Foundation's initiative to create professional science master's (PSM) degree programs. "We talked to employers in technical fields that were heavily dependent on science and technology for their businesses, and we found a strong interest in hiring people at the master's level," recalls Michael Teitelbaum, a founding director of the Sloan initiative. In addition to graduate-level science experience, employers wanted hires to come in with understanding and skills in business, marketing, project management, communications, and teamwork.

Sloan started by seeding a few master's programs at PhD-granting universities. The programs combined science with business skills. The PSM degrees were not seen as "a stepping stone or a consolation," says Teitelbaum, but as a route to science-intensive careers outside academe. "People were smart enough to get a degree in physics, but they didn't like the academic career prospects," he says. "We thought it was a shame if they felt they had to leave science. Would they be interested in a science master's degree that prepared them for industry? The answer turned out to be yes."

The National Professional Science Master's Association, launched in 2005, grew out of the Sloan initiative. Programs that meet qualifications including coursework, internship requirements, and industry advisers can join. Some 345 programs at 157 institutions—including a handful in Australia, South Korea, and the UK—are among its members. The programs span many sciences and specializations, from agriculture to nanoscience.

Rice University offers PSM degrees in subsurface geoscience, space studies, environmental analysis, and bioscience and health policy. "When we recruit," says Rice PSM program director Dagmar Beck, "we target students who love science, but don't want to go into a lab and do research." Many people study science as undergraduates and work in jobs where they never use their science skills again, she says. Graduates from the Rice PSM program work, for example, in the aviation and petroleum industries and for environmental, medical, and governmental organizations.



A YEAR AFTER EARNING AN EXITING MASTER'S DEGREE in the US, some 39% of recipients from the combined classes of 2014, 2015, and 2016 were in the workforce. The chart shows the sectors of employment. Of the remaining recipients, 6% were unemployed, 8% had left the country, and 47% were pursuing higher degrees. (Data courtesy of the Statistical Research Center at the American Institute of Physics.)

A PSM program's contacts with industry strongly influence the curriculum and create networks for the students to find internships and jobs. On the advice of industrial board members, Rice's geosciences program, for example, is introducing a class on shale, fracking, and other new technologies. And a couple of years ago, the university's environmental PSM faculty began teaching students to write sustainability reports and create environmental impact statements.

Potential employers often look for engineers, says David Garrison, founding chair of the physics master's program at the University of Houston–Clear Lake, which participates in the APS Bridge Program and offers a PSM degree in technical management. "Physics is a more unknown quantity, so we have been working with local industry. Once they realize that physicists are trained to solve a huge range of problems, they love them," he says.

Case Western Reserve University offers a PSM in physics for entrepreneurship. The program straddles physics, law, and business, says director Ed Caner. "Our students have a mindset that they want to be an entrepreneur or to work for a small company." One student went to work for a company that does optical coating. The graduate focused on minimizing the losses in batch processing. "He looked at things from a sales standpoint and from a physics standpoint. That is where our students shine." Full tuition is about $60 000. It's a challenge attracting students because many already have debt, Caner notes. But he says most graduates are able to pay off their master's loans in a few years.

"Underserving our community"

People with a master's degree in physics go into a range of fields (see figure); in the private-sector category, jobs include staff scientist, software developer, project manager, and various engineering-related titles. According to data from AIP's Statistical Research Center, the combined master's degree classes of 2015 and 2016 saw typical private-sector starting salaries of $52 000–$76 000. Physics bachelors started with salaries of $45 000–$75 000 in private-sector science, technology, engineering, and mathematics jobs,

JERRY MANN

JEFF BARGIEL, a graduate of Case Western Reserve University's professional master's in physics entrepreneurship is back with other alumni to tell current students about their startups. His involves nontoxic herbicides.

and holders of a physics PhD earned initial salaries of $85 000–$118 000.

Even if every physicist wanted to become a professor, the jobs aren't there. Hard numbers are not available, but based on combined data from NSF and AIP, in 2013 roughly a third of physicists held tenure or tenure-track positions 10–14 years after earning their PhD. So promoting and valuing viable career alternatives might seem obvious. Still, in university settings it can be difficult to get buy-in from faculty for master's programs. Faculty members who are focused on research and producing intellectual heirs "and the next Nobel Prize winner" don't see why they should spend time on master's students, says Teitelbaum. "Master's education is more labor-intensive for teachers." That's one reason that the PSMs have flourished at institutions where the master's is the highest degree in the field, he adds. And people involved in master's programs say it's best to have at least one faculty member who has a strong commitment to the program.

Mentoring master's students is a challenge, says DePaul's Pando. "You spend a lot of time bringing them to a level that is acceptable, and right when they get there, they leave. It's rewarding to see them succeed, but I don't get much of a return in terms of my own research agenda."

At PhD-granting institutions, the motivation to mentor master's students is also lowered by the incentive structure for faculty: Universities tend to reward faculty more for graduating PhDs than masters, and many states provide more funding to public universities per PhD graduated than per master's degree produced. "It's a tension," says physicist Geoff Potvin of Florida International University.

"We are underserving our community by not preparing students for the host of things they will do with their careers," continues Potvin. "It's a cultural blind spot." A master's can help people become saleable. They are more qualified than bachelor's recipients. And they can be perceived as more attractive than PhDs, who sometimes want to pursue their own research or may lack experience in teamwork, communications, business, and the like. Says Potvin, "The advanced preparation in math, problem solving, and programming that master's students receive is highly valued by many employers outside of physics."

Toni Feder

Helium users are at the mercy of suppliers

Researchers seek government help in addressing supply shortage as prices are expected to continue soaring.

ALYSSA HONG

NMR SPECTROMETERS, important instruments for training chemists, must be periodically replenished with liquid helium.

"We're in a crisis mode" when it comes to helium, says William Halperin, a physics professor at Northwestern University. A shortage of the inert gas and a rise in its price are plaguing experimental physicists and chemists whose research requires low temperatures. Although helium prices and availability are perennial gripes in the community (see Physics Today, January 2017, page 26), in recent months the supply has become so restricted by growing industrial demand that users have been forced to decommission superconducting magnets, a measure that could permanently render some useless.

In the last year, there have been three "shocks" to the helium supply, says Sophia Hayes, a Washington University in St Louis (WUSTL) chemistry professor who studies such topics as spin orientation in semiconductors and new materials for capturing carbon dioxide for sequestration. The supply has become so scarce and prices so high that Hayes has shut down two of six NMR spectrometers in her laboratory. The instruments are a standard tool for university chemistry departments, and many institutions have half a dozen or more of them. At the core of each is a high-field superconducting magnet that must at all times be kept cooler than liquid helium's boiling point of 4.2 K.

If helium levels get too low, magnets will warm to their resistive state. The conversion of stored current to heat could damage the coil irreparably or prevent magnets from reattaining their original field strength. It's a slow and expensive process to return the magnets to their superconducting mode, and they can require 1000 liters of helium—costing up to $25 000 at today's prices, says Halperin.

Helium is a nonrenewable resource, and liquid helium has a limited shelf life. But distributors have recently been unwilling to supply it on the usual short notice, says Halperin. Unless, that is, customers are willing to pay an emergency fee of $25–$50 a liter.

"My situation is analogous to treading near the edge of a treacherous cliff," says Joseph DiVerdi, a Colorado State University chemist. He maintains a 30-year-old 8.5 tesla NMR magnet that requires 60 liters of liquid helium every eight weeks. He's dealt with "enormous" price increases and stretched-out lead times amid threats of rationing. "I harbor fears about timely availability," he says. "The day my supplier fails to deliver on the schedule mandated by the magnet itself is the day that our impactful program goes down, permanently."

Helium prices vary widely, depending on volume, region, the number of delivery points to be served at each institution, and the existence of long-term contracts. The University of California (UC) has one contract, with New Jersey–based Matheson Tri-Gas, that covers its entire sprawling system. Stuart Brown, a UCLA physicist, says he pays in the low teens per liter for the helium that cools the three superconducting magnets he uses to explore the properties of exotic quantum materials, superconductors, and frustrated magnets.

But Matheson began rationing helium last fall. Its primary source, ExxonMobil's processing facility in Shute Creek, Wyoming, will be partially shut down for maintenance for an extended period in the summer. Matheson may have to declare force majeure on UC's contract, and other suppliers are also rationing helium to their customers as growing demand for the gas outstrips production. The upshot: Users will have to scramble to find alternative sources, at a premium price. "The chemists are particularly panicked," says Brown. For them, shutting down instruments would hinder graduate student education and compromise researchers' competitiveness on grants.

A 2016 report from the American Physical Society (APS), the American Chemical Society (ACS), and the Materials Research Society estimated that 400 US research groups, mostly in the physical sciences, rely on liquid helium for experiments. In addition, research groups that use liquid-helium-enabled instrumentation, such as NMR spectrometers and superconducting quantum interference devices, number in the thousands.

The situation at WUSTL has reached the point where helium users have just instituted a triage system: Applications that must stay cold continuously, such as NMR spectrometers and particle accelerators, get first dibs. Urgent experiments go next, followed by those that could be put off for a few weeks or months if necessary.

Hayes has compiled anecdotal reports of the helium shortage from fellow researchers nationwide—all of them anonymized and with their suppliers' names removed. A user at a Maryland university reported having to decommission a magnet last July due to lack of helium. An NMR researcher in Colorado has a magnet that requires 250 liters every four weeks; a recent 50% price increase brings the annual cost for that magnet alone to $56 000.

A researcher at a New York university said the cost of replenishing an NMR magnet with 45 liters of helium every 13 weeks had jumped 40% over two months, from $850 to $1200. An NMR user in Texas said they were looking into sharing 100-liter dewars—the smallest amount that the vendor will supply—with another nearby school that also needs just over half of a dewar to fill its machine. If forced to shut the magnet down, the researcher said, the region would lose its only solid-state, publicly available spectrometer, and with it the ability to train undergraduates.

Crunch to continue

Research makes up a small fraction of total US helium consumption, just 8%, according to Intelligas Consulting, a market research firm. Larger uses include magnetic resonance imaging, weather-balloon and other lifting, electronics manufacturing, materials analysis, and instrument calibration. Phil Kornbluth, a helium market consultant, says total US demand is a little more than 56 million cubic meters (mcm) annually—about one-third of world consumption. With an annual output of about 96 mcm, the US is the world's largest producer.

Kornbluth estimates the current deficit of supply worldwide at around 10%. Some researchers report a level of rationing greater than that, he says, because the shortage has not affected all the major suppliers equally. Globally, supply has been nearly static. Consumption has grown in the aerospace sector and in the East Asian semiconductor industry, particularly in China, which is second only to the US in helium consumption.

Helium prices probably have yet to peak, says Kornbluth. The supply crunch should begin to ease next year when a new helium purification and liquefaction facility in Qatar is expected to come on line and add 11 mcm to the global supply. Russian energy giant Gazprom has a new source in eastern Siberia that is expected to begin operation in 2021 and eventually supply up to 55 mcm per year. A second, smaller new Russian source, also in eastern Siberia, will start production around the same time. A major helium prospect in Tanzania may be developed if helium prices remain high.

Another key cause of the shortfall is the continued decline in the ability of the US Bureau of Land Management (BLM), which manages the federal helium reserve in Amarillo, Texas, to deliver helium to private suppliers. For a decade or so beginning in 2004, the BLM was selling 59 mcm annually. But as the crude helium (50–70% pure) is withdrawn from the underground storage formation, the pressure drops, slowing extraction. According to the BLM, deliveries will be limited to around 20 mcm this year, a little more than half the 2016 amount.

After passage of 2013 legislation to

privatize the reserve, the BLM began holding annual auctions of helium, accompanied by sale of a smaller quantity at a fixed price. The final public auction and sale, totaling 8.5 mcm, was held last summer, and sales are now restricted to federal users. Universities that use at least 7500 liters of helium for federally sponsored research are eligible for reserve helium. But there are no restrictions on the price that distributors can charge for refining and liquefying the 99% pure helium product research users need.

As mandated by the legislation, the sale of all the government's reserve assets must occur no later than 30 September 2021. At that point, an estimated 68 mcm of helium will remain in storage, says Sam Burton, manager of the BLM's Amarillo Field Office. The terms under which that helium is to be sold have yet to be worked out.

WILLIAM HALPERIN

THE CENTRAL HELIUM FACILITY at Northwestern University can liquefy up to 50 liters per day from instruments across the campus.

Increasing leverage

The helium market is largely opaque, with most of the world supply controlled by a handful of vendors that include Air Products, Air Liquide, Matheson, Linde, and Praxair. Contracts typically prohibit customers from discussing the price they pay for their helium. Suppliers who were contacted for this story did not return requests for comment. Linde and Praxair just completed a merger, which resulted in the mandated divestiture of their helium assets. Germany's Messer Group has acquired a large portion of those assets and will become a new US supplier.

Because of their large numbers and small individual requirements, researchers are largely at the mercy of their suppliers. To increase their leverage, APS and ACS in 2016 organized a one-year pilot purchasing arrangement for a small number of universities through the Defense Logistics Agency (DLA), which had long been purchasing helium for other federal purposes. The subsequent two-year supply contract negotiated by the DLA expired on 31 January.

No vendor would offer the DLA a new two-year pact, and only at the last minute did a supplier agree to a one-year contract extension—at nearly double the price of the expiring arrangement, says Mark Elsesser, manager of science policy at APS. Multiple sources say the offered price under the one-year DLA deal is \$21–\$23 per liter, compared with around \$12 previously. Nearly all the 20 universities who signed up with the DLA have agreed to the price, Elsesser says.

In December, APS and ACS arranged conference calls between helium users and staffers on the House of Representatives committees on Science, Space, and Technology and on Natural Resources. In February, researchers conferred with the White House Office of Science and Technology Policy (OSTP).

An OSTP spokesperson declined to comment on the talks but noted that helium was identified on a list of critical minerals published last May by the Interior Department in response to an executive order by President Trump. That directive calls for a report assessing progress with recycling and finding technological alternatives to the listed minerals, strategies for reducing their consumption, and other steps. The report, which was supposed to be completed last summer, has yet to be released.

Reducing demand

A partial solution to alleviate the shortage is to recapture and liquefy the helium that boils off. The cost of a small-scale liquefier, capable of producing 20 liters a day, is \$100 000 to \$150 000, says Halperin. Few principal investigators can afford such an up-front cost. NSF has a \$1 million dedicated program to pay for a half-dozen of its largest helium-consuming grantees each year to acquire liquefiers.

At WUSTL, the four NMRs that Hayes has kept cooled require a total of 2200 liters of helium annually. Even with a subsidy from the chemistry department, her lab's annual helium bill is nearly \$39 000. Hayes says she could cut that bill to \$7700 at current prices—excluding the initial investment and annual operating costs for the system—with a liquefaction system that recycles with 80% efficiency. WUSTL has committed funding to liquefy enough helium for at least two machines.

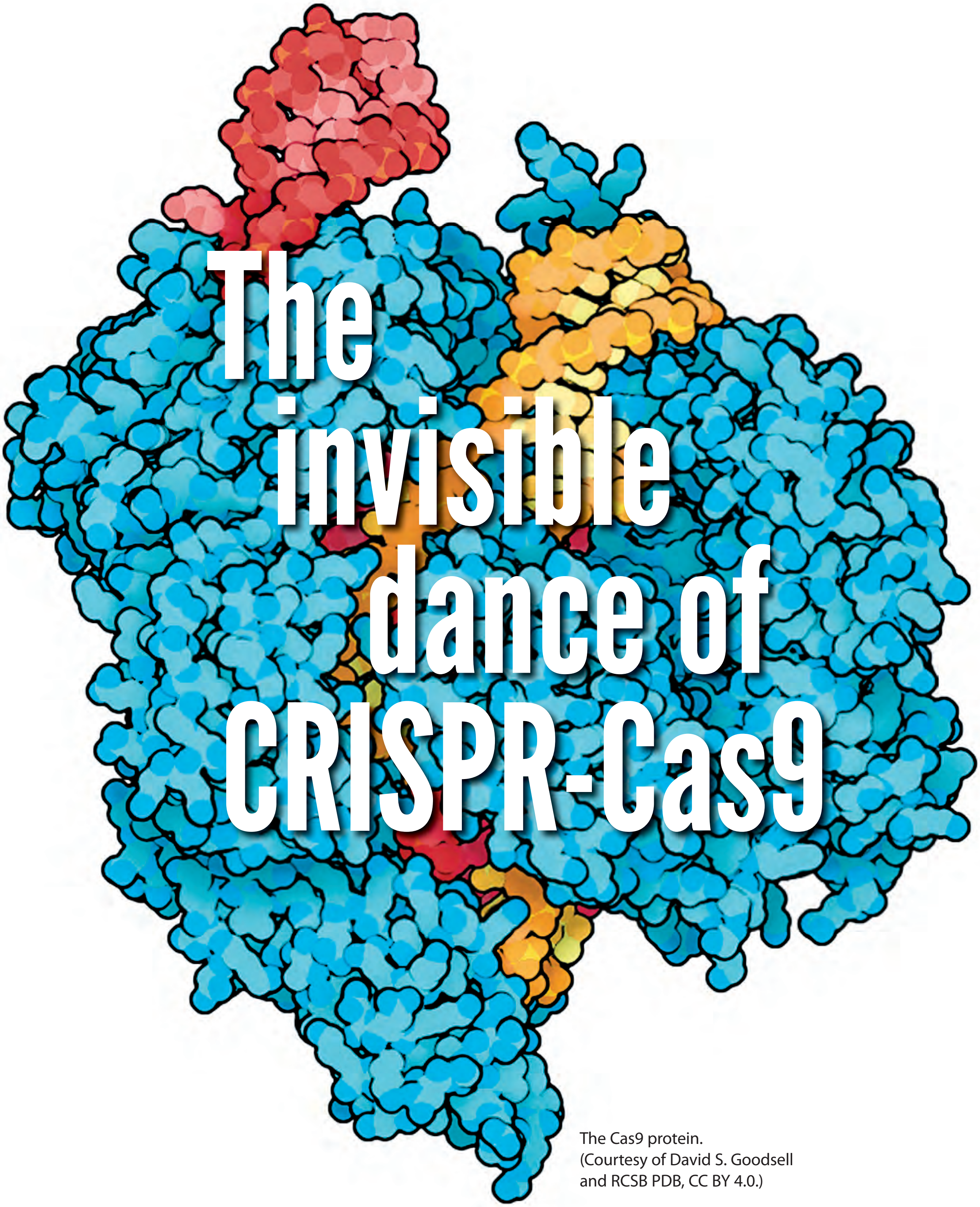
Commercially available "dry" refrigerators require no helium, but the vibration they produce can make them unsuitable for the fine-resolution measurements made with NMR spectrometers, says Hayes. They also have large power requirements.

Halperin manages a central helium liquefying facility for Northwestern. It's one of just a few facilities in the country where helium is piped in from users across the campus. Even with that capability, Northwestern requires as much as 10 000 liters of additional liquid helium per year. Halperin's own lab recycles with 95% efficiency; 65% is recovered campus-wide because some researchers use helium inefficiently, he says. Such central systems, which can produce 40–50 liters per day, can cost several million dollars.

In the meantime, more efficient use of helium by researchers would help. In Europe, says Hayes, "they protect every puff of gas they can get out of a dewar. Why do we do it differently?"

David Kramer PT

The invisible dance of CRISPR-Cas9



The Cas9 protein.
(Courtesy of David S. Goodsell and RCSB PDB, CC BY 4.0.)

Giulia Palermo is an assistant professor of bioengineering at the University of California, Riverside. **Clarisse G. Ricci** is a postdoctoral fellow at the University of California, San Diego. **J. Andrew McCammon** is the Joseph E. Mayer Professor of Theoretical Chemistry and Distinguished Professor of Pharmacology, also at UCSD.

Giulia Palermo, Clarisse G. Ricci, and J. Andrew McCammon

Simulations unveil the molecular side of the gene-editing revolution.

Since the discovery of the DNA double helix, the main molecular repository of genetic information, scientists have been struggling to find ways to efficiently manipulate genes. The ability to mark, modify, or regulate specific sequences of DNA in a controlled fashion is of key importance because of the ways that gene editing could be used to improve human life. For example, genetic therapies are being developed to permanently cure cancer and other life-threatening diseases.

In 2012 a breakthrough in biological research led to the discovery of a facile genome-editing technology, now commonly referred to as CRISPR-Cas9, that can be easily programmed to cleave and modify specific genes in living organisms.[1,2] Because of its unprecedented versatility, precision, and cost-effectiveness, CRISPR-Cas9 is rapidly paving the way for revolutionary discoveries in biosciences, medicine, and biotechnology.

Today new genetic experiments performed with the technology are vastly improving our understanding of human health and disease. In biotechnology, CRISPR-Cas9 is being used to grow drought-resistant crops and driving advances in biofuel production. It also represents a new frontier in medicine. Genetic tools based on CRISPR-Cas9 will likely be used to design new drugs and revolutionary gene therapies. Physicians can now envision curing severe genetic diseases at their source. That capability could also provide new hope for people suffering from life-threatening illnesses such as cancer and cardiovascular diseases.

Even as CRISPR-Cas9 gains widespread use in the lab, biochemists' understanding of how it works at the molecular level has remained opaque. Although experimental observations provided glimpses of those inner workings, molecular dynamics simulations have recently brought them into sharper focus. The simulations reveal an intricate biomolecular dance whose key steps—the recognition, binding, and cleavage of nucleic acids—must be performed with exquisite timing and precision.

