PHYSICS TODAY

May 2021 • volume 74, number 5

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How frogs suppress noise

Charting the proton sea

Ernest Rutherford's ambitions

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ON THE COVER: Similar to humans who struggle to understand a conversation at a noisy gathering, frogs in loud environments sometimes misidentify vocalizations in their vicinity. Some frogs, including the red-eyed tree frog from Central America, shown here, solve the cocktail party problem by having males make their calls louder than the background noise. But female green tree frogs dampen the cacophony around them by inflating their lungs. To learn more about frog acoustics, see the story on **page 17**. (Photo by iStock.com/alptraum.)

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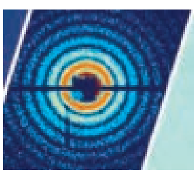

APS March Meeting

In 2020 the American Physical Society canceled its March Meeting because of coronavirus concerns. This year the meeting went virtual. PHYSICS TODAY's Paul Guinnessy interviewed a range of attendees, who recounted their mixed but generally favorable experiences.

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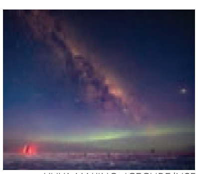

YUYA MAKINO, ICECUBE/NSF

Glashow resonance

More than 60 years ago, Sheldon Glashow predicted that the collision of an electron with an energetic electron antineutrino could form a negatively charged W boson. Now the IceCube collaboration has reported, with a confidence level above 2σ, results consistent with such an event.

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RENSSELAER POLYTECHNIC INSTITUTE

Black in the ivory

Rensselaer Polytechnic Institute president Shirley Ann Jackson was the second Black woman in the US to earn a PhD in physics and has since been a leading researcher and policy expert. In an interview, she talks about her experiences as an undergraduate and graduate student at MIT.

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FROM THE EDITOR

Postdocs then and now

Charles Day

Alexei Kojevnikov's recently published book is titled *The Copenhagen Network: The Birth of Quantum Mechanics from a Postdoctoral Perspective.*[1] During the period that Kojevnikov focuses on, 1920 to 1929, the postdoc had not achieved its subsequent status as an established career stage. But it was a necessary one. Funding for physics in Europe after World War I was meager. Even Werner Heisenberg and Wolfgang Pauli struggled to find permanent employment after they earned their PhDs. For them and others, temporary positions were a lifeline.

A central figure in the book is Niels Bohr, who served as the founding director of the Institute for Theoretical Physics of the University of Copenhagen. Denmark was neutral during the war. Lingering animosities that kept Austrian and German physicists from collaborating with British and French physicists in their home countries were less fraught in 1920s Copenhagen. Bohr's ability to raise money from the Rask-Ørsted Foundation, the Rockefeller Foundation, and other