A genetic breakthrough

The CRISPR-Cas9 technology is fundamentally a bacterial defense system against viral infections. When a virus invades a bacterium, parts of the foreign DNA are inserted between peculiar genetic sequences, called clustered regularly interspaced short palindromic repeats, or CRISPR, in the bacterial DNA. The DNA "spacer" sequences are markers of a viral invasion and are transcribed into complementary sequences of RNA. The RNA transcripts then bind with a specific enzyme called Cas9 and form the CRISPR-Cas9 complex. (For a glossary of genetic-engineering terms, see the box below.)

Because of its base-pair complementarity with viral DNA, the guide RNA segment in the CRISPR-Cas9 complex leads and docks the Cas9 enzyme at precise regions of the foreign genetic material. Once there, Cas9 cleaves the viral sequences and neutralizes the viral invasion, as shown in figure 1. After the infection, the spacer DNA remains stored between CRISPR sequences as a "memory" that immunizes against past infections.

The great breakthrough in CRISPR biology came with the realization that Cas9 could be reprogrammed to cleave not only viral DNA but also other DNA sequences[2] by changing the guide RNA filament associated with Cas9. The enzyme is thus able to remove any undesired fragment of DNA and leave a tailor-made fragment in its place. Moreover, CRISPR-Cas9 is able to recognize DNA at specific sites by the presence of a short sequence known as protospacer adjacent motif (PAM), which consists of a few nucleotides and lies adjacent to the sequence to be cleaved.

In viral infections, PAM recognition is the first step to binding and subsequent cleavage of the adjacent DNA sequence by Cas9. If PAM is not present, CRISPR-Cas9 does not bind or cleave any DNA sequence, even if it perfectly matches the guide RNA segment. Thus CRISPR-Cas9 can be programmed only to cleave DNA sequences that are preceded by an appropriate PAM sequence. But not all DNA sequences are naturally preceded by a recognizable PAM sequence.

One of the most valuable goals in genome editing is the biomolecular engineering of Cas9-like enzymes that recognize any desired PAM sequence. Achieving that goal would expand the targeting capability of the technology.[3] And it's an example of how Cas9 can be further improved for genetic engineering. But to intelligently manipulate Cas9, biologists need a detailed understanding of how CRISPR-Cas9 recognizes, binds, and cleaves DNA.

Over the past five years, scientists have identified the fun-

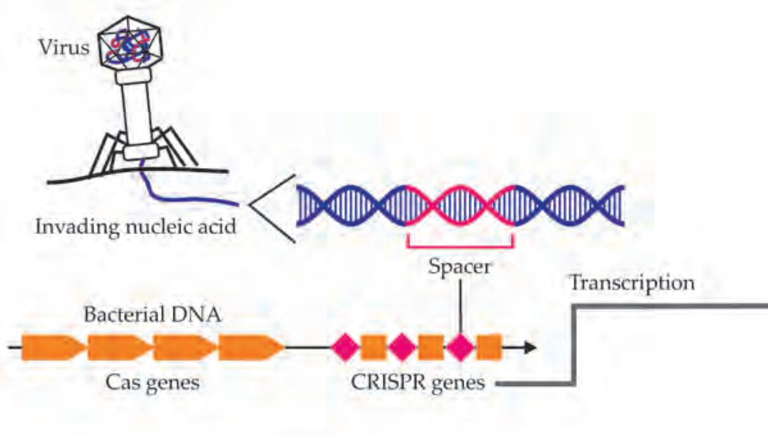


FIGURE 1. CRISPR-CAS9 IMMUNE DEFENSE MECHANISM. In an infection, segments of the viral nucleic acids (spacers) are inserted between clustered regularly interspaced short palindromic repeats (CRISPR) in a cell's genetic material and form an array of CRISPR genes. The array is then transcribed into an RNA segment that functions as a guide for the Cas9 protein. The guide RNA binds to the protein to form a CRISPR-Cas complex. Because CRISPR-Cas9 contains a guide RNA segment that is complementary to viral DNA, it recognizes and binds foreign viral DNA as long as the DNA contains an adjacent PAM segment. Once bound to viral DNA, CRISPR-Cas9 separates and cleaves the two viral DNA strands, thus making them inactive.

A GENETIC-ENGINEERING GLOSSARY

Catalysis. The breaking of a chemical bond, facilitated by an enzyme.

CRISPR. An acronym for clustered regularly interspaced short palindromic repeats. Peculiar genetic sequences in bacteria, between which viral DNA segments are inserted, serve as markers of an infection.

CRISPR-Cas9. The complex formed by a CRISPR RNA transcript and a Cas9 protein.

DNA. Deoxyribonucleic acid, the molecular repository of genetic information for all cellular life forms and many viruses. It is located in the nucleus and is normally found as a double helix, two intertwined strands.

Enzyme. A biomolecule, normally a protein, that catalyzes a specific chemical reaction by lowering the activation energy.

Gene. A segment of DNA that encodes the genetic information required for the synthesis of functional biological products. Mostly proteins, the products could also be some types of RNA.

Genome. The entire genetic information in a living organism, encoded in DNA (or in RNA in some viruses).

HNH and RuvC. Nuclease domains of the Cas9 protein, responsible for cleaving the complementary and noncomplementary DNA strands, respectively.

Mutation. An alteration in DNA structure that produces permanent changes in the genetic information encoded therein. Detrimental mutations are associated with aging and cancer.

Nuclease. An enzyme that cleaves the internucleotide (phosphodiester) linkages in the strands of nucleic acids.

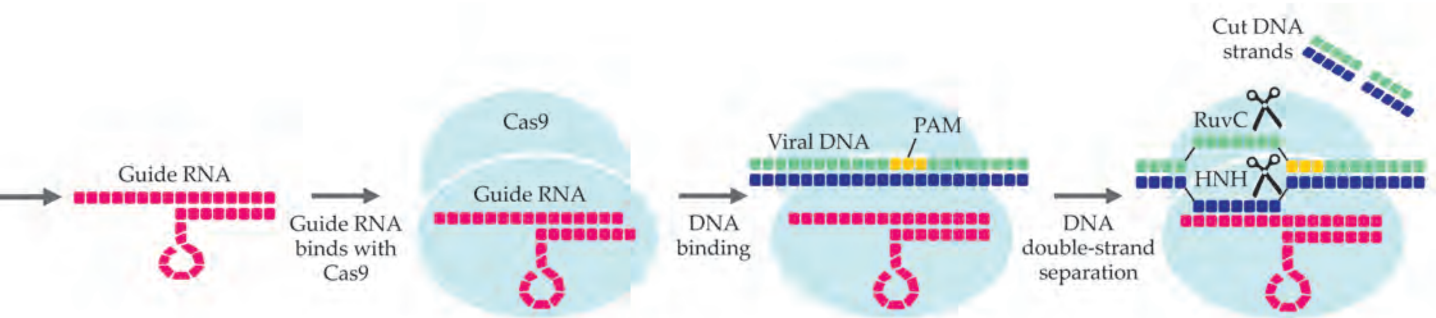
PAM. An acronym for protospacer adjacent motif, a short segment of a few nucleotides that occurs in the viral DNA adjacent to the sequence that is cleaved by Cas9.

Protein (or enzyme) domain. A compact unit within a protein chain that can exist and function independently of the rest of the chain.

RNA. Ribonucleic acid, the molecular carrier of genetic information for all cellular life forms. It is normally found as a single strand that can adopt widely different and complex three-dimensional structures, but it can also form hybrid double helices with a complementary DNA strand, as in CRISPR.

Transcript. The RNA product of a DNA transcription.

Transcription. The synthesis of an RNA segment complementary to a DNA template.



damental biophysical aspects of CRISPR-Cas9. They've used state-of-the-art biochemical experiments and emerging electron-microscopy techniques to discover the intricate mechanism by which Cas9 edits genes.[4] We now know, for instance, that upon PAM recognition, the complementary strand of the target DNA interacts with the RNA filament and produces a hybrid DNA–RNA double helix,[3] as shown in figure 2.

X-ray crystallography reveals the overall architecture of Cas9, which is formed by several domains with specialized functions.[4] When ready for catalysis, Cas9 positions its two nuclease domains—those specialized in cutting DNA—in close proximity to the two DNA strands. In that conformation, Cas9 can simultaneously cleave the two DNA strands to produce the characteristic double-strand breaks.

Sophisticated experimental studies have led to our current understanding of the biological function of CRISPR-Cas9. Our collection of experimentally obtained snapshots of Cas9 has given us a peek into the invisible dance that it performs as it binds to and cleaves nucleic acids. But to actually watch the conformational changes that compose the dance and understand how they are related to function is an extremely challenging experimental task. Here is where the power of computer simulations comes into play. They provide a dynamic, microscopic view that is out of reach when using experimental techniques.

The power of physical simulations

Molecular dynamics (MD) simulations, which use classical Newtonian physics to follow the motions of atoms through time, precisely capture the dynamics of biomolecules.[5] In classical MD, atoms are approximated as spheres, chemical bonds are approximated as springs, and the interactions are modeled by a set of parameterized functions, commonly referred to as force fields. Figure 3a illustrates the atomic-scale simulations.

In the past few decades, progress in computational capability has made MD simulations significantly more powerful—and inexpensive, compared with any experimental method. A desktop computer can simulate biomolecular processes on the nanosecond time scale. Supercomputers and sophisticated methodologies can control the speed of the dynamics and allow scientists to observe processes that occur over milliseconds.

The state-of-the-art "accelerated" MD methodology uses quadratic functions to effectively decrease the potential energy barriers and accelerate the transitions between low-energy states,[6] as shown in figure 3d. The simulations sample a wider configuration space and capture biological processes that cannot be described via conventional MD simulations. The advances have made it possible to simulate complex

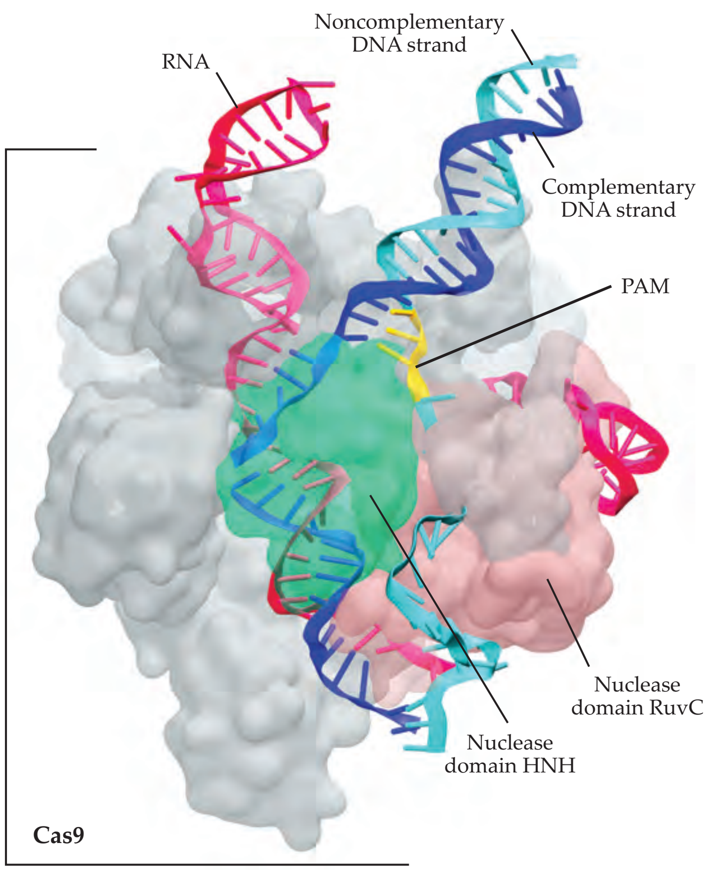


FIGURE 2. MOLECULAR ARCHITECTURE OF THE CRISPR-CAS9 COMPLEX, from cryoelectron microscopy experiments and computational modeling.[4,10] The Cas9 protein (gray) is bound to a guide RNA segment (magenta) and a matching DNA sequence (the complementary strand is dark blue; the noncomplementary strand, light blue; and the PAM segment, yellow). The Cas9 protein contains two nuclease domains, HNH (green) and RuvC (pink), which cleave the complementary and noncomplementary DNA strands, respectively.

and slow biophysical events, such as folding, binding, and large-scale conformational transitions in biomolecules.[6,7]

At the same time, advances in the description of nucleic acids have enabled accurate simulations of proteins bound to DNA or RNA.[8] Given the complexity of the CRISPR-Cas9 system, MD simulations are only meaningful over very long time scales. Accelerated MD methods therefore represent the best approach available to access biophysical processes that are representative of CRISPR-Cas9 biology. Indeed, accelerated simulations can access more than the conformational changes observed by conventional MD (see figure 3c, 3d).

MD techniques can also support experiments by revealing CRISPR-Cas9 at work on the molecular level and unveiling specific interactions and forces that are behind the Cas9 function. In the next section, we summarize the most exciting outcomes of computer simulations of CRISPR-Cas9 and the ongoing challenges in the field of genetic engineering.

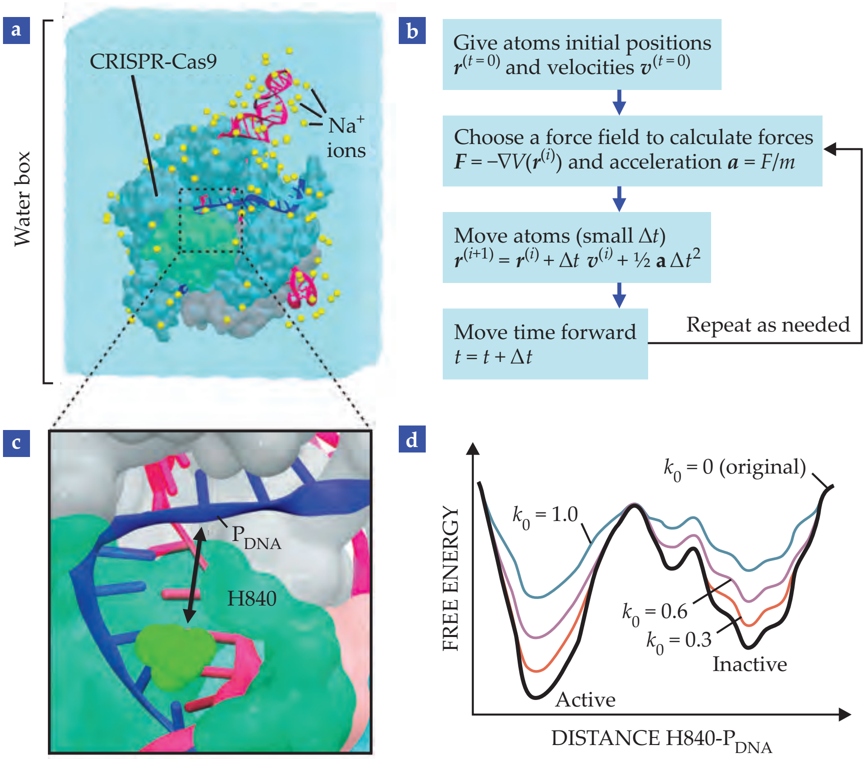


FIGURE 3. MOLECULAR DYNAMICS (MD) SIMULATIONS produce a temporal trajectory of **(a)** CRISPR-Cas9 embedded in a water box that contains sodium ions at physiological concentration. **(b)** In a nutshell, MD consists of giving atoms initial positions and velocities, choosing a set of functions and parameters to describe the forces acting on each atom, and advancing time using Newton's equations of motion. The resulting trajectory of atomic coordinates can be used to track the system's properties over time. **(c)** Gaussian accelerated molecular dynamics[6] (GaMD) describes the movement of histidine H840 (the catalytic residue in HNH) to the cleavage site in the target strand (P_{DNA}) for catalysis.[10] **(d)** In GaMD, quadratic functions modify the original potential energy of the system in order to overcome the barrier between active and inactive states. The extent of acceleration is controlled by parameters of the Gaussian function. The greater the value of k_0, the greater the acceleration and the easier the system overcomes the barrier between states.

Watching CRISPR-Cas9 at work

RNA binding is a critical step for Cas9 activation because it primes the protein to bind to DNA.[4] It is therefore of paramount importance to understand the mechanism by which Cas9 binds with RNA. To that end, computational scientists have recently used enhanced-sampling MD techniques to simulate the recruitment of RNA by Cas9. Those simulations offered the first direct observation of domain movements that reshape the unbound Cas9 architecture into its RNA-bound state,[9] illustrated in figure 4a.

During the conformational changes, Cas9 temporarily exposes basic residues to the solvent and creates a "positive cavity" that attracts and accommodates the negatively charged RNA filament. The observation of that positively charged cavity revealed the exact way in which electrostatic forces facilitate RNA–Cas9 binding.

Even after Cas9 is bound to its guide RNA, the CRISPR-Cas9 complex is not yet ready to catalyze the cleavage of DNA. Cas9 must first undergo a sequence of gradual conformational transitions and eventually relocate the two catalytic domains, HNH and RuvC, to optimal positions in order to cleave the complementary and noncomplementary DNA strands.

Using a combination of "steered" and accelerated MD simulations, computational scientists observed those conformational transitions and were able to identify the main players during Cas9 activation.[9] In particular, the simulations revealed a striking plasticity of the HNH domain, which appears to be the main switch controlling the conformational dynamics. Prior to activation, the catalytic residues of HNH point away from the DNA cleavage site and in the opposite direction. To become active, HNH therefore needs to rotate by 180° and approach the site—a process captured by simulations and illustrated in figure 4b.

Starting from preactivated structures, MD simulations also enabled the first attempt to determine the final, completely activated structure of Cas9, where both HNH and RuvC domains are well positioned to cleave the DNA strands.[9] Independent computational studies have confirmed and reproduced those results.[10,11] In 2017 electron microscopy revealed an active structure of CRISPR-Cas9 in remarkably good agreement with the computational structure.[12]

MD simulations have also been used to perform a computational experiment designed to understand how the nucleic acids are involved in Cas9 activation. Although it's known that the two DNA strands must be properly positioned for cleavage to occur, little was understood about how the noncomplementary strand—the one not hybridized with the guide RNA—functions in Cas9 activation. In the computational experiment, researchers simulated the CRISPR-Cas9 complex both in the presence and in the absence of the noncomplementary DNA

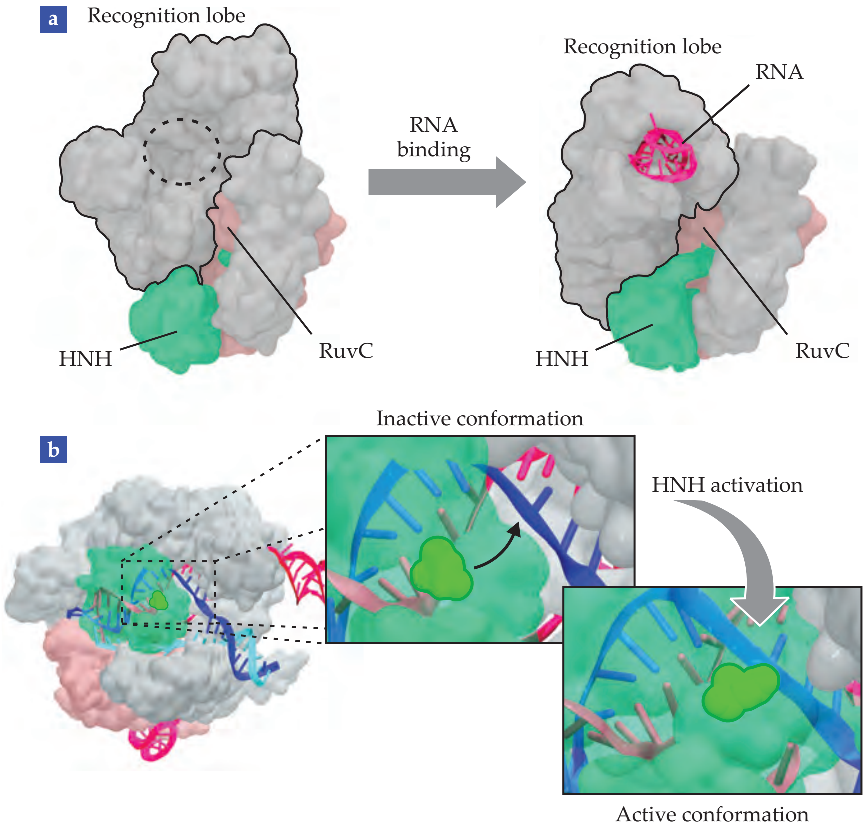


FIGURE 4. MOLECULAR MECHANISMS OF CRISPR-CAS9, revealed by molecular dynamics simulations. **(a)** Rearrangements made to the recognition lobe reshape the molecular architecture of unbound Cas9 into its RNA-bound conformation. **(b)** The movement of HNH into its final catalytic state prepares it to cleave the DNA. The conformational change, shown as insets, brings the HNH catalytic residue close to the cleavage site in the DNA complementary strand. In all structures, Cas9 nuclease domains HNH and RuvC are green and pink, respectively. RNA is magenta; DNA is dark blue (complementary strand) and light blue (noncomplementary strand).

strand.[13] In the noncomplementary strand's absence, HNH moved away from the cleavage site and adopted a conformation that made it inactive. But when the complementary strand was present, it facilitated the 180° rotation of HNH toward the catalytic site.

Scientists at the University of California, Berkeley, followed those simulations with sophisticated spectroscopic techniques to distinguish the conformational states of Cas9 in bulk and as a single molecule.[14] The experiments confirmed the early computational outcome: They showed that the repositioning and docking of HNH at the cleavage site indeed requires the presence of the noncomplementary DNA strand.

Allosteric communications

One interesting aspect of the CRISPR-Cas9 complex is the ability of its domains to communicate with each other through a process known as allostery.[15] Such communications are an important feature of many biological systems, and they allow perturbations at spatially distant regions of the protein to affect how the active site functions. The perturbation can be the binding of a ligand to an allosteric site, whose local effect is somehow transmitted all the way to functional regions where the ligand interferes with conformation and dynamics. Ligands that can exert remote control over a protein's active region are commonly referred to as allosteric effectors.

Intriguingly, allostery often does not involve huge (or even obvious) conformational changes, which makes it difficult to understand how the information travels throughout the protein. In fact, because of the subtle nature of allosteric signaling, experiments often fail to provide a full description of their effects. MD simulations, on the other hand, are valuable tools for studying allosteric effects. They provide a rich description of atomic fluctuations, from which correlated motions can be extracted.

To study allosteric communications in the CRISPR-Cas9 complex, computational scientists have used a mathematical approach based on Shannon's entropy to identify pairs of atoms that display interdependent motions during the simulations. The approach produces pairwise correlation coefficients that dictate how much the position of one atom restricts the position of another, and vice versa.

With those coefficients at hand, it is possible to build network graphs by applying the same algorithms that Facebook and other media outlets use to describe social networks. The algorithms organize individuals into different communities and identify the most efficient communication pathways between thousands of people—or atoms, in the case of MD simulations. By describing Cas9 as a network of interactions, scientists can track the main communication pathway in the CRISPR-Cas9 complex.[16] It turns out that PAM—the small sequence of DNA that initiates recognition and binding—works as an allosteric effector and facilitates communication between the two catalytic domains, RuvC and HNH.

MD simulations enabled modeling the final, completely activated structure of Cas9, where both HNH and RuvC domains are well positioned to cleave the DNA strands.

Importantly, the cross talk between RuvC and HNH is what allows Cas9 to cleave the two DNA strands in a concerted fashion. Thus PAM is required not only to ensure DNA recognition by Cas9 but also to activate the two domains for catalysis.

The future of CRISPR-Cas9

The studies discussed in this article are all based on classical MD simulations and focus on the sequence of conformational changes that prepare Cas9 for DNA cleavage. The actual cleavage mechanism, however, cannot be simulated by classical MD. That's because it requires a proper description of the electronic effects in chemical reactions.

To understand the catalytic mechanism by which Cas9 cuts the DNA, computational scientists need to employ high-level quantum mechanics simulations, which describe the formation and breakup of chemical bonds. Such simulations have recently determined the structure of the reactant state of Cas9.[17] Building on that structure, which depicts a fully reactive CRISPR-Cas9 catalytic complex, we expect future quantum mechanics simulations to shed light on the catalytic mechanism of the system and yield crucial information on how to optimize or tune Cas9's activity.

We hope to have convinced you of the power of molecular simulations for understanding how CRISPR-Cas9 edits genes. Gaining that knowledge is the first step to improving the technology for genome-editing purposes. Despite the remarkable advantages of CRISPR-Cas9 relative to other such systems, some issues still need to be addressed before it can be considered a safe genetic therapy. One concern is the occurrence of so-called off-target cleavages, which occur when CRISPR-Cas9 mistakenly cuts DNA sequences that are similar but not identical to the target sequence.

Because off-target cleavages can produce unpredictable and detrimental mutations, the specificity of CRISPR-Cas9 must be improved before it can be safely used for clinical purposes. In that respect, recent computational simulations promise to provide valuable insights on the molecular determinants of off-target effects.[18] They are sure to help in designing novel and highly specific Cas9-like enzymes.

Our work is supported in part by the National Institutes of Health, the National Biomedical Computation Resource, the San Diego Supercomputer Center, and the Extreme Science and Engineering Discovery Environment, which provided computer time. We thank Yinglong Miao for discussions about accelerated MD simulations.

REFERENCES

1. J. A. Doudna, E. Charpentier, *Science* **346**, 1258096 (2014).
2. M. Jinek et al., *Science* **337**, 816 (2012).
3. C. Anders et al., *Nature* **513**, 569 (2014).
4. F. Jiang, J. A. Doudna, *Annu. Rev. Biophys.* **46**, 505 (2017).
5. M. Karplus, J. A. McCammon, *Nat. Struc. Biol.* **9**, 646 (2002).
6. Y. Miao, V. A. Feher, J. A. McCammon, *J. Chem. Theory Comput.* **11**, 3584 (2015).
7. Y. Miao, J. A. McCammon, *Proc. Natl. Acad. Sci. USA* **115**, 3036 (2018).
8. G. Palermo et al., *Acc. Chem. Res.* **48**, 220 (2015).
9. G. Palermo et al., *Proc. Natl. Acad. Sci. USA* **114**, 7260 (2017).
10. G. Palermo et al., *Q. Rev. Biophys.* **51**, e9 (2018).
11. Z. Zuo, J. Liu, *Sci. Rep.* **7**, 17271 (2017).
12. C. Huai et al., *Nat. Commun.* **8**, 1375 (2017).
13. G. Palermo et al., *ACS Cent. Sci.* **2**, 756 (2016).
14. Y. S. Dagdas et al., *Sci. Adv.* **3**, eaao0027 (2017).
15. S. H. Sternberg et al., *Nature* **527**, 110 (2015).
16. G. Palermo et al., *J. Am. Chem. Soc.* **139**, 16028 (2017).
17. G. Palermo, *J. Chem. Inf. Model.* (2019), doi:/10.1021/acs.jcim.8b00988.
18. C. G. Ricci et al., *ACS Cent. Sci.* (2019), doi:/10.1021/acscentsci.9b00020.

PT


YOUR FINDINGS
CAPTURE
WHAT'S
POSSIBLE
Now it's time to share them
UNLOCK YOUR POTENTIAL
Visit publishing.aip.org
AIP
Publishing

Paul Halpern is a professor of physics at the University of the Sciences in Philadelphia. He is the author of *Einstein's Dice and Schrödinger's Cat* (2015) and *The Quantum Labyrinth: How Richard Feynman and John Wheeler Revolutionized Time and Reality* (2017).

ALBERT EINSTEIN, celebrity physicist

Paul Halpern

In Einstein's later years, although his contributions to physics became increasingly marginal and abstract, the press continued to trumpet his far-flung unification schemes as if they were confirmed scientific breakthroughs.

What is a scientific revolution? The answer depends on whom you ask. According to most historians of science, true revolutions or major breakthroughs are rare—something as profoundly distinctive as quantum mechanics would likely make the cut, but countless other developments would fall short. On the other hand, the press has maintained its own ideas. Driven by the pressure for headlines, journalists have advanced their own notions of what is important and newsworthy. In the case of Albert Einstein (see figure 1), who became a familiar household name in the 1920s, practically anything he said or did publicly drew headlines.

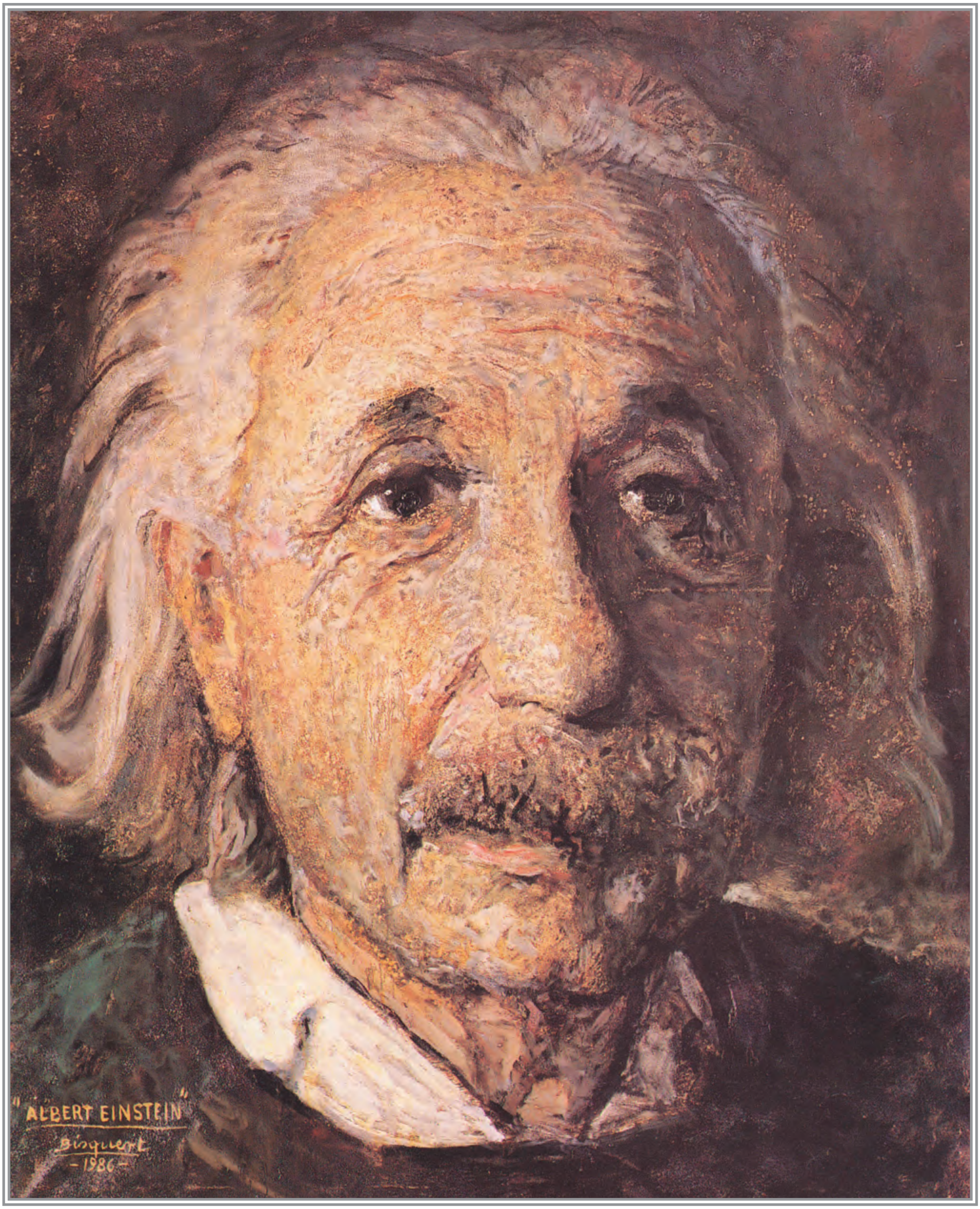
Early in Einstein's career, the press attention he garnered was an outgrowth of a true breakthrough: the eclipse observations of 1919 that helped confirm his general theory of relativity. The scientific community and the press agreed that Einstein's work altered perceptions of space, time, mass, energy, and gravitation. Moreover, during a time of xenophobia, globally minded Americans gravitated to him as an outspoken foreign scientist expressing an international outlook.[1] From that point on, Einstein was a celebrity, heralded for his quirky personality and passionate activism in addition to his scientific achievements.[2]

That celebrity status inspired the media to continue publicizing Einstein's theoretical meanderings, even when they had little support from other scientists. The scientific community largely ignored his idiosyncratic search for a unified field theory, which increasingly veered from the mainstream consensus and which other physicists came to view as unproductive and outré. The press, however, continued to trumpet his supposed breakthroughs, depicting Einstein as the quintessential eccentric scientific genius.

The relationship between Einstein and the press is a case in which a scientist's fame triumphed over the substance of his work. Einstein's unified field theory attempts were discredited again and again because of the lack of viable solutions, let alone experimental evidence. But they received far more coverage than many of the important experimental and theoretical results by other physicists during the same period, such as advances in nuclear and particle physics. Exaggerated reporting misled readers about the value of Einstein's research.

The eclipse that changed the world

Aside from a few brief stories about his advocacy of pacifism during World War I, the first mention of Einstein in the international press coincided with the announcement of the solar eclipse results obtained on 29 May 1919. Two British


"ALBERT EINSTEIN"
Bisquert
-1986-

expeditions went to observe the eclipse: one to Sobral, Brazil, and the other to Príncipe, an island off the coast of western Africa. Noted astronomer Arthur Eddington headed the latter group.

At a meeting on 6 November of that year, the Royal Society deemed both teams' findings consistent with the gravitational light-bending predictions of Einstein's general theory of relativity. The next day, the *Times* of London trumpeted the results with the front-page headline, "Revolution in science. New theory of the universe: Newtonian ideas overthrown."

The story soon spread around the world. The first *New York Times* story, with the relatively subdued headline "Eclipse showed gravity variation: Diversion of light rays accepted as affecting Newton's principles. Hailed as epochmaking," appeared on 9 November. But it was followed by a piece on 10 November with a more alarming headline, "Lights all askew in the heavens: Men of science more or less agog over results of eclipse observations. Stars not near where they seemed or were calculated to be, but nobody need worry." More than a dozen other articles or reports about Einstein and his work appeared later that month in the *New York Times*, mainly debating whether the results were valid, if they affected daily life, and whether they were understandable by mere mortals.

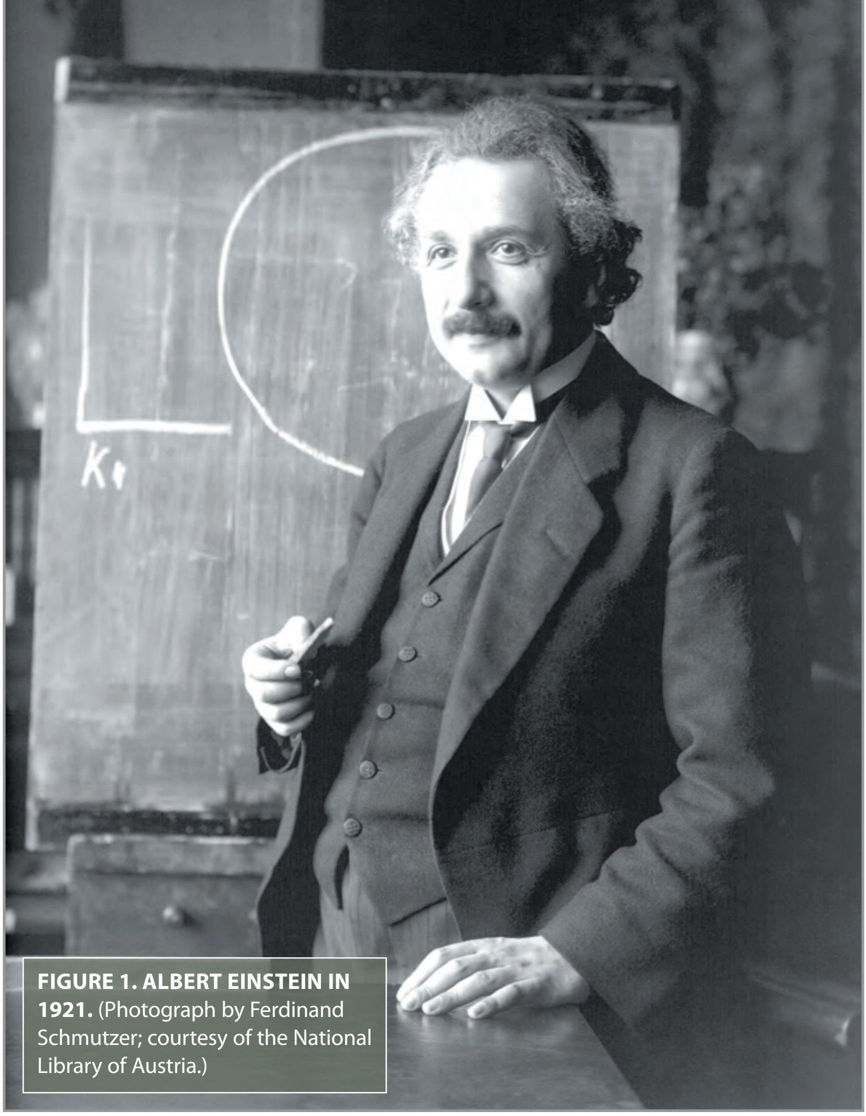


FIGURE 1. ALBERT EINSTEIN IN 1921. (Photograph by Ferdinand Schmutzer; courtesy of the National Library of Austria.)

After the war, science coverage in general had dramatically increased in the US mainstream press. Although specialized science publications such as *Scientific American* and *Popular Science Monthly* had attracted readers for decades, the rise of chemical warfare and other military uses of science had spurred a push among scientists for greater newspaper reporting of its benevolent side. In 1919 the American Chemical Society started its News Service, which began issuing press releases about the field.

Two years later newspaper publisher E. W. Scripps and noted biologist William Ritter launched Science Service, an agency designed to promote a positive image of science through news stories and photos.[3] By 1927 the *New York Times* had hired its first designated science editor, Waldemar Kaempffert, lending even greater prestige to that branch of journalism. Science journalism had become an integral part of press coverage, and Einstein's rise to fame coincided with a greater hunger for science pieces.

But almost no science journalists were schooled in contemporary theoretical physics. How could they get a handle on Einstein's more abstruse work? In practice, they couldn't, so they needed to improvise. They touted the importance of Einstein's theories while only vaguely interpreting them for the public. Readers began to perceive Einstein's work as fundamentally enigmatic—not even fully understandable by science journalists. That mystique bolstered his fame even further.

Einstein's celebrity status landed him many speaking engagements around the world, including a spring 1921 visit to the East Coast of the US. He spoke at Columbia, Princeton, and other universities and was invited to the White House to meet with President Warren Harding. Princeton University Press published a popular book, *The Meaning of Relativity*, from the scientific talks Einstein delivered during that tour. The 1921 Nobel Prize in Physics only added to his reputation as a superstar.

What affine, fine theory!

By the early 1920s, Einstein had already started to consider extensions of general relativity, including three variations proposed independently by Hermann Weyl, Theodor Kaluza, and Eddington. The goal was to combine electromagnetism and gravitation into a unified field theory that would geometrize both phenomena. As historian Jeroen van Dongen has written, Einstein hoped to extend the mathematical methods he applied so successfully to gravitation and develop a single set of equations describing a geometric field theory.[4]

After pondering the three theories, Einstein became most intrigued by Eddington's so-called affine theory, which changed the definition of the Christoffel connection (also known as the affine connection), the mathematical entity that represents how parallel lines are transported through spacetime along a curved manifold. That definition gave the connection additional flexibility, hypothetically allowing it to describe electromagnetic potentials.

Finding Eddington's model incomplete, Einstein aspired to develop his own version. In March 1923 Einstein submitted a draft of his new theory, which he had developed on a sea voyage to Japan, to the Prussian Academy of Sciences in Berlin. The *New York Times* trumpeted his submission in a 23 March article, "Einstein to announce theory 'surpassing even relativity.'" The piece falsely suggested that Einstein had found a way of explaining terrestrial magnetism, a complex mechanism that was not fully understood at the time.

Einstein worked on the affine theory for two more years. By the end of 1925, he realized that he could find no singularity-free solutions (a singularity is a point or region at which physical parameters become infinite) to the field equations he had developed. He decided to scrap his extension of Eddington's work. For the next several years, he explored different options, including an investigation of Kaluza's theory.

Kaluza's work added a fifth dimension to Einstein's field equations. An extra mathematical restraint, called the cylindrical condition, forbade direct observation of it. But that undetectable fifth dimension allowed room in the equations to house electromagnetic terms. Those components could be shown under certain circumstances to obey Maxwell's equations and thus offered tantalizing hints of unification. However, the theory was not invariant under general transformations of coordinates, and having to impose a particular coordinate system for the theory to work seemed artificial. It also didn't have physically realistic solutions. Nevertheless, motivated in part by Swedish physicist Oskar Klein's publication of an independent five-dimensional unification attempt, Einstein spent parts of 1926 and 1927 exploring ways to bring Kaluza's notion to fruition.

Distant parallelism

In 1928 Einstein was diagnosed with heart disease and his physician urged him to rest. As he recovered, he worked on an idea for unification called distant parallelism, which proposed an independent web of connections between each point in spacetime that supplemented the standard relationships of general relativity. In early January 1929, Einstein submitted a paper to the Prussian Academy and issued an announcement. Though the paper was extremely preliminary, lacking any inkling of experimental evidence, the *New York Times* published a front-page story about it on 12 January, proclaiming that "Einstein himself considers it by far his most important contribution to mankind—scientifically more important than his original theory."

Einstein's article "Zur einheitlichen Feldtheorie" ("On unified field theory") was published in *Sitzungsberichten der Preussischen Akademie der Wissenschaften* (*Proceedings of the Prussian Academy of Sciences*) on 30 January. Within three days, the first printing of the journal offprint—a thousand copies—sold out, and another thousand copies were soon printed. Soon thereafter, *Nature*'s News and Views section published a more accessible account of the work, including a quote by Einstein: "Now, but only now, we know that the force which moves electrons in their ellipses about the nuclei of atoms is the same force which moves our earth in its annual course about the sun, and is the same force which brings to us the rays of light and heat which make life possible upon this planet."[5]

With Einstein's 50th birthday approaching, his new idea rapidly caught fire, at least in the popular press. The *New York Times* published almost a dozen articles that year about distant parallelism, rivaling its coverage of the 1919 eclipse results. Although by then the bulk of the physics community was focused on quantum mechanics and related fields and had no interest in Einstein's attempts at unification, reporters managed to gauge the reaction of at least a few physicists. Harold Sheldon, chair of New York University's physics department, opined that "such things as keeping airplanes aloft without engines or material support, as stepping out of a window into the air without fear of falling, or of making a trip to the moon … are avenues of investigation suggested by this theory."[6]

One of the few knowledgeable physicists who kept up with Einstein's unified models was Wolfgang Pauli (see figure 2). Einstein saw Pauli as an important sounding board—honest, thorough, critical, but often right. To Einstein's dismay, Pauli found many flaws in distant parallelism, including its inability to match key predictions of general relativity, such as gravitational light bending. It also did not match the expected features of electromagnetism as mapped out by Maxwell's equations. Finally, it did not take into account key electron properties gleaned from the Dirac equation.

In December, Pauli wrote to Einstein, "I would take any bet with you that you will have given up the whole distant parallelism at the latest within a year from now, just as you had given up previously the affine theory. And I do not want to rouse you to contradiction by continuing this letter, so as not to delay the approach of the natural decease of the distant parallelism theory."[7]

Privately, Pauli told Pascual Jordan, "Einstein is said to have poured out, at the Berlin colloquium, horrible nonsense about new parallelism at a distance. The mere fact that his equations are not in the least similar to Maxwell's theory is employed

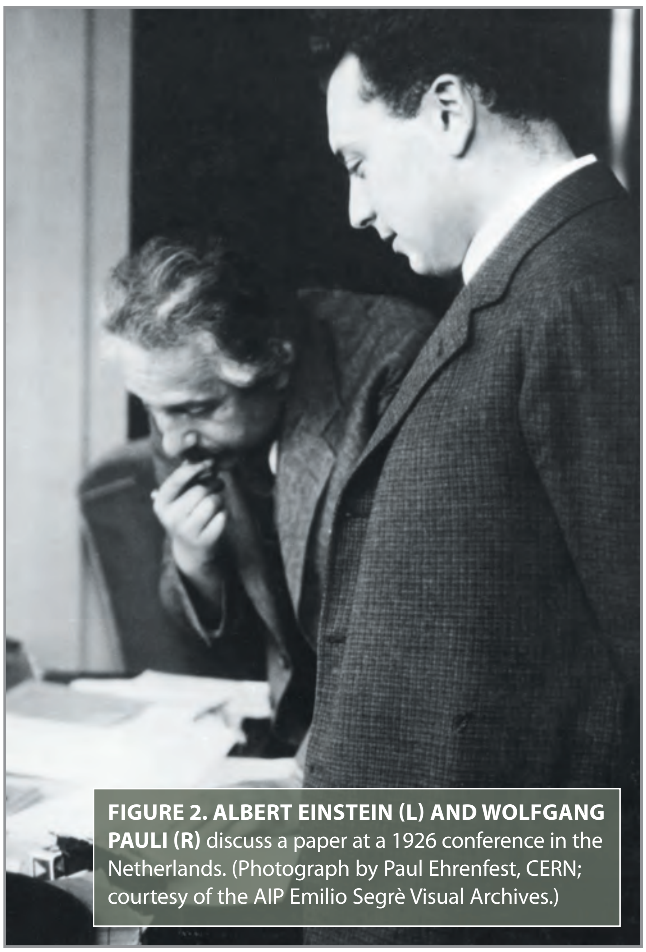


FIGURE 2. ALBERT EINSTEIN (L) AND WOLFGANG PAULI (R) discuss a paper at a 1926 conference in the Netherlands. (Photograph by Paul Ehrenfest, CERN; courtesy of the AIP Emilio Segrè Visual Archives.)

by him as an argument that they are somehow related to quantum theory. With such rubbish he may impress only American journalists, not even American physicists, not to speak of European physicists."[8]

Pauli's perceptions that American journalists would be the ones most interested in Einstein's work were right on the mark. More than in European journalism, there was a tradition in US journalism of using hype to sell papers. Newspapers in the US did not even seem to notice the failure of Einstein's earlier attempts at unification, their lack of viable solutions and experimental evidence, or the other problems with his theories. Journalists placed them in virtually the same category of general relativity, which had actually passed several key tests. Although Pauli maintained a continued interest in unifying the natural forces, he remained cynical about the way such ideas were represented by the press—later mocking, for example, the overblown press treatment of a similarly undeveloped and unsupported unification model Werner Heisenberg advanced in the late 1950s.

Einstein thought at first that Pauli was too harsh about distant parallelism and that he failed to see its elegance. However, after about another year of exploring the concept, he had to concede that Pauli was right. Throughout the 1930s and early 1940s, Einstein explored further variations of the Kaluza idea. On 23 January 1931, the *New York Times* took note of his new direction, without ever mentioning the failure of the old and the rudimentary state of the new. After Einstein gave a Caltech seminar on one of his fledgling ideas—a five-dimensional projective geometry—the paper reported,

> A key to the innermost secrets of nature has been presented to a class of distinguished physicists and mathematicians by Albert Einstein in the latest and greatest creature of his world-famed brain, the unified field theory.
>
> Theoretical physicists proclaimed it as the most simple theory that will explain all the secrets of space and the universe. . . .
>
> Dr. Einstein explained that the fundamental equation is presented for mathematicians to proceed and work out equations for experimental work. Experimental proof of his unified field theory is already at hand, he revealed, in its application to laboratory results with weak electro-magnetic and gravitational fields.

In other words, the article asserted that Einstein had developed a litmus test involving charged particles acting under electromagnetic and gravitational fields. In fact, he had not. That story represented yet another example of hyped coverage of a mere attempt at grand theoretical unification.

The hermit at the IAS

In 1933, when the Nazi regime took power in Germany, Einstein took a position at the Institute for Advanced Study (IAS) in Princeton, New Jersey (see figure 3). There, he dropped projective geometry and pursued different five-dimensional unification attempts with various assistants, including Walther Mayer, Peter Bergmann, and Valentine Bargmann. IAS director Abraham Flexner zealously guarded Einstein's privacy and relatively few news stories about him and his research appeared in the mid to late 1930s.

Such isolation was a marked contrast with Einstein's previous visits to the US, when numerous public talks and tours brought him into far more contact with photographers and reporters. Even in Berlin during the late 1920s, reporters were so eager to interview him that one sought him out at the private estate where he had wanted to celebrate his 50th birthday quietly.

In March 1939, close to the end of Flexner's directorship, Einstein celebrated his 60th birthday. By then readers were curious about his progress toward his lifelong quest. Louis Levick, a New York journalist representing the National Association of Science Writers, managed to snag an interview. Einstein told him that with coauthors Peter Bergmann and Valentine Bargmann, he was close to a final theory. Levick's report was cited in a *Christian Science Monitor* piece, "Einstein nears discovery of new theory," on 14 March 1939.

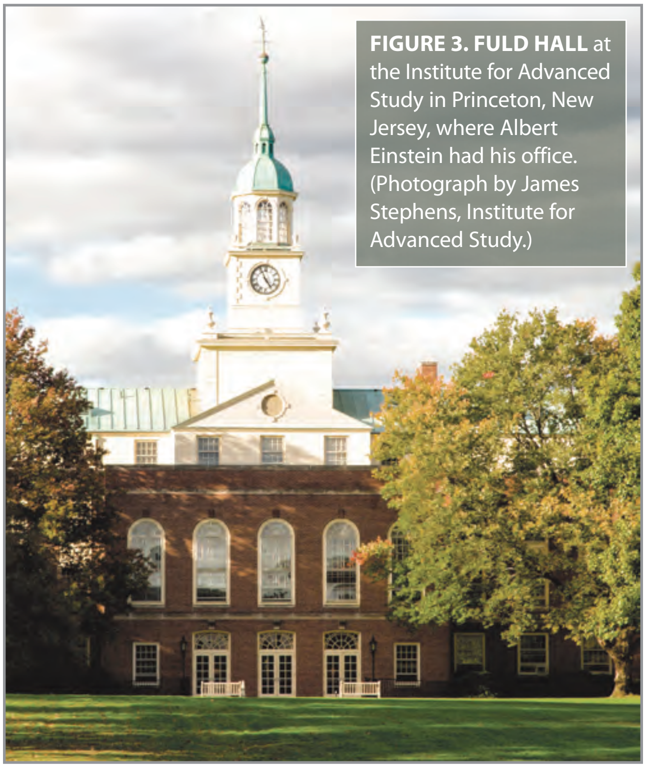


FIGURE 3. FULD HALL at the Institute for Advanced Study in Princeton, New Jersey, where Albert Einstein had his office. (Photograph by James Stephens, Institute for Advanced Study.)

Einstein's confidence did not last long. In 1945 he collaborated with Pauli, who was visiting the IAS, on a paper that suggested that five-dimensional theories lack singularity-free solutions. That conclusion quashed Einstein's passion for five-dimensional theories once and for all. It was back to the drawing board.

Two years later one of Einstein's friends and collaborators, Erwin Schrödinger, turned into a competitor. He was living at the time in Ireland, and he announced his own supposed unification breakthrough to the Royal Irish Academy. The international press trumpeted Schrödinger's theory; "Dublin man outdoes Einstein," the *Christian Science Monitor* announced on 31 January 1947.

When a journalist asked Einstein to respond, he issued this revealing statement about press sensationalism: "Such com-

FIGURE 4. **A 1934 HEADLINE** associated Einstein with efforts to harness atomic energy. (© Pittsburgh Post-Gazette; courtesy of the AIP Emilio Segrè Visual Archives.)


SECOND NEWS SECTION

For News, Subscriptions or Advertising Call ATlantic 6100.

SATURDAY MORNING, Pittsburgh Post-Gazette DECEMBER 29, 1934.

SPORTS, FINANCIAL, CLASSIFIED SECTION

This WORLD of OURS

FOR MEN ONLY

Constantly Expressive—Einstein Warms Up to His Subject

ATOM ENERGY HOPE IS SPIKED BY EINSTEIN

Efforts at Loosing Vast Force Is Called Fruitless.

SAVANT TALKS HERE

Now Indicates Doubt Of Relativity Theory He Made Famous.

muniqués given in sensational terms give the lay public misleading ideas about the character of research. The reader gets the impression that every five minutes there is a revolution in science, somewhat like the coup d'etat in some of the smaller unstable republics. In reality one has in theoretical science a process of development to which the best brains of successive generations add by untiring labor, and so slowly leads to a deeper conception of the laws of nature. Honest reporting should do justice to this character of scientific work."[9]

The theory of a lifetime

After World War II, Einstein's status as a superstar ascended even higher after the public learned that it was Einstein and Leo Szilard's letter to President Franklin Roosevelt in 1939 that had helped persuade the US government to initiate the Manhattan Project. He was widely credited with anticipating the massive power of atomic weapons with his mass–energy conversion formula. But that same association tarnished some of Einstein's saintly credentials. He had become, for better or worse, one of the scientists most associated with the start of the nuclear age (see figure 4).

One of the figures he became linked with in the public eye was J. Robert Oppenheimer, the scientific director of the Manhattan Project, who after the war became the third director of the IAS. Although Oppenheimer was far more practical than Einstein, he had a mystical side, too, such as his interest in Hindu scripture and his lone treks through the desert, qualities that, as historian of science David Hecht has demonstrated, similarly brought Oppenheimer considerable press attention as a "scientific icon."[10]

Oppenheimer, however, was known for solid, mainstream science and was lauded as an effective administrator. In contrast, Einstein's unified field theory work was abstruse, impractical, and disconnected from experimental results, which only bolstered his image as a mystical figure. The more esoteric and remote Einstein's mathematical meanderings grew and the more disconnected his results were from mainstream research, the more robust his popular image as a lone seeker of truth came to be.

Beginning in the late 1940s, as he approached the age of 70, Einstein worked on variations of another unified field theory approach, which he called a generalized theory of gravitation. It was a four-dimensional method, not a Kaluza–Klein method, and in some ways a variation of his earlier affine theory. In the January 1948 edition of *Reviews of Modern Physics*, Einstein published one version of his generalized theory, stating without fanfare that it "constitutes a certain progress in clarity as compared to the previous presentations."[11]

In March 1950 Princeton University Press (PUP) planned to release a third edition of *The Meaning of Relativity* to be timed loosely with Einstein's 71st birthday. Einstein was contractually obliged to update his work for each edition. For the third one he agreed to submit a new appendix that would inform readers about the generalized theory of gravitation. The director of PUP, Datus Smith Jr, and its editor, Herbert Bailey Jr, were counting on that appendix, an account of Einstein's latest unification efforts, to boost interest in the work, and hopefully sales as well.

Unknown at first to Smith and Bailey, Einstein had independently made arrangements with *Scientific American* to write an article about the generalized theory of gravitation. In December 1949 Smith and others learned about those plans, which had the potential of deflecting interest from the book to the article.[12] PUP felt compelled to act quickly to protect its association with Einstein's new theory.

The American Association for the Advancement of Science's (AAAS's) Annual Science Exposition, held that year in December at the Hotel Statler in New York, offered the perfect opportunity for PUP to make its own announcement. PUP had reserved a table in the science publishers' section so it could display copies of some of the books in its catalog, including the second edition of *The Meaning of Relativity*. To stake their claim, the editors issued a brief press release announcing that Einstein's final theory would be published in the upcoming third edition. They also displayed a duplicate of Einstein's typewritten manuscript for the new appendix. The press release offered the bold—but wholly unsupported—claim that "this epoch-making paper ranks with the original publication of the Theory of Relativity as a milestone of scientific achievement."[13]

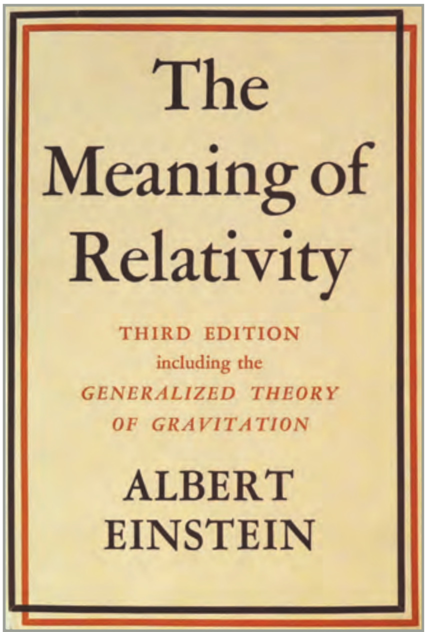


FIGURE 5. THE COVER OF THE THIRD EDITION of *The Meaning of Relativity*. (Photograph by Leo Boudreau.)

Normally, journalists walk by such publishers' tables without taking notice. But since it was Einstein, the international press immediately jumped on the announcements. Reporters were hungry for details. A piece in the *Irish Times* on 2 January 1950 declared that Einstein's new theory was so esoteric that only Schrödinger and a few other brilliant physicists would be able to understand it: "Unfortunately, Dr. Einstein is in a field by himself, and only a handful of men in other parts of the world can succeed even in scrambling through the hedges with which it is surrounded. . . . Ireland is fortunate in as far as one of her citizens, Dr. Schroedinger, belongs to the select band of human beings who may be able to understand and, what is more, to explain some aspects of the new theory."

One noted science writer who happened to be at the AAAS meeting was Lincoln Barnett, author of *The Universe and Dr. Einstein* (1948), a favorable biography of the famed physicist. He took note of the announcement of Einstein's new manuscript and wrote an article for *Life* magazine about the reaction at the AAAS meeting to the announcement of his new theory.[14] To the consternation of the PUP editors, the *Life* piece didn't mention the new edition—for which Barnett ended up apologizing to them.

In early January Einstein decided to revise some of the details of his generalized theory for the appendix. He sent PUP an amended copy of his manuscript, which delayed the production process. A few weeks later, he noticed some typographical errors in the equations and notified PUP. By then it was too late to stop the presses; PUP was forced to print an extra errata page and include it with every copy of the third edition (see figure 5). Ironically, the much-hyped "ultimate" equations turned out to be a moving goalpost, subject to revision after revision.

A *New York Times* article, "Einstein publishes his 'master theory,'" appeared on 15 February 1950. "His latest intellectual synthesis," reporter William Laurence claimed, "may reveal to man vast forces beyond imaginings still hidden from him." As with previous coverage, there was significant hype and little discussion of Einstein's repeated setbacks in his quest for a unified theory.

Finally, Einstein's long-awaited contribution to *Scientific American*, "On the generalized theory of gravitation," appeared in its April 1950 issue. Despite the buildup, only about one-third of the article attempted to explain the rudiments of the new theory. The rest of it was a condensed scientific history of assorted topics such as atomism, optics, Maxwell's theory of electromagnetism, and relativity itself. With a measure of irony, Einstein explained in the article, "As for my latest theoretical work, I do not feel justified in giving a detailed account of it before a wide group of readers interested in science. That should be done only with theories which have been adequately confirmed by experiment."

A cautionary tale

Einstein died on 18 April 1955, with his quest for unification never completed. Nonetheless, the write-up of his final unification attempt was included in the fifth edition of *The Meaning of Relativity*, published posthumously in 1956 and reissued many times since then. There was relatively little mainstream press coverage of Einstein's final theoretical endeavors. However, a *New York Times* article published on 2 May 1955 noted that one of the pages of his notes and calculations was missing and sought by his estate. The piece claimed that the missing notes included an equation of unknown significance.

Einstein's relationship with the press was complex, to say the least. Newspaper accounts brought Einstein fame and allowed him to travel the world, give talks, and promote his causes. Nevertheless, as a lover of privacy, he came to resent the many intrusions of reporters. Even so, he did not cloister himself or refuse to say anything about his work; he enjoyed sharing his ideas with a broad audience, including his perspectives on science, philosophy, religion, politics, and other matters. Einstein himself was generally careful not to overstate the extent of his own progress toward a unified field theory. However, he often placed his work within the context of the history of such attempts, which gave reporters the opportunity to deem his contributions historic breakthroughs, or at least on the verge of being so.

Historians cannot fault Einstein, however, for journalists' propensity to hype his later work while largely ignoring the actual major developments in theoretical physics of the 1930s and 1940s, such as the tremendous progress in quantum electrodynamics and particle theory. Readers, they supposed, wanted to learn about the doings of a familiar genius, not necessarily about the true state of the field in which he made his mark.

Moreover, as Joseph Martin has recently detailed, there has been a marked asymmetry between press coverage of scientific topics perceived as cutting edge, such as high-energy physics and cosmology, and those seen as mundane. One key reason for the gap is that familiarity with earthly, tangible materials makes their inner workings—extraordinary as they may be, such as in the case of certain quantum phenomena—seem less exotic and therefore a reminder of the limitations of this world.[15] Einstein's far-reaching but unproven work thereby drew more attention than more mundane achievements that were grounded in solid laboratory results.

The press's focus on Einstein's solitary work during his later years has had several lingering consequences. Before Einstein, most coverage of science and technology in the mainstream press was limited to the inventions of figures like Michael Faraday, Nikola Tesla, and Thomas Edison, and, starting in the early 20th century, Nobel Prize recipients. Einstein's fame has led to more coverage in general of theoretical physics, albeit with a slant toward fields such as particle physics and cosmology.

On the other hand, Einstein's treatment in the press has led to continued distortion of the way theoretical physics is usually performed and progresses. Journalists have tended to tell stories of single individuals making rapid breakthroughs, rather than ones about incremental efforts involving a number of researchers working either collaboratively or competitively. For example, in the case of black hole thermodynamics, the press extolled Stephen Hawking's work and focused on his achievements throughout his life while largely ignoring the important contributions of Jacob Bekenstein.

Press coverage of Einstein is a cautionary tale of the need for journalists to check their facts, even in the case of the work of brilliant scientists. Readers need guidance in distinguishing experimental verification, or at least testable hypotheses, from hype. While we can thank Einstein for a huge bump in the amount of coverage of theoretical physics in the press, the perception of him as a font of ever-flowing insights prevented a rigorous discussion of his later work. Einstein's fame made the search for a unified theory enthralling—ultimately too dazzling, as time went on, for reporters to step back and critically examine his results.

Thanks to Melinda Baldwin and Alberto Martinez for helpful suggestions and to the Princeton University Library and Archives. This article is adapted from "Celebrity physicist: How the press sensationalized Einstein's search for a unified field theory," Physics in Perspective, *volume 20, page 254, 2018.*

REFERENCES

1. M. Missner, *Soc. Stud. Sci.* **15**, 267 (1985).
2. J. Illy, ed., *Albert Meets America: How Journalists Treated Genius during Einstein's 1921 Travels*, Johns Hopkins U. Press (2006).
3. C. D. Bennet, "Science Service and the origins of science journalism, 1919–1950," PhD dissertation, Iowa State U. (2013).
4. J. van Dongen, *Einstein's Unification*, Cambridge U. Press (2010).
5. A. Einstein, quoted in News and Views, *Nature* **123**, 174 (1929), p. 175.
6. H. H. Sheldon, quoted in "Einstein reduces all physics to 1 law," *New York Times*, 25 January 1929, p. 5.
7. W. Pauli to A. Einstein (19 December 1929), trans. in T. Sauer, *Hist. Math.* **33**, 399 (2006), p. 428.
8. W. Pauli to P. Jordan (30 November 1929), trans. in H. F. M. Goenner, *Living Rev. Relativ.* **7**, 2 (2004), p. 88.
9. A. Einstein, "Statement to the Press" (February 1947), box 28, folder 22-146, Albert Einstein Duplicate Archive, Princeton U. Library.
10. D. K. Hecht, *Technol. Cult.* **49**, 943 (2008).
11. A. Einstein, *Rev. Mod. Phys.* **20**, 35 (1948).
12. D. Smith to L. Barnett (23 January 1950), box 7, Princeton University Press Records, Princeton U. Library.
13. Princeton University Press, press release (26 December 1949), box 7, Princeton University Press Records, Princeton U. Library.
14. L. Barnett, *Life*, 9 January 1950, p. 22.
15. J. D. Martin, *Sci. Context* **30**, 475 (2017).

PT

Igor Ferrier-Barbut is a researcher at the Institut d'Optique and CNRS in Palaiseau, France.

Ultradilute Quantum Droplets

A new class of quantum mechanical liquids is stabilized by an elegant mechanism that allows them to exist despite being orders of magnitude thinner than air.

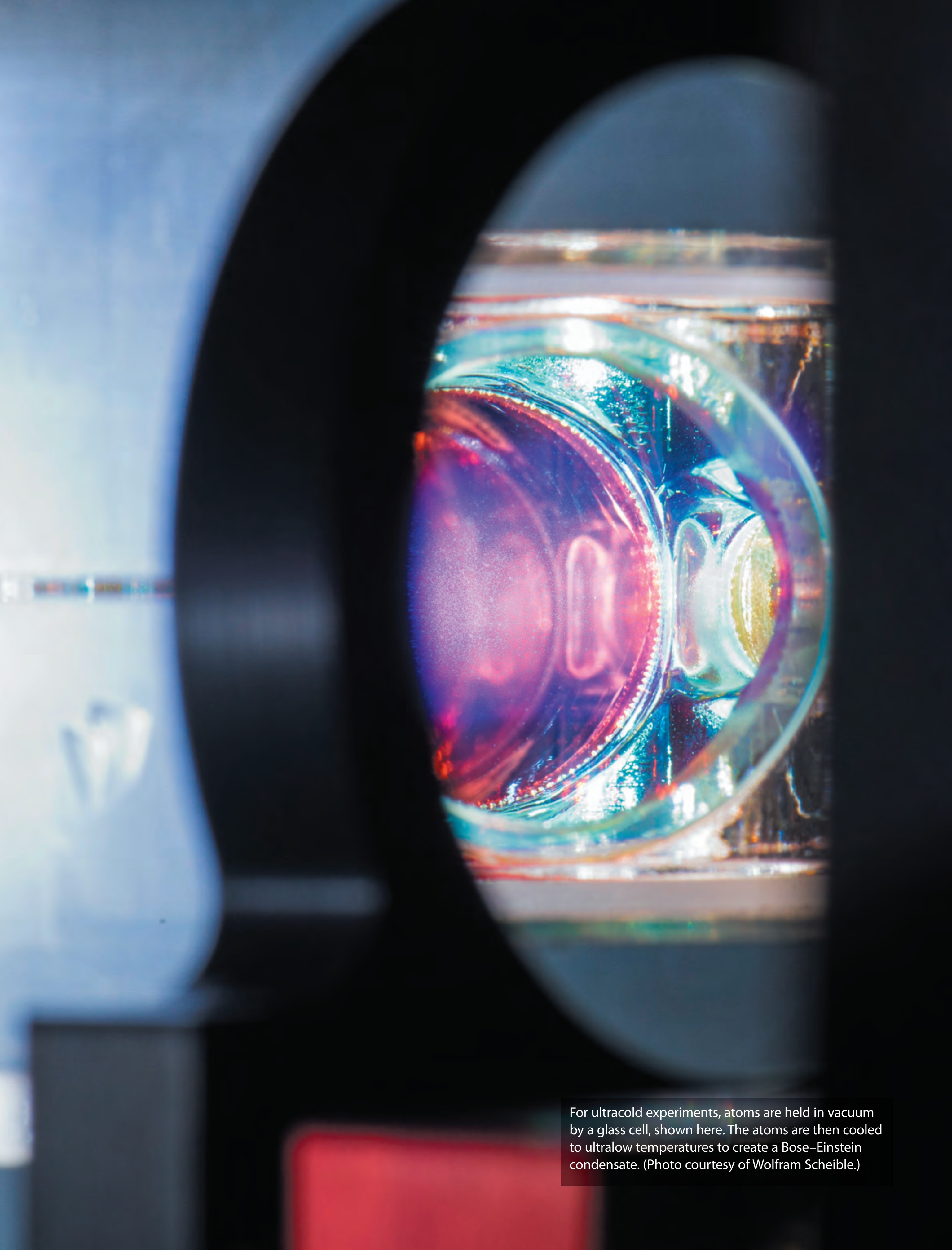
Igor Ferrier-Barbut

In his PhD thesis from 1873, Johannes van der Waals devised a theoretical framework to describe the gas and liquid phases of a molecular ensemble and the phase transition from one to the other. That work resulted in the celebrated equation of state bearing his name. To this day, the van der Waals theory is still the prevailing picture in most physicists' minds to explain the emergence of the liquid state. It asserts that the liquid state arises at high densities from an equilibrium between attractive interatomic forces and short-range repulsion. Now, a new type of liquid has emerged in ultracold, extremely dilute atomic systems for which the van der Waals model does not predict a liquid phase.

Using the tools of laser cooling and trapping, experimenters can reach the ultracold regime to create atomic quantum gases.[1] Quantum interference effects between atoms are an important part of the statistical descriptions of those systems. However, if a monatomic ensemble is simply cooled, any chemical species will form a liquid instead of a gas due to van der Waals forces and the system will never reach the quantum regime. So to see quantum effects, the classical liquid state must be avoided. That requires extremely low densities that keep the distances between atoms much larger than the range of attractive forces that would bind the liquid. But keeping the atoms far apart traps them in a dilute, metastable state. A whole new mechanism is needed for atoms in such dilute conditions to form a liquid phase.

Mean-field quantum gases

Atoms in the quantum regime must be described as waves rather than classical point-like objects. They come in two flavors, bosons and fermions. That characterization dictates particles' collective behavior: Bosons interfere constructively, whereas fermions do so destructively. In the materials used to make ultradilute liquids, constructive bosonic interference leads to the accumulation at very low temperature of all the atoms into the same quantum state with zero momentum. That collective



For ultracold experiments, atoms are held in vacuum by a glass cell, shown here. The atoms are then cooled to ultralow temperatures to create a Bose–Einstein condensate. (Photo courtesy of Wolfram Scheible.)

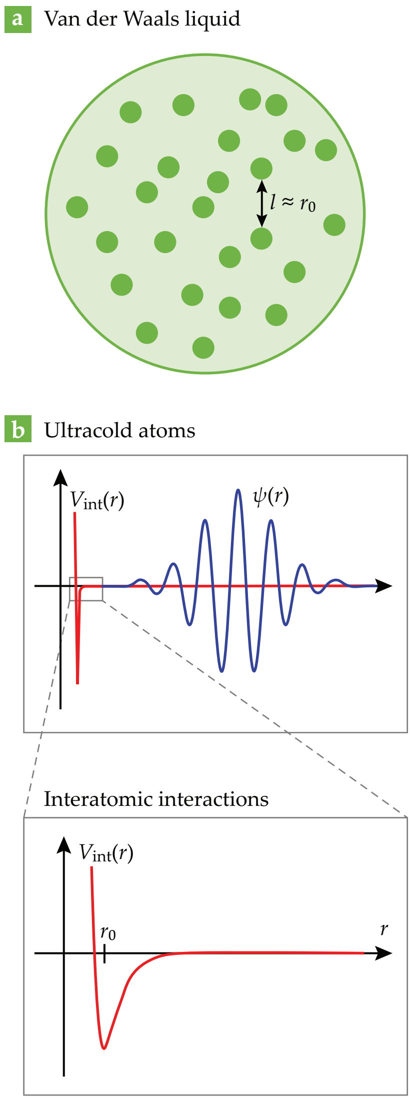


FIGURE 1. (a) IN A VAN DER WAALS LIQUID, the nearest-neighbor interatomic distance l is on the order of the typical distance r_0 over which the interaction potential varies. **(b)** In the ultracold regime, two interacting atoms are described as matter waves $\psi(r)$. Their wavelengths are too large to resolve the details of the effective interaction potential $V_{\text{int}}(r)$ that only extends a radial distance r_0 from the atom. The effective interaction therefore has zero range, and van der Waals liquids cannot be found in ultracold conditions.

state is known as a Bose–Einstein condensate (BEC) and is now routinely produced experimentally (see, for example, the article by Keith Burnett, Mark Edwards, and Charles Clark, PHYSICS TODAY, December 1999, page 37).

Bose–Einstein condensation is a pure quantum interference effect that requires no interaction between atoms. Interatomic forces do still affect that state, but rather than the familiar attractive potential with repulsive core, interactions take a much simpler form in ultracold and ultradilute conditions. Forming a BEC requires the interparticle distance l to be much larger than the typical interaction range r_0 to prevent the material from forming a classical liquid. Additionally, the thermal de Broglie wavelength λ_{dB}, which describes the typical atomic wavelength, needs to be larger than l. Together those conditions require that λ_{dB} be much larger than r_0. In other words, the atomic waves cannot resolve the details of the interaction potential (see figure 1). As a result, the particles behave as if they were interacting through a zero-range contact potential that can be written as $V(r) = g\,\delta(r)$, where $\delta(r)$ is the Dirac delta function, g is a coupling constant, and r is the interatomic separation distance.

Despite the conceptual simplicity of the interaction, calculating the ground state of N bosons interacting through a contact potential is difficult and requires approximations. First is the mean-field approximation, which assumes that atoms all still occupy only one state, as they would in the absence of interactions; the interactions only modify the state with respect to the single-particle case. The ground-state energy E of an ensemble with uniform density n in a volume V is then simply $E/V = 1/2\,gn^2$. That equation says that the BEC can exist only in the gas phase: If g is positive, meaning that the particles are repulsive, then the energy of the system is lowest when n is minimized—in practice, that means the system always expands, which is why external trapping potentials are needed to confine BECs. On the other hand, if g is negative and the particles are attractive, the energy is minimized when n is maximized, so the ensemble collapses on itself. Both situations have been observed experimentally, but neither forms a liquid.

A game-changing correction

As usual, corrections to a quantum ensemble's energy go beyond the mean-field approximation. The first of those corrections was calculated in the 1950s. At the time, the goal was to develop a theoretical description of superfluid helium. (For more information on superfluid helium droplets, see the article by Peter Toennies, Andrej Vilesov, and Birgitta Whaley, PHYSICS TODAY, February 2001, page 31.) The He–He interaction potential is far too complex to analytically solve in the many-body limit, so a zero-range potential was used as an academic exercise. The first exact calculation of the next leading-order term in the energy came from Tsung-Dao Lee, Kerson Huang, and Cheng-Ning Yang in 1957 and is thus termed the LHY correction.[2] At that level of approximation, the ground state is composed of a large fraction of atoms still in the zero-momentum condensed state and also of a small noncondensed fraction, known as the quantum depletion, in higher momentum states. The interpretation of the LHY correction is that it accounts for the fact that the collective modes of the BEC are not fully at rest, even in the ground state, but undergo zero-point fluctuations as dictated by Heisenberg's uncertainty principle.

Accounting for the zero-point energy in the ground state leads to a modified energy, $E/V = 1/2\,gn^2 + \alpha_{\text{LHY}}(gn)^{5/2}$, where α_{LHY} depends only on the atomic mass and Planck's constant. The new expression recovers the mean-field term from before, along with an extra term from accounting for the quantum mechanical nature of the fluid. The correction becomes more important at higher densities,[3] as shown in figure 2a. The beyond-mean-field theory at the LHY level is in excellent agreement with experiments that have observed the quantum depletion and measured the LHY energy correction.[4,5] However, since the correction depends only on g and is repulsive, just like the mean-field term, the energy minimization works the same way and the atomic ensemble remains a gas.

The crucial ingredient for qualitatively altering the nature of the BEC was first laid out in 2015 in an imaginative theoretical proposal by Dmitry Petrov at CNRS in Orsay, France, and was incidentally experimentally observed shortly afterward by a group headed by Tilman Pfau at the University of Stuttgart in Germany.[6,7] The two papers used different systems but with the same idealized situation: Imagine a bosonic system described by two separate interactions rather than one, with coupling constants g and g'. The energy is just the sum of the two contributions, so if the interactions both have the same sign, no qualitative change in behavior occurs.

An interesting situation arises when the two interactions are competing, meaning one is attractive (negative) and the other repulsive (positive). The mean-field energy becomes $E/V = 1/2\,\delta g n^2$ where $\delta g = g - g'$. Assuming g and g' are of the same order of magnitude, the mean-field energy is reduced but the qualitative behavior of the system does not change. Because of that reduction, however, the beyond-mean-field corrections are not necessarily negligible. The total energy is now given by $E_{tot}/V = 1/2\,\delta g n^2 + \alpha'_{LHY}(gn)^{5/2}$, where α'_{LHY} depends on the ratio g'/g. As long as g and g' are individually not small, the LHY correction remains relatively large even as the mean-field term shrinks. The presence of two interactions can create collective high-energy excitations that have a large zero-point energy, which allows the LHY correction to be largely repulsive even as the mean-field term remains attractive.

Importantly, the first term in the expression for E_{tot}/V depends on δg, whereas the second depends on g and g'/g. When g and g' are of the same order and $g' > g$, the mean-field term is attractive ($\delta g < 0$) and the LHY correction is repulsive (g, $\alpha'_{LHY} > 0$). The resulting energy, shown in figure 2b, reaches a minimum at a finite density by balancing the weakened mean-field attraction at low n and the beyond-mean-field repulsion at high n. That competition enables the formation of a self-bound liquid.

A liquid and a gas differ essentially by their density.[8] In this article, we define a gas by its expansion to fill the whole available volume; a liquid does not fill the whole volume, but instead forms a self-bound droplet with a fixed density. The peak density of a droplet in infinite volume can be thought of as the order parameter for the liquid–gas phase transition. It takes a nonzero value in the liquid phase but vanishes for a gas.

Making an ultradilute droplet

The question is, what experimental system is ruled by two different interactions? In general, only one type of contact interaction results from the details of the short-range forces. Petrov's proposal to overcome that was to mix two types of bosons in which like atoms repel each other with one coupling constant, g_l, and unlike atoms attract each other with a coupling constant g_u. Using two different species allows the system to be effectively described by two different interactions, both coming from short-range forces.

Petrov showed that when the previously described conditions for g and g' (here g_l and g_u) were met, the mixture would form a liquid. Remarkably, the liquid would still be extremely dilute, so the interatomic distance l remains much larger than the interaction range r_0. Another consequence of the low density is that the quantum depletion remains weak, so the LHY-level approximation remains valid. The existence of such a liquid is not explained by a van der Waals–like mechanism but instead stems from a many-body effect that is a consequence of the quantum mechanical nature of the bosonic ensemble. Petrov's proposal identified several concrete atomic mixtures in which such intraspecies repulsion and interspecies attraction could be found, which suggested that a liquid BEC could be realized in contemporary experiments.

Instead of two species, the Stuttgart experiments were performed on a single species of atoms with two different interactions. The experiments used dysprosium atoms, which have a large magnetic moment. As a result, they are subject not only to a repulsive contact interaction but also to an anisotropic dipole–dipole interaction. The dipole interaction is longer-ranged than the contact interaction[9] and characterized by a coupling constant g_d that, in the experiments, was slightly larger than the contact coupling g. When the atoms are mostly distributed head-to-tail, the attractive dipole interaction leads to the same competition between attractive and repulsive interactions as in the two-species system.

The mean-field energy at the center of a droplet again reads $E/V \approx 1/2\,\delta g n^2$, although the equality is no longer exact because the effective dipolar interaction is slightly altered when the dipoles are not exactly head-to-tail, and it predicts collapse because $\delta g < 0$. However, in experiments the bosonic system formed stable, long-lived droplets—as before, once beyond-mean-field effects are accounted for, the ensemble forms a liquid.[10,11] Following the observation of liquid droplets with dysprosium,

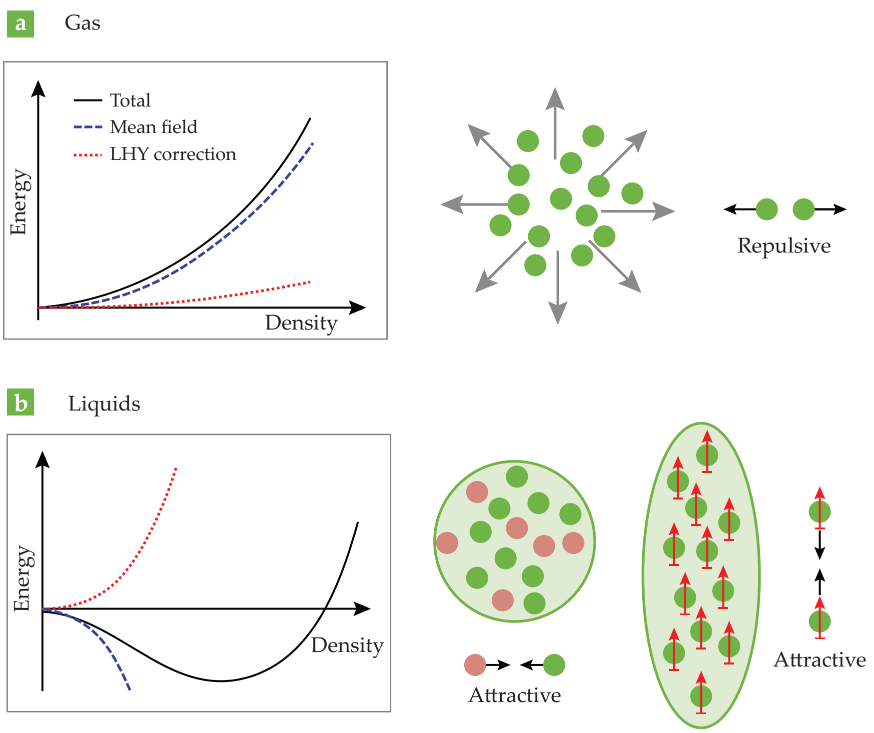


FIGURE 2. (a) A TYPICAL SINGLE-SPECIES BOSE–EINSTEIN CONDENSATE has repulsive short-range interactions. The sum of the mean-field energy and the Lee-Huang-Yang (LHY) correction is positive and therefore repulsive, so the atoms are not bound and form a gas. **(b)** Bose–Einstein condensates of atomic mixtures or magnetic atoms can have both attractive and repulsive interactions. When the mean-field energy and the LHY correction have opposite signs, the total energy can develop a minimum at finite density, which causes the atoms to form self-bound liquid droplets.

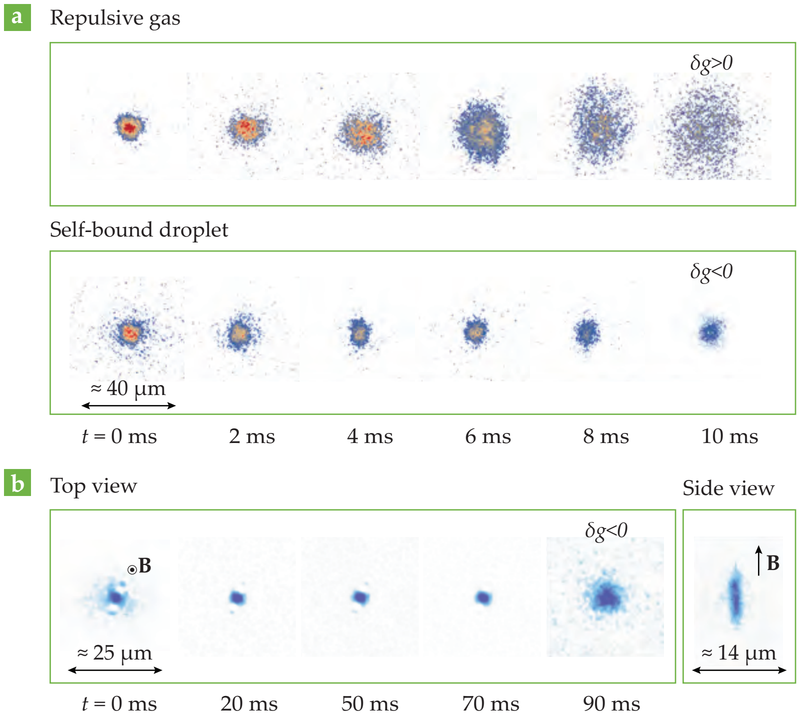


FIGURE 3. SELF-BOUND DROPLETS in the absence of an external trapping potential can be imaged experimentally. The densities of two such systems are shown here. **(a)** When the mean-field energy of a Bose–Bose mixture is repulsive (top row), it results in a gas phase, and the droplet expands over time. When the mean-field energy is attractive (bottom row), the size of the self-bound droplet remains constant over time, although its density, shown in false color, decays due to three-body losses. (Adapted from ref. 13.) **(b)** A droplet of dipolar magnetic atoms stays confined until the atom number decays below the critical atom number, at which point it starts expanding as a gas. The side view of the droplet clearly shows its elongation along the magnetic field **B**. (Adapted from ref. 14.)

experiments at the University of Innsbruck, Austria, under the direction of Francesca Ferlaino showed the same stabilization with erbium atoms,[12] which, like dysprosium, have a large magnetic moment. The experiments confirmed that the stabilization mechanism is general to atoms that possess competing short-range repulsion and longer-range dipole interactions.

Many experimental groups can produce bosonic atomic mixtures with a variety of elements and isotopes. The mixture that won the race for the first observation of a two-component liquid phase was a blend of two internal states of the same isotope of potassium. By creating the proper mixture of internal states in the right magnetic field, two teams, one led by Leticia Tarruell at the Institute of Photonic Sciences in Barcelona, Spain, and the other by Marco Fattori at the University of Florence, Italy, both observed the ultradilute quantum liquid phase.[13] They confirmed their findings by removing all external trapping potentials, thus placing the BEC in an infinite volume. If the condensate were still a quantum gas, it would have expanded until the density was too thin to be measurable. Instead, the researchers saw self-bound droplets that did not expand in free space and could easily be observed for long times.[13]

The experimental results shown in figure 3 for Bose mixtures and magnetic atoms[14] are visual proof of the gas–liquid phase transition. The theoretical prediction and later observation of quantum liquids marked a paradigm shift because they showed that the LHY correction, which was thought to be a small quantitative shift due to weak quantum fluctuations in a many-body system, can stabilize a liquid phase. That phase would be impossible under mean-field conditions. The diluteness of those liquids is remarkable, with typical densities being about four orders of magnitude lower than air and about eight orders of magnitude lower than liquid helium at room pressure.

Oscillating and disappearing droplets

Ultradilute liquids also exhibit another feature rooted in their quantum mechanical nature. Their simplified energy description captures the liquid and gas phases, but it completely ignores finite-size and surface effects by assuming a uniform density n. In any real liquid droplet, the density is not uniform; it increases from zero at the droplet's edge to a peak value at its center. For matter waves such as BECs, such density gradients cost kinetic energy, as dictated by the Schrödinger equation. In droplets of dilute quantum liquids, kinetic energy acts as a surface tension, contributing an additional energy that depends on the density gradient at the surface. The consequence can be dramatic, because if the surface tension shifts the total energy from negative to positive, then the self-bound solution no longer exists and the ground state is a gas. Quantum liquids thus have another very peculiar feature: Kinetic energy, accounting for single-particle quantum fluctuations, can drive a liquid-to-gas transition.

Another way to think about the effective surface tension is that the density distribution created by all the atoms in a droplet acts as a trapping potential on each individual atom because of the effectively attractive interaction. If the trapping potential is strong enough to hold a bound state, then it supports a self-bound liquid solution. If not, then the ensemble forms a gas. A third possibility is that the liquid exists in a metastable state, but for low enough atom number, the trapping becomes too shallow and only the gas exists. The depth of the effective potential is determined by the number of atoms, N, and the difference between the two interaction strengths, δg. For larger values of N and more negative δg, the trapping volume is larger and the attraction is stronger, so the effective potential becomes more binding. A liquid–gas phase diagram can therefore be drawn as a function of system size and interaction strength,[6,15] as shown in figure 4. The critical atom number N_c that marks the gas–liquid transition varies as $|\delta g/g|^{-2/5}$, so the minimal atom number to sustain a self-bound droplet grows dramatically as δg approaches zero.

The structure of the phase diagram has been confirmed experimentally[13,14] using a mechanism that experimenters usually try to avoid: three-body losses. The number of atoms in a liquid drop decreases as a result of collisions that recombine two atoms into one molecule. To respect conservation of energy and momentum, such a recombination can only happen if three atoms are involved in the collision, so the loss rate grows strongly with density. When a liquid droplet is created, losses

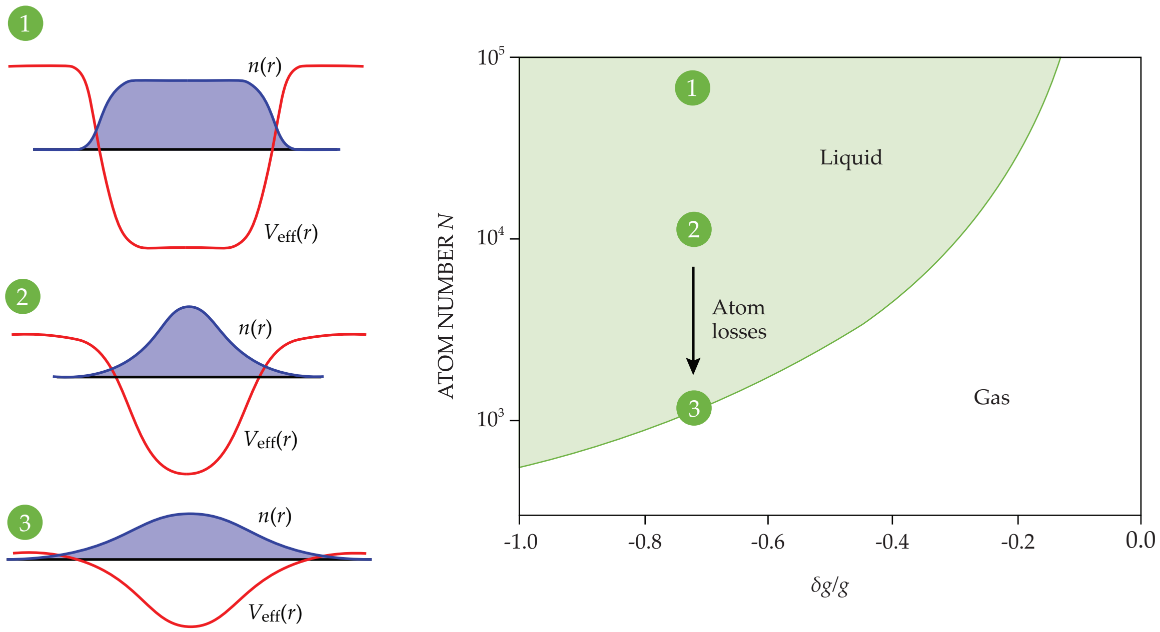


FIGURE 4. THE PHASE DIAGRAM FOR AN ULTRADILUTE DROPLET depends on the atom number N, the contact coupling g, and the difference between the mean-field and beyond-mean-field coupling constants δg. At high N (point 1 in the phase diagram), the density $n(r)$ of a droplet has a flat-top profile, which creates a deep self-binding potential $V_{\mathrm{eff}}(r)$ and a liquid droplet. Experiments obtain lower N (point 2), and the density does not reach the flat top, but the self-trapping remains relatively deep. Atom losses deplete the droplet over time until the self-bound state barely exists (point 3). When N decreases further, the droplet crosses the phase boundary and becomes a gas.

typically limit its lifetime to between a few and tens of milliseconds. During that time, the atom number decays until it reaches the liquid–gas phase transition. At that point the self-bound liquid turns into a gas, the atoms expand in space, and the density immediately drops, as in the final frame of figure 3b (90 ms).

Once the liquid transitions to a gas, the three-body losses stop, and the number of atoms stays constant. Experimenters can therefore readily identify the critical atom number N_c for the liquid–gas transition at a given δg. They can also adjust the attraction strength using so-called Feshbach resonances, which vary the coupling constant g for contact interactions by means of a magnetic field. By varying the coupling constant and measuring the critical atom number, researchers mapped the phase diagram for the different experimental quantum liquids.

Although the two-component and dipolar liquids share the same stabilization mechanism, each also has its own characteristics. Quantum liquids of dipolar atoms are anisotropic: For the dipolar interaction to be attractive, the atoms need to be aligned. As a result, droplets are elongated along the dipole direction, as can be seen experimentally in figure 3. The shape of the dipolar droplets results from a competition between dipolar interactions trying to align the atoms and a surface tension that favors a round droplet. In atomic mixtures, the density ratio between the two species is locked to a value fixed by the precise short-range interactions. However, one species can end up in overabundance, which causes a gas halo of untrapped majority atoms to form around the droplet.

The elongation of dipolar droplets and the fixed density ratio for mixtures lead to specific, collective oscillation modes, illustrated in figure 5. Dipolar quantum droplets feature a scissor-like oscillation that corresponds to an angular oscillation of the droplet around the dipole's axis.[16] Quantum mixture droplets, on the other hand, exhibit excitations in which the two components move either in or out of phase relative to each other. Accurately mapping their spectrum of collective excitations should yield precious information about their precise equation of state beyond the current description.

The future of ultradilute liquids

The discovery of physically realizable ultradilute liquids highlights the strengths of ultracold atom experiments. Using exquisite control of the constituents of a many-body system and the interactions that characterize it, such experimental setups can expose the key mechanism that underpins the many-body state. The family of ultradilute quantum liquids will likely continue to grow because the same stabilization mechanism can be found in other systems.[17] Theoretical proposals have already been laid out for mixtures of other constituents, such as bosons and fermions.

Exploring the possibility of making such liquids in lower dimensions is also of great interest because quantum fluctuations are enhanced, so any attractive potential allows for a self-bound liquid solution. Additionally, quantum droplets are localized matter waves in three dimensions, so they bear similarities to matter-wave solitons, which can be fully accounted for within mean-field theory and have been observed solely in lower dimensions. In strongly confined systems, competition between solitons and quantum droplets can lead to a crossover or abrupt transition between the two states.[18] Localized matter waves could also be useful for performing interferometry, and the prospect of using quantum droplets experimentally to avoid trapping potentials remains to be investigated. (For an experimental example of matter-wave interferometry, see PHYSICS TODAY, April 2015, page 12.)

The exploration of the properties of ultradilute quantum liquids is in its infancy. The quantum depletion and LHY correction are, in theory, accompanied by quantum entanglement, and observing the presence of entanglement in the liquid phase

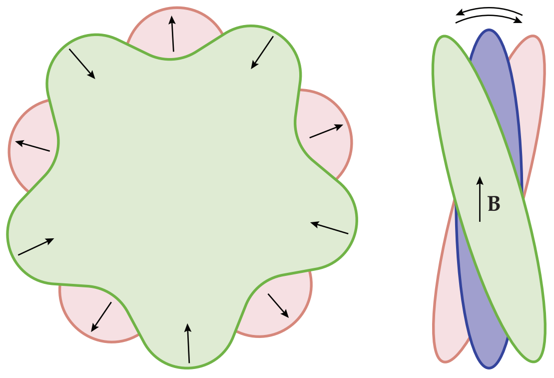


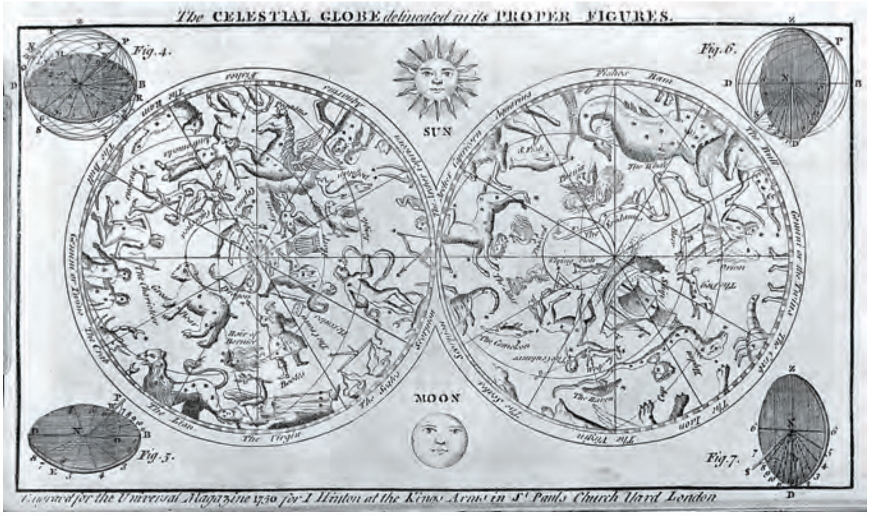
FIGURE 5. ISODENSITY CUTS OF QUANTUM DROPLETS at different times show their collective oscillation modes. Ripplons are typical for normal liquid droplets. They arise from surface tension, which creates a restoring force when the droplet is deformed, and are expected to exist in mixture droplets.[6] The scissors mode is a signature of the breaking of rotational invariance in dipolar droplets. It consists of an angular oscillation of the elongated droplet around the direction of the magnetic field **B** and has been observed in dysprosium droplets.[16]

would be remarkable. The thermodynamics of such systems is also unknown—it is not yet clear whether or how thermal equilibrium is reached within a droplet.

While the theoretical descriptions of ultradilute liquids have progressed and approximations that include the LHY correction allow for an analytical expression for their energy, many-body theories still lack a precise description of such liquids. However, in some existing experimental systems the usually dominant mean-field energy is masked, so beyond-mean-field effects that include interactions can be effectively magnified and measured. Corrections beyond the LHY description of the bosonic ensemble remain unobserved, but ultradilute quantum liquids finally provide a new testing ground for theories of quantum many-body interactions.

REFERENCES

1. I. Bloch, J. Dalibard, W. Zwerger, *Rev. Mod. Phys.* **80**, 885 (2008).
2. T. D. Lee, K. Huang, C. N. Yang, *Phys. Rev.* **106**, 1135 (1957).
3. A. J. Leggett, *New J. Phys.* **5**, 103 (2003).
4. R. Chang et al., *Phys. Rev. Lett.* **117**, 235303 (2016); R. Lopes et al., *Phys. Rev. Lett.* **119**, 190404 (2017).
5. N. Navon et al., *Phys. Rev. Lett.* **107**, 135301 (2011).
6. D. S. Petrov, *Phys. Rev. Lett.* **115**, 155302 (2015).
7. H. Kadau et al., *Nature* **530**, 194 (2016).
8. J. Barker, D. Henderson, *Rev. Mod. Phys.* **48**, 587 (1976).
9. T. Lahaye et al., *Rep. Prog. Phys.* **72**, 126401 (2009).
10. A. R. P. Lima, A. Pelster, *Phys. Rev. A* **84**, 041604 (2011).
11. I. Ferrier-Barbut et al., *Phys. Rev. Lett.* **116**, 215301 (2016).
12. L. Chomaz et al., *Phys. Rev. X* **6**, 041039 (2016).
13. C. R. Cabrera et al., *Science* **359**, 301 (2018); G. Semeghini et al., *Phys. Rev. Lett.* **120**, 235301 (2018).
14. M. Schmitt et al., *Nature* **539**, 259 (2016).
15. F. Wächtler, L. Santos, *Phys. Rev. A* **94**, 043618 (2016); D. Baillie et al., *Phys. Rev. A* **94**, 021602 (2016).
16. I. Ferrier-Barbut et al., *Phys. Rev. Lett.* **120**, 160402 (2018).
17. D. S. Petrov, G. E. Astrakharchik, *Phys. Rev. Lett.* **117**, 100401 (2016); D. Edler et al., *Phys. Rev. Lett.* **119**, 050403 (2017); D. Rakshit et al., https://arxiv.org/abs/1801.00346.
18. P. Cheiney et al., *Phys. Rev. Lett.* **120**, 135301 (2018). PT



Connecting the micro- and macroverses

Enjoy Our Universe
You Have No Other Choice

Alvaro De Rújula
Oxford U. Press, 2018.
$25.95

Our understanding of the universe is in the midst of a revolution that rivals the one brought on 100 years ago by the birth of quantum mechanics and the discovery of the expansion of the universe. The standard model of particle physics provides a well-tested mathematical description of the basic forces and particles of nature and a springboard for speculation about a grander unification of all forces, and the lambda-cold dark matter (ΛCDM) cosmology describes the universe from quantum fluctuations and quark soup to the formation of galaxies and today's accelerated expansion.

Profound puzzles lie at the frontiers of inner and outer space and link them: the identity of the mysterious dark matter that binds galaxies and clusters, the nature of the dark energy whose repulsive gravity drives accelerated expansion, and the cause of the putative early inflationary epoch whose quantum fluctuations became the seeds for cosmic structure. Few books have attempted to tell the full story of the microverse and macroverse and their deep, unexpected connections. Alvaro De Rújula's *Enjoy Our Universe: You Have No Other Choice* has done so with success.

De Rújula is a brilliant and opinionated Spanish particle theorist who spent most of his career at CERN. There he participated in the current revolution of our understanding of the universe. He is also known for his dazzling illustrations drawn on transparencies. Fifty or so are reproduced in the book in full color, capturing the reader's attention and getting the author's points across. His unique voice comes through loud and clear in the text, just as Stephen Hawking's does in *A Brief History of Time: From the Big Bang to Black Holes* (1988).

De Rújula tells us that his book is "intended for anyone—independently of the education (s)he has suffered—who is interested in our basic current scientific understanding of the Universe." You won't find the multiverse or superstring theory here; he sticks to what we really know—which is already amazing enough—and eschews speculation.

The book is organized into 37 bite-sized chapters, each in essence a mini-lecture. (Oops, I have revealed the big secret, De Rújula is teaching the reader a lot of physics.) Some of the chapters are as short as one page—for example, chapter 8, which sums up the standard model. Others cover more technical detail or asides to the main narrative, such as chapter 15, "Is Basic Science Useful?"

The author also has a star system for flagging the more challenging material; like the Michelin guide, he awards each chapter from one to three stars. Brace yourself: Chapter 13, on renormalizable relativistic quantum field theories, rates only two stars. In the same spirit, *Enjoy Our Universe* features 104 footnotes, some of which are quite entertaining, and a useful glossary of terms and acronyms. De Rújula revels in acronyms, including ones of his own creation such as WEAHM (With Exactly All His Might), so the glossary is essential.

The first four short chapters are a warm-up on the basics of science. De Rújula does a wonderful job of covering the scientific method and conveying that science is a human activity. He even makes a discussion of units interesting. From there, he moves on to explain the standard model of particle physics. This is where *Enjoy Our Universe* really shines. Particle theory is De Rújula's specialty, and he participated in many of the field's most important events, including the discoveries of the charm quark in 1974 and the Higgs boson in 2012. On the other hand, although it is important to understand the twin paradox, and the pedagogy is great, two chapters on the twins is a bit much.

The last third of the book is devoted to modern cosmology and the ΛCDM model, the cosmological counterpart to the standard model. It is all there and clearly explained, but with less passion and a few errors. For instance, De Rújula includes a picture of Edwin Hubble with his 1909 championship University of Chicago basketball team, but in the text refers to Hubble as an outstanding football player and law major. Neither is true. De Rújula also doesn't do justice to the tortured path to recognizing the expansion of the universe for what it is—the expansion of space—and he muddles the fascinating history of the cosmic microwave background. However, none of these are major flaws.

The biggest surprise is what De Rújula doesn't cover or comment on: supersymmetry, superstrings, particle dark matter, or other big mysteries. The author is not a fan of supersymmetry or superstrings, which have so dominated particle theory for 30 years, and I was hoping to hear him opine as he did in his 1986 *Nature* essay "Theoretical physics: Superstrings and supersymmetry" or in his 1985 workshop talk entitled "Supersymmetry or Superstition?" The title of his final chapter, "In Spite of Our Admitted Ignorance," had me ready for his thoughts on dark matter and dark energy. I was eager to learn where he thinks the two now-intertwined fields are going. But I was disappointed when the book ended abruptly and with a whimper rather than a bang.

There is much to recommend in this book: the beautiful drawings that chronicle, teach, and entertain; the passionate recollection of the 1974 "Charm Revolution," in which De Rújula was instrumental; the story of Michael Faraday, the first scientist with a vision to unify physics; and the art and history sprinkled throughout. As you will learn if you read *Enjoy Our Universe*, De Rújula is an engaging tour guide of this remarkable revolution in physics.

Michael S. Turner
University of Chicago
Chicago, Illinois

The life of a physicist in Victorian Britain

JOHN TYNDALL demonstrates a foghorn to Queen Victoria and her entourage.

John Tyndall's death was nearly as remarkable as his life. The celebrated Irish physicist was known for his popular lectures on science, his daring climbs in the Swiss Alps, and his discovery of the phenomenon that we now know as the greenhouse effect. By the time he was in his early seventies, Tyndall suffered from severe insomnia and took a pair of medications to combat it: chloral and magnesia. But on 4 December 1893, his wife, Louisa, unfortunately confused the two bottles, which resulted in his death from chloral overdose 10 hours later.

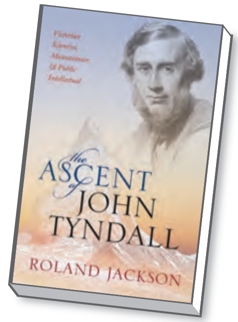
The grief-stricken Louisa set out to complete a "life and letters" volume in her husband's honor, the usual way to commemorate a great thinker in Victorian Britain. Books such as *Life and Letters of Thomas Henry Huxley* (1900) and *The Life and Letters of Faraday* (1870) helped secure the legacies of other men of science. But Louisa was unable to complete the massive task of transcribing her husband's correspondence before her own death in 1940. Despite fame during his lifetime, Tyndall faded into near-obscurity during the 20th century.

Now historian Roland Jackson has given Tyndall a weighty biography, *The Ascent of John Tyndall: Victorian Scientist, Mountaineer, and Public Intellectual*, that explores both Tyndall as a person and his place in Victorian science. *The Ascent of John Tyndall* chronicles the man's varied and fascinating life using quotes from his journals and from his extensive correspondence. From those sources, Jackson provides a fine-grained account of Tyndall's day-to-day life—his social circles, his financial situation, his romantic hopes and disappointments. Here is a typical passage: "Tyndall now terminated his employment with [Richard] Carter.… [He] believed that Carter owed him £257, but offered to settle for £200, of which £180 was left on account. Carter hosted a farewell dinner on 16th August, inviting [Thomas] Hirst and their colleague Jemmy Craven too. A few days later, Tyndall left for Manchester and from thence the south."

Many readers will welcome the chance to immerse themselves in Tyndall's world this way, but others may find themselves bogged down and skimming passages on topics that interest them less.

Tyndall came from humble origins. Born around 1820 in the Irish town of Leighlinbridge, he began his working life as a land surveyor. His interest in science blossomed in early adulthood,

The Ascent of John Tyndall
Victorian Scientist, Mountaineer, and Public Intellectual
Roland Jackson
Oxford U. Press, 2018. $34.95



and after doctoral work in Germany, his research on diamagnetism eventually won him a position at London's Royal Institution. There, Tyndall became known for his work on the mechanics of glacier formation, the properties of light, and the absorption and emission of radiant heat—including the earliest description of the greenhouse effect. His lively Friday Evening Discourses at the Royal Institution became a sought-after ticket for fashionable Londoners and, along with his popular writings, made him one of Britain's most famous scientific figures. Tyndall was also a daring mountaineer; the chapter on his Alpine adventures—including a harrowing accident climbing the Matterhorn—is especially gripping.

After many romantic disappointments in his twenties and thirties, Tyndall eventually married Louisa Hamilton, the oldest daughter of Lord Claud Hamilton, in 1876. Despite the age difference—Tyndall was 55 and Louisa, 30—the marriage was a happy one. Louisa was an intelligent woman who gave Tyndall an enormous amount of help with his correspondence and proofreading, occasionally at the cost of her own health.

But even Louisa's example could not shake Tyndall's belief in the intellectual inferiority of women. Jackson does not shy away from Tyndall's beliefs on topics such as sex and race or excuse them as mere by-products of the Victorian era; as he writes in the introduction, "that they were typical of the time does not reduce their impact today." Even so, the book occasionally has a tendency to soften or quickly move past unpleasant statements and views.

For example, when writing about Tyndall's belief in female inferiority, Jackson concludes that "it was not only over women that Tyndall sought to assert his scientific authority. His books and lectures all conveyed a superior expertise that he communicated to a relatively inexpert public." But Tyndall's work as a popularizer and his faith in his own knowledge do not change the fact that he could regard men but not women as potential equals.

Similarly, Jackson delves into Tyndall's participation in the "Eyre affair," the 1867 trial of Jamaican governor Edward John Eyre, whose declaration of martial law during a protest resulted in the murder of more than 400 black Jamaicans. Tyndall spoke out in Eyre's defense, and Jackson quotes passages in which Tyndall argued that enslaved men and women in Jamaica were inherently inferior to "Englishmen." Jackson writes that "Tyndall and others did not see this as prejudice; it was simply the way things were." But many others in the 1860s did not see it that way, and in a book of this length and detail, a fuller discussion was warranted.

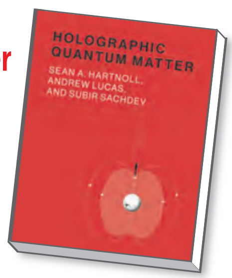
I came to this book familiar with Tyndall; I spent five years as a postdoc and editor on the John Tyndall Correspondence Project. Even so, I learned something new on every page of *The Ascent of John Tyndall*. Jackson's careful scholarship has produced a thorough and absorbing account of Tyndall's life and work. Historians of science and anyone fascinated by Victorian life will be glad that Tyndall has a biography at last.

Melinda Baldwin
Physics Today
College Park, Maryland

KTSIMAGE/ISTOCK/THINKSTOCK

The unexpected duality of gravitational and condensed-matter physics

Holographic Quantum Matter
Sean A. Hartnoll, Andrew Lucas, and Subir Sachdev
MIT Press, 2018. $65.00



High-energy and condensed-matter physicists have long enjoyed a fruitful interchange of ideas and techniques. The microscopic laws that govern elementary particles share a surprising number of similarities with the collective behavior of matter at macroscopic scales. For example, the standard model of particle physics relies heavily on the notion of spontaneously broken global and local symmetries, concepts that have their roots in the observed behavior of ferromagnets and superconductors.

A relatively new example of the continuing dialog between the two fields is holographic quantum matter, a subject physicists have been vigorously pursuing for more than a decade. Developments originating in superstring theory have led to the remarkable realization that strongly interacting quantum matter can be modeled in terms of gravitational physics in one higher dimension and that gravitational physics can also be modeled as quantum matter. That approach is variously referred to as gauge/gravity duality, holography, holographic duality, or the anti–de Sitter/conformal field theory correspondence, and there is by now a vast literature on the subject. *Holographic Quantum Matter*, a new book by Sean Hartnoll, Andrew Lucas, and Subir Sachdev, gives an excellent conceptual overview of the field while providing enough technical detail for the reader to perform relevant computations.

A few key ideas that underlie holographic duality are useful to keep in mind to appreciate the scope and limitations of that approach. First of all, we have the large-N approximation. Since the 1970s physicists have known that strongly interacting quantum systems can simplify drastically if the number of degrees of freedom is taken to be large. Indeed, the theory becomes effectively classical when expressed in terms of the appropriate collective variables. Remarkably, under the right circumstances this collective description includes gravity in one higher dimension. Hence classical general relativity, coupled to matter fields of various types, emerges out of strongly interacting quantum matter.

If the gravitational theory is sufficiently simple—that is, accurately governed by a Lagrangian with a small number of fields and interactions—holographic duality becomes useful. The emergence of a new holographic spatial dimension leads to physics at different scales in the original system being projected to physics at different locations in the holographic direction.

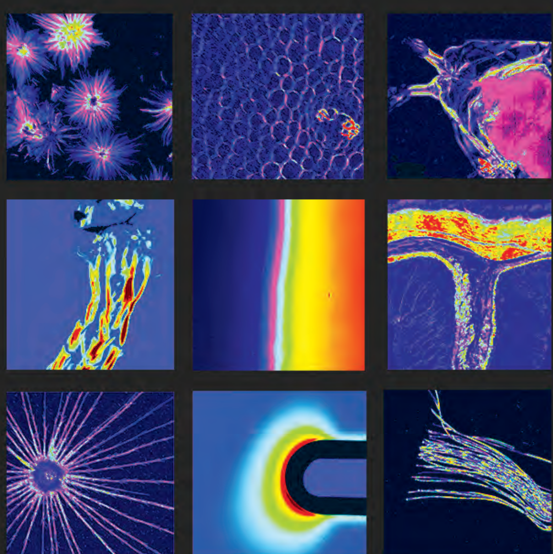
Next, entropy generation and dissipation are key concepts governing the out-of-equilibrium dynamics of interacting matter. Thermal systems are mapped by the duality to black holes, whose thermal nature is due to Hawking radiation. Entropy generation arises when matter falls through the black hole horizon, a process readily described by solving, often numerically, systems of differential equations.

Finally, the physics of ordinary metals can be formulated in terms of quasiparticles and the associated Landau–Fermi liquid paradigm. Physicists have a strong understanding of the thermodynamic and transport properties of such systems, but there is intense interest in materials that fall outside that paradigm. When no quasiparticles are present, the physics is instead governed by a quantum critical soup of gapless degrees of freedom. Traditional quasiparticle-based tools are ineffective in that context, but holographic duality maps those systems to classical field theory modes, yielding a description that is tractable analytically.

The authors of *Holographic Quantum Matter* systematically develop all these fundamental ideas along with their applications to thermodynamic and transport phenomena, both near and far from equilibrium. Some connection is made to experiments in systems such as cuprate superconductors, graphene, and heavy fermion compounds. To properly absorb the material, the reader should be comfortable with general relativity and quantum field theory and should have broad familiarity with condensed-matter physics, although some topics could be learned on the fly as needed. The reader should come away appreciating that holographic duality provides a novel class of solvable models for strongly interacting quantum matter. However, holographic duality is best viewed as a way of placing certain universal phenomena in a tractable framework. It is not reasonable to expect a specific gravitational model to accurately describe in full detail a specific physical system of interest.

The authors are exceptionally well qualified to review the given subject; they are responsible for many of the developments discussed in this review. The prose is clear and authoritative throughout. I appreciated the efforts the authors made to identify unifying themes rather than simply describing one model after another. The extensive list of references will be very helpful for the reader who wishes to delve deeper. Each chapter contains a collection of well-thought-out problems taken from the literature. I recommend *Holographic Quantum Matter* without question to anyone who wishes to pursue research at the interface of condensed-matter and high-energy physics or to anyone interested in a broad overview of an active and fruitful field.

Per Kraus
University of California, Los Angeles

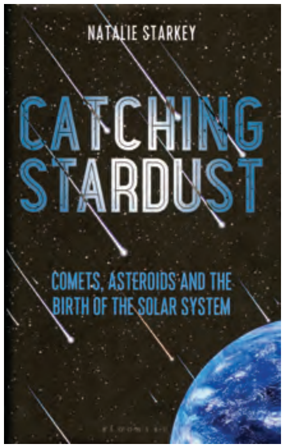


NEW BOOKS & MEDIA

Catching Stardust

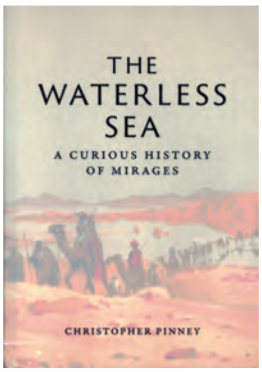
Comets, Asteroids and the Birth of the Solar System

Natalie Starkey
Bloomsbury, 2018. $27.00



Comets and asteroids, the basic building blocks of the solar system, can provide clues to the formation of the planets and perhaps even to the development of life itself. In *Catching Stardust*, geologist and cosmochemist Natalie Starkey explores the history of these small solar-system bodies, some of the missions launched to study them, their potential as sources of metals and other important raw materials, and the danger posed by a possible catastrophic collision with Earth. Written for a general audience, the book attempts to convey our planet's extensive past and explore what the future may hold. —CC

The Waterless Sea



A Curious History of Mirages

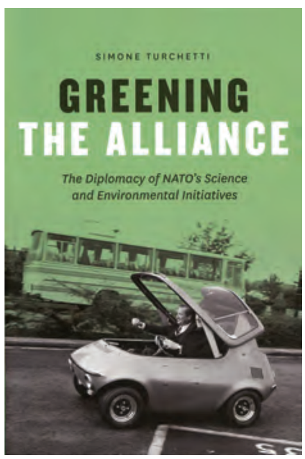
Christopher Pinney
Reaktion Books, 2018. $29.00

Anyone who has driven down a hot asphalt country road will have seen in the distance what appears to be a pool of standing water that remains perpetually out of reach. In *The Waterless Sea*, anthropologist Christopher Pinney delves into the many accounts of fantastic mirages that have been reported over the centuries. No mere optical illusions, he says, mirages are real and are produced by atmospheric optics. Their interpretations, however, have been shaped by culture, politics, religion, and science. Their illusory qualities drive Pinney's philosophical discussion, which touches on a number of topics, such as their use as metaphor and moral lesson. Historical photos, prints, lithographs, and paintings illustrate Pinney's erudite narrative. —CC

Greening the Alliance

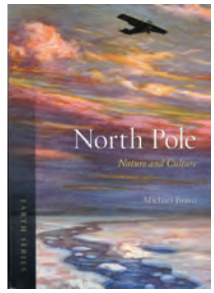
The Diplomacy of NATO's Science and Environmental Initiatives

Simone Turchetti
U. Chicago Press, 2019. $37.50 (paper)



In this fascinating new study, University of Manchester historian Simone Turchetti explores NATO's sponsorship of environmental science during the Cold War. NATO alliance members invested significant funds in environmental science and conservation during the late 20th century, which led to the collection of significant atmospheric, oceanographic, and climate data. Turchetti argues that NATO prioritized those sciences because of their potential to enhance surveillance capabilities, but he also shows that NATO's scientific efforts helped smooth diplomatic negotiations among member nations. The book is a welcome contribution to the scholarly literature on environmental science, diplomatic history, and science in the global Cold War. —MB

North Pole

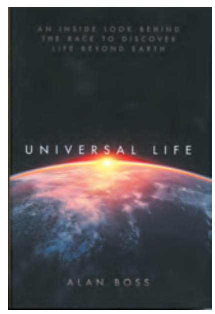


Nature and Culture

Michael Bravo
Reaktion Books, 2019. $24.95 (paper)

Until a little more than a century ago, no one had actually visited the North Pole. That did not stop natural philosophers, armchair geographers, novelists, and others from speculating about it. In *North Pole: Nature and Culture*, Michael Bravo of the Scott Polar Research Institute discusses the "mysterious power and allure" of one of the most inhospitable places on Earth. His ambitious text begins with the study of astronomy and the North Pole Star by early peoples such as the Inuit and the ancient Greeks, and then moves on to Renaissance polar maps and globes, the development of navigation by magnetic compass, polar expeditions, and a discussion of the North Pole as a literary and narrative device that has inspired numerous works of fiction and political satire. The slim, 254-page volume is nicely illustrated with more than 100 paintings, engravings, and photos. —CC

Universal Life



An Inside Look Behind the Race to Discover Life Beyond Earth

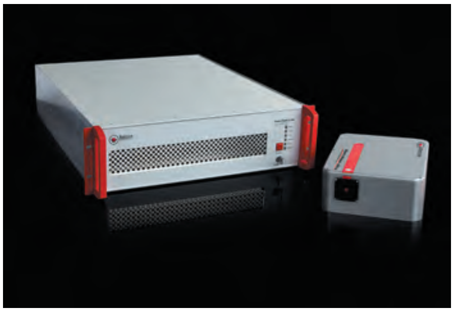
Alan Boss
Oxford U. Press, 2019. $24.95

Launched on 6 March 2009, the *Kepler* space telescope was NASA's first mission dedicated to finding Earth-like planets, or exoplanets. In *Universal Life*, Alan Boss, an astrophysicist and chair of NASA's Exoplanet Exploration Program Analysis Group, presents a history of modern planet hunting, starting with *Kepler* and moving on to a host of other missions proposed over the past several decades. Boss's narrative focuses on the day-to-day trials and travails of seeing a mission through from proposal to launch and beyond. The book is the third in a series that includes *Looking for Earths: The Race to Find New Solar Systems* (1998) and *The Crowded Universe: The Search for Living Planets* (2009). —CC PT

Focus on lasers, imaging, and microscopy

The descriptions of the new products listed in this section are based on information supplied to us by the manufacturers. PHYSICS TODAY can assume no responsibility for their accuracy. For more information about a particular product, visit the website at the end of the product description. For all new products submissions, please send to ptpub@aip.org.

Andreas Mandelis



Ultrafast near-IR fiber laser

Toptica's FemtoFiber ultra 920 laser provides pulses centered at 920 nm with a duration typically less than 100 fs and a repetition rate of 80 MHz. It reaches an average power greater than 1 W, which the company says is a novel achievement in view of the instrument's ultrashort-pulse capability. The pulses are generated by a mode-locked, ring-type, erbium-based fiber oscillator consisting of a semiconductor saturable absorber mirror and a high-power fiber amplifier. To ensure reliability, only polarization-maintaining fibers are used in the signal path. The compact, air-cooled laser is suitable for nonlinear microscopy applications such as two-photon excitation of fluorescent proteins and second-harmonic generation-based contrast mechanisms. It can also be used for semiconductor inspection. ***Toptica Photonics Inc****, 5847 County Rd 41, Farmington, NY 14425, www.toptica.com*

High-frame-rate cameras

The i-Speed 510 and 513 high-speed video cameras join model 508 in iX Cameras' 5-series of compact midrange cameras. With a custom 12-bit 1920 pixel × 1080 pixel CMOS image sensor, the 510 can record 4980 fps at full HD resolution, and the 513 offers 6382 fps. For all three models, the maximum frame rate is 500 000 fps. With the fast-mode shutter option, the 5-series can achieve exposure times of 250 ns. The 510 and 513 deliver 10 GPx/s and 13 GPx/s throughput, respectively. The sealed electronics design has an internal cooling system that vents heat from inside the cameras to the atmosphere. The compact units incorporate up to 144 GB of memory; an internal solid-state drive (SSD) of up to 8 TB is optional. The series also introduces a swappable external SSD with storage capacities up to 2 TB, so large data files in final video formats can be moved quickly and easily. ***iX Cameras****, 8 Cabot Rd, Ste 1800, Woburn, MA 01801, www.ix-cameras.com*

Portable atomic force microscope

According to NanoMagnetics Instruments, its ezAFM+ atomic force microscope not only offers high imaging power at the nanoscale but is also flexible, portable, and cost-effective. A user-friendly design makes it suitable for basic research and nanotechnology education. The ezAFM+ features scan ranges of 120 µm × 120 µm × 40 µm or 40 µm × 40 µm × 4 µm, a resolution of 2 µm, and a noise floor of 65 $\text{fm}\sqrt{\text{Hz}}$. It offers four microscopy imaging modes—contact, phase, lateral force, and magnetic force—and an HD video camera with a 390 µm × 230 µm field of view, a 2516 pixel × 1960 pixel image sensor, and a 30 fps frame rate. The standard sample size is 10 mm × 10 mm × 5 mm, but the microscope can be configured to accept any sample size. Extended imaging options include liquid cell and scanning tunneling microscopy. A 38-mm-stroke two-axis motorized sample positioner and a 2-mm-stroke two-axis manual sample positioner are available as accessories. ***NanoMagnetics Instruments****, 266 Banbury Rd, Ste 290, Oxford OX2 7DL, UK, www.nanomagnetics-inst.com*

Fast submicron-resolution imaging of intact samples

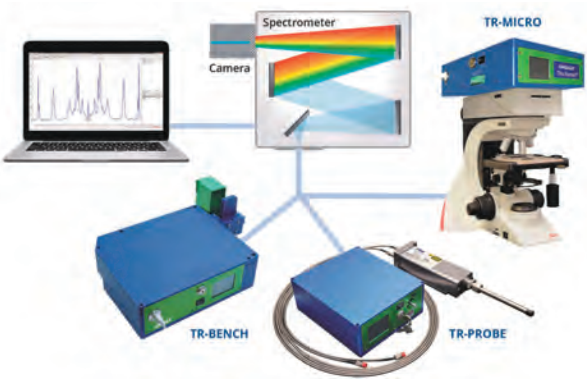
Zeiss has introduced two advanced models to its Xradia Versa x-ray microscope family. Improved source and optics technology enable the Xradia Versa models 610 and 620 to deliver nondestructive imaging of intact samples without sacrificing resolution and contrast. The series features 500 nm spatial resolution and 40 nm minimum voxel size. It lets users observe submicron features on a broad range of sample types and sizes and maintains high resolution across large working distances. Applications include investigating the energy materials under operating conditions and visualizing defects associated with semiconductor-package-level failure. Life sciences researchers can use the Xradia 600-series Versa to study soft tissue, such as neural tissue and vascular networks; mineralized tissue, such as bones; and plant structures, such as roots. ***Carl Zeiss Microscopy GmbH***, *Carl-Zeiss-Promenade 10, 07745 Jena, Germany, www.zeiss.com*

Thermal sensors for laser measurements

A new addition to MKS Instruments' Ophir line of LP2 laser power/energy sensors, model L50(150)A-LP2-35 is a compact thermal measurement sensor suitable for use with high-power-density and long-pulse lasers. It features an LP2 antireflection coating that, according to the company, provides the highest damage threshold in the industry: 33 kW/cm^2 at 150 W full CW power. The coating absorbs 95% at most wavelengths and is spectrally flat at ±1% from 0.25 μm to 2.2 μm. It lets the sensor measure concentrated, lower-power beams and short exposures of higher power. The L50(150)A-LP2-35 has a 35 mm aperture. It can measure laser power from 100 mW to 50 W continuously and up to 150 W intermittently, measure power up to 4000 W from a short 0.4 s exposure to the laser, and measure laser energy from 40 mJ to 3000 J. ***Ophir-Spiricon LLC***, *3050 N 300 W, North Logan, UT 84341, www.ophiropt.com*

Dual-functionality imaging microscope

According to Tomocube, its HT-2 microscope is the first to combine holotomography and 3D fluorescence imaging in one unit. It is designed to enable long-term tracking of specific targets in live cells while minimizing stress. The morphological, chemical, and mechanical properties of cells are recorded by 3D refractive index tomograms, and the fluorescence imaging capability adds molecular specificity information. The HT-2 incorporates a customizable three-channel LED light source (385 nm, 470 nm, and 570 nm) and a motorized Z-drive with a step resolution of 150 nm to generate highly detailed Z-stack images. A digital micromirror-device optical light shaper, which consists of several hundred thousand micromirrors arranged in a rectangular array, eliminates the need for moving parts in the light path and delivers stable performance during long-term studies. ***Tomocube Inc**, 2nd Floor, KHE Bldg, 48 Yuseong-daero 1184 beon-gil, Yuseong-gu, Daejeon 34109, South Korea, www.tomocube.com*



Terahertz-Raman spectroscopy modules

The Coherent TR-series of THz-Raman spectroscopy modules deliver spectral information in the terahertz frequency—or low wavenumber—range, which provides unique data about subtle phase differences, crystallinity, orientation, and other sample characteristics. The modules can be used to upgrade an optical microscope or a visible-to-near-IR or Raman spectrometer. The products allow simple access to that key "structural fingerprint" frequency range and enable nondestructive characterization of structural changes in real time. Coherent TR-series modules feature the company's patented narrowband filter technology. By using Raman scatter near the excitation Rayleigh wavelength, the modules provide frequency-resolved terahertz data with the convenience and low cost of using visible or near-IR light, such as glass optics and fibers and silicon-based CCD/CMOS detectors. ***Coherent Inc**, 5100 Patrick Henry Dr, Santa Clara, CA 95054, www.coherent.com*

NEW LITERATURE

Nanopositioning products catalog

Physik Instrumente has published *Nanopositioning for Microscopy*, a brochure that explains nanopositioning mechanisms for high-resolution microscopy applications. Positioning optics or samples with resolution in the subnanometer range is feasible and critical for improving the resolution, focusing speed, and stability of images taken with techniques such as fluorescence, widefield, laser scanning, atomic force, transmission electron, superresolution, optical stereo, and correlative microscopy. The informative flow charts and application tables simplify the process of selecting the best drive technology for each application. Available in print and as an interactive PDF with links to additional information on the company's website, it addresses the needs of scientists and engineers by providing a comprehensive overview of nanopositioning sample stages, nonmagnetic linear motor stages, fast piezo nanofocus drives, objective and lens scanners, and multiaxis motion systems with up to six degrees of freedom. ***Physik Instrumente LP**, 16 Albert St, Auburn, MA 01501, www.pi-usa.us* PT

PHYSICS TODAY PRODUCT PICKS

12 or 14 Bit Analog/Digital Fiber Optic Links

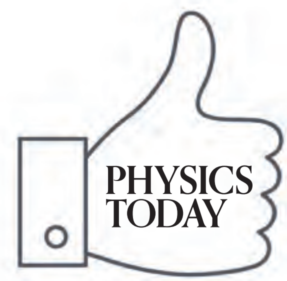
The US-made LTX5515 series will multiplex 1 analog signal with 12/14 bit precision and up to 4 digital channels. The LTX5525 series will support up to 16 digital channels, with both devices transmitting over a single fiber at a rate of 2 Gigabits and a bandwidth of DC to 25 MHz. Applications include data acquisition for plasma physics experiments, noise-free signal transmission and control of equipment at high voltage potentials in hostile EMI environments, or through Faraday shields. LTX72XX series available for bi-directional applications.

Terahertz Technologies, Inc.
Sales@teratec.us
www.teratec.us

McPHERSON VUV

Masterpiece gratings for better SNR and efficient coverage from 30 to 2200 nanometers. Configure the 234/302 spectrometer for direct-detection CCD, gated microchannel plate, and scanning mode single channel detectors

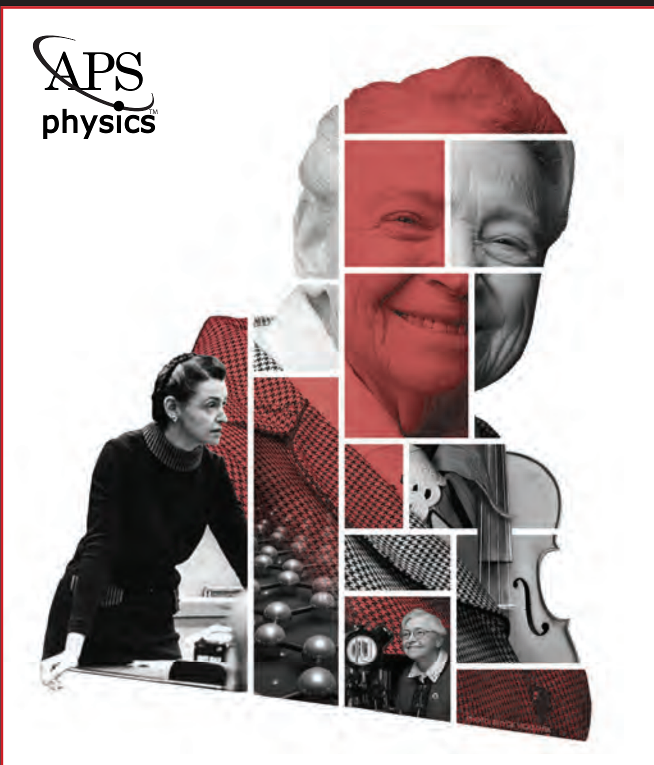
Visit **www.McPhersonInc.com** today and call 1-978-256-4512



More than **3 Million** fans

Find out what you are missing!

LIKE US TODAY! Facebook.com/PhysicsToday



MILLIE DRESSELHAUS

Fund for Science and Society

Created by the American Physical Society to honor the remarkable scientific career and community legacy of the late Millie Dresselhaus.

To learn more, please visit go.aps.org/dresselhaus

or contact Irene Lukoff, APS Director of Development at (301) 209-3224 or lukoff@aps.org.

OBITUARIES

Ennackal Chandy George Sudarshan

Ennackal Chandy George Sudarshan, a titan of 20th-century theoretical physics who made seminal contributions to several fields, passed away in Austin, Texas, on 13 May 2018. His vector−axial vector (V−A) theory of the weak interaction and optical equivalence theorem sparked revolutions in high-energy physics and quantum optics.

George was born on 16 September 1931 in Pallam, India. After completing a BSc from Madras Christian College in 1951 and an MA from the University of Madras in 1952, he joined the Tata Institute of Fundamental Research in Mumbai, where he worked on cosmic-ray showers with Homi Bhabha. He also became the scribe for quantum mechanics lecturer Paul Dirac and took excellent notes for him. He was recruited by Robert Marshak of the University of Rochester as a doctoral student and within two years formulated the V−A theory of the weak interaction.

After receiving his PhD in 1958, George did a brief stint as Julian Schwinger's research fellow at Harvard University before returning to Rochester, where he developed the optical equivalence theorem. He then worked at the University of Bern and Syracuse University before joining the University of Texas at Austin in 1969. He also served as the director of the Institute of Mathematical Sciences in Chennai, India, from 1984 to 1991.

In the mid 1950s, the discovery of parity violation demanded a consistent theory of the weak force. George's comprehensive analysis of all weak-decay data convinced him that if there was a universal Fermi interaction, with parity violation built in, it had to include the axial-vector interaction, since charged pion decay could be viewed as beta decay of a nucleus with zero atomic mass. He came to the far-reaching conclusion that a V−A structure of weak interaction could explain all but four crucial experimental results. When researchers repeated the experiments, they yielded the results his theory predicted. That discovery was crucial to the later unification of the weak and electromagnetic interactions by Steven Weinberg, Abdus Salam, and Sheldon Glashow.

George's work with Marshak, Susumu Okubo, Weinberg, and others on weak interactions led to the successful application of final-state interactions to the decay of lambda hyperons and contained the general method for solving singular integral equations. With Marshak and Okubo, George discovered the general theorem on sum rules with symmetry breaking and the first application of symmetry groups to obtain sum rules. George also helped introduce other applications of group-theoretic methods that led to the relations between the magnetic moments of sigma particles and the transition moments of sigma and lambda particles.

The classical and semiclassical theories of optical field coherence had been developed by Emil Wolf and Leonard Mandel during the 1950s and 1960s. Roy Glauber proposed in February 1963 a quantum model for optical coherence, which involved normally ordered quantum correlation functions.

George's diagonal representation of the density operator in terms of coherent states appeared in April 1963. He showed that the coherent states' overcompleteness could be used to represent every density operator in the diagonal form and that a general quantum correlation function could be computed in a simple way once it was re-expressed in normally ordered form. Known as the optical equivalence theorem, George's result showed how quantum optical correlations could be expressed in terms of a quasi-probability density and in a manner analogous to classical correlations. The novel and crucial feature was that the quasi-probability density could take on negative values, which is the signature of an optical field's quantum nature, as seen in the anti-Hanbury Brown–Twiss effect and photon antibunching.

With Baidyanath Misra, George predicted the quantum Zeno effect, so named because the decay of an unstable quantum state, measured sufficiently frequently, is hindered. His work with Piravonu Mathews and Jayaseetha Rau generalizing the classical stochastic processes to the quantum domain was the precursor to his later work on the development of quantum correlations between parts of a large system. That led to the theory of stochastic semigroups from which emerged the Gorini-Kossakowski-Sudarshan equation that forms the basis for the study of large open systems. George provided a nonrelativistic proof of the spin-statistics theorem by imposing appropriate restrictions on the kinematic part of the Lagrangian of a field theory derivable from a Weiss–Schwinger type of principle of least action.


Ennackal Chandy George Sudarshan

One of George's most famous papers, written with Vijay Deshpande and Olexa-Myron Bilaniuk, was on faster-than-light particles, later named tachyons, which caught the imagination of a generation of physicists and science fiction writers. George was always ready to branch out into new fields, and as a natural progression of his studies on open systems and dynamical maps, he was analyzing problems in quantum tomography and quantum computing during his last years.

George received the first physics prize from the World Academy of Sciences in 1985. Among his other awards were India's second-highest civilian award, the Padma Vibhushan, in 2007 and the Dirac Medal from the Abdus Salam International Centre for Theoretical Physics in 2010.

Gentle, witty, humorous, and kind, George touched everyone with his generosity and warmth.

M. K. Balasubramanya
Texas A&M University–San Antonio

M. D. Srinivas
Centre for Policy Studies
Chennai, India PT

The “Job Opportunities” section of *Physics Today* has been discontinued.

LOOKING FOR A JOB?

Hundreds of physics jobs are now found online at physicstoday.org/jobs.

LOOKING TO HIRE?

Post jobs online at physicstoday.org/jobs.
Print job ads are still available for purchase as run-of-book display ads.

Questions? Email us at ptjobs@aip.org.

PHYSICS TODAY | JOBS

INDEX TO ADVERTISERS

ADVERTISING SALES MANAGEMENT

American Institute of Physics
One Physics Ellipse
College Park, MD 20740
+1 301.209.3393
www.physicstoday.org/advertising

Sales and Marketing Manager
Christina Unger Ramos • cunger@aip.org

Recruitment Advertising
ptjobs@aip.org

Ad Traffic Coordinator
Unique Carter • ucarter@aip.org

ADVERTISING SALES CONSULTANTS

USA and CANADA

AL, AR, AZ, CO, DC, FL, IA, ID, IL, IN, KS, KY, LA, MD, MI, MN, MO, MS, MT, ND, NE, NM, NV, OH, OK, SD, TN, TX, UT, VA, WI, WV, WY, and West Canada
Mike Shevlin
p: +1 847.749.0168
m: +1 847.602.6844
mshevlin@theshevlingroup.com

AK, CA, CT, DE, GA, HI, MA, ME, NC, NH, NJ, NY, OR, PA, RI, SC, VT, WA, and East Canada
CEL Associates II
Jody Estabrook
p: +1 774.283.4528
m: +1 978.835.2013
jodyestabrook@comcast.net

Merrie Lynch
+1 617.357.8190
merrie.lynch@celassociates2.com

INTERNATIONAL

Northern and Western Europe
John Gold
+44 208.641.7717
johnfgold@gmail.com

Central and Eastern Europe
Leo Ploner
+49 172.8231.062
leo@ploner.de

Asia/Pacific
Jake Wilson
+61(0)413 949 644
jwilson@imraust.com.au

PHYSICS TODAY
www.physicstoday.org/advertising

Orit Peleg is an assistant professor of computer science at the University of Colorado Boulder's BioFrontiers Institute.

Mechanical hive mind

Orit Peleg

Honeybees work together to maintain a stable structure that adapts to environmental changes.

How do small animals buffer themselves against large fluctuations in their environment? One strategy is to form a superorganism, wherein individuals group together to overcome challenges a single organism cannot. Spectacular examples abound, and the behavior is a hallmark of social insects, such as termites, ants, and bees (see the Quick Study by John W. M. Bush and David L. Hu, PHYSICS TODAY, June 2010, page 62). This Quick Study focuses on the collective behavior of honeybees and describes how they stay warm and safe during their migrations to new nest sites.

At times, thousands of bees hold onto each other to create suspended clusters that can dynamically change shape to withstand mechanical stresses and regulate their bulk temperature. The stability of a cluster relies on individual bees that respond to local variations in strain. That behavior, in turn, improves the collective stability of the cluster as a whole, at the expense of increasing the mechanical burden experienced by individuals.

Collective behavior

The behavior isn't unique to honeybees. An individual organism—a bacterium, an insect, or a mammal, for instance—promotes the group's survival by sensing and responding to information from its local environment. A classic example is the positions of neighboring individuals in the group. That local information animates schools of fish and flocks of birds and allows them to collectively change direction abruptly and avoid predators. Similarly, collective decision making allows groups to locate food sources: Bacteria produce and detect chemical gradients, ants lay and detect pheromone trails, and bees use waggle dances to communicate and promote foraging.

Another process, also mediated via local information, is collective construction. It allows individuals to use materials from their natural habitat to build elaborate structures that are significantly larger than the size of an individual. Paper-wasp nests and termite mounds are two cases in point. Another type of collective construction is structures produced by individuals linking their bodies. Penguin colonies huddle together to stay warm in Antarctica, ants link their bodies to make bridges and rafts so they can traverse rough terrain and survive floods, and, as we'll see, clusters of honeybees have their own adaptations to keep their colony coherent and protected from environmental threats.

Honeybee colonies

European honeybees, *Apis mellifera* Linnaeus, reproduce via the queen laying eggs, and colonies reproduce via fission, a process in which the colony divides roughly in half. The new colony is the swarm that leaves in search of a new permanent location while the rest of the bees remain behind. During that effort, the bees temporarily form themselves into a cluster that can hang from various surfaces—tree branches, roofs, and even fences and cars. It can also remain in place for several days while scout bees search the surrounding area for suitable nest sites.

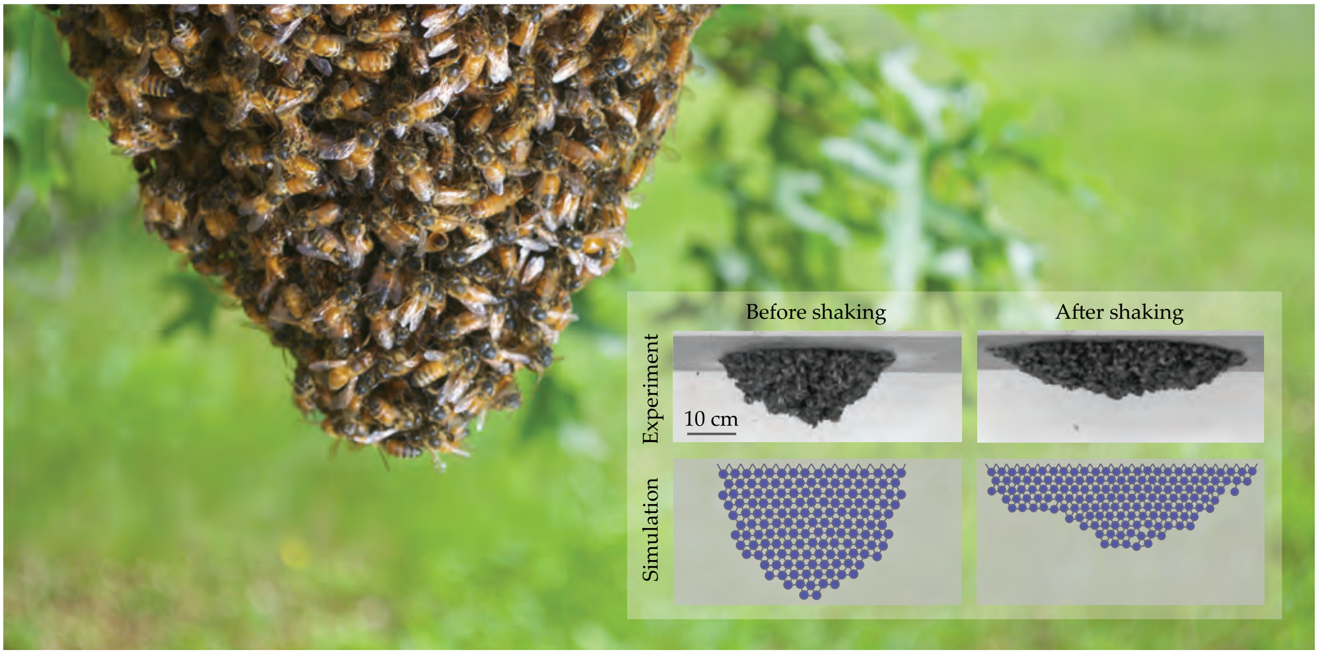
But the honeybees are still vulnerable. While suspended, the colony has no nest to protect itself from the elements. To cope with the exposure, clusters adjust their density and surface-to-volume ratio to maintain a near-constant core temperature—roughly 35 °C—despite large fluctuations in the ambient temperature. To generate metabolic heat, bees repeatedly contract and relax their flight muscles; to cool down, they ventilate the cluster by spreading out to increase the exposed surface of the swarm. Generally, a cluster takes the shape of an inverted cone, but the competing effects of gravity and mechanical perturbations of wind and rain produce a dynamic shape.

Morphology in motion

How can such a cluster, which is orders of magnitude larger than an individual, maintain mechanical stability in the face of environmental perturbations? My colleagues Jacob Peters, Mary Salcedo, and L. Mahadevan (all at Harvard University) and I addressed that question last year by performing a series of biological experiments and comparing the results with our computational models. Mechanical cues should play an essential part in the cluster's morphogenesis, we reasoned. To test the idea, we watched what happened when a cluster of approximately 10 000 bees was mechanically shaken.

The cluster was attached to a wooden board that oscillated along the horizontal or vertical axis at different frequencies (0.5–5 Hz) and accelerations (0.01–0.075 g). In response to the horizontal shaking, the conical cluster swung to and fro in a pendular mode, with a frequency of about 1 Hz. The bees dynamically adjusted the aspect ratio of their cluster and became, within minutes, a wider, more stable cone, as shown in the figure. As the frequency of the shaking increased, so did the forces on individuals, and they collectively widened the base of the cone to compensate. Its height shortened as a result. Once the horizontal perturbations ceased, the cluster reverted to its original shape, albeit at a slower rate than the bees took to flatten it.

When the motion was predominantly vertical, though, the shape remained constant until a critical force was reached that cracked the bonds between individual bees and caused the swarm to break apart. To understand the directional dependency in the cluster's response to motion, we modeled the clus-



A HANGING CLUSTER OF HONEYBEES changes its shape to improve the collective stability of the hive. Inset shows the experimental shapes and simulations of the cluster in equilibrium before and after horizontal shaking. (Images courtesy of Orit Peleg and Jacob M. Peters. For videos of the dynamic motion of a cluster, see O. Peleg et al., *Nat. Phys.* **14**, 1193, 2018.)

ter as an elastic material in which bees are represented by spheres connected to each other through elastic bonds. We monitored the mechanical strains on the bonds between pairs of bees and noticed that they are lower during vertical shaking than during horizontal shaking.

A positive correlation between swarm spreading and local mechanical strains suggests that the bees are monitoring those strains, not the global acceleration of the mechanical shaking. Moreover, the mechanical strains are lower when the cluster is spread out than when it is elongated. Apparently, the bees interpret low local mechanical strains as a cue to stop spreading.

The last component needed to reproduce the cluster's spreading is a directional bias. To that end, we monitored the spatial distribution of the strain inside the cluster and noticed that the strain decreases with distance from the attachment board. We combined all those ingredients into an agent-based model in which the bees monitor local strains and crawl up the strain gradient when those strains exceed a specific threshold. That response improves the collective stability of the cluster as a whole, at the expense of greater average mechanical burden experienced by the individual bees. One might call the behavior mechanical altruism.

Our model reproduced our experimental results: outward spreading in response to horizontal shaking and no spreading in response to vertical shaking. Because the spreading is a collective process, we wondered just how the bees pull it off. To study that aspect of the problem, we tracked the movements of bees on the surface of a spreading cluster. A change in relative displacement between neighboring bees drives the shape adaptation: Individual bees sense the local deformation of the cluster relative to their neighbors and move to regions of lower displacement.

In the continuum limit, that movement corresponds to the bees' ability to sense strain gradients and move from regions of lower strain (near the cluster's tip) toward regions of higher strain (near the fixed base). Importantly, that behavioral law is invariant to rigid translation of the cluster and depends only on the mechanical environment each bee experiences.

Our work has expanded the traditional understanding of collective behavior via stigmergy, whereby organisms respond to local cues with little or no long-range effects. The behavioral response of bees in the swarm is a new, previously unreported way to establish the relation between long-range elasticity and beneficial nonlocal effects mediated by physics.

Nonlocal interactions in assemblages of social insects may be the tip of an iceberg of ways in which organisms take advantage of physical interactions and simple behavioral rules for adapting to changing mechanical environments. As a broadly trained physicist studying animal behavior, I am fascinated by those painstakingly evolved solutions because they reveal new, optimal types of signal processing. By harnessing those natural solutions, honed by eons of evolution, we not only understand collective animal behavior more deeply, but we can also leverage the understanding to create bioinspired designs in the fields of dynamic construction, swarm robotics, and distributed communication.

Additional resources

▶ O. Peleg et al., "Collective mechanical adaptation of honeybee swarms," *Nat. Phys.* **14**, 1193 (2018).
▶ B. Heinrich, "The mechanisms and energetics of honeybee swarm temperature regulation," *J. Exp. Biol.* **91**, 25 (1981).
▶ S. A. Ocko, L. Mahadevan, "Collective thermoregulation in bee clusters," *J. R. Soc. Interface* **11**, 20131033 (2014).
▶ G. Kastberger, E. Schmelzer, I. Kranner, "Social waves in giant honey bees repel hornets," *PLOS One* **3**, e3141 (2008).
▶ T. D. Seeley, *Honeybee Democracy*, Princeton U. Press (2010).
▶ D. J. T. Sumpter, *Collective Animal Behavior*, Princeton U. Press (2010). PT

A southern bloom

This true-color image of the South Atlantic Ocean was acquired 24 December 2018 by the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard NASA's *Terra* satellite. Off the southeastern coast of Argentina, between the Valdes peninsula (top) and the Falkland Islands (Islas Malvinas, bottom), two turquoise filaments stand out in the otherwise uniform deep blue of the open ocean. They are a phytoplankton bloom, most likely coccolithophores. The unicellular, photosynthetic microalgae enshroud themselves with calcite shields they later shed. Even though individual organisms are just 100 μm in diameter, they show up in blooms such as this one because their concentration can exceed 10^5 mm^{-3}.

Blooms occur when environmental conditions—the amount of solar radiation, nutrient availability, temperature, and other variables—are just right. Phytoplankton are at the base of the ocean's food chain, and they play a crucial role in many biogeochemical cycles, including the carbon cycle. Their response to and influence on global warming is an active area of research. (Submitted by René Garreaud, Universidad de Chile.) —RJF

TO SUBMIT CANDIDATE IMAGES FOR BACK SCATTER VISIT http://contact.physicstoday.org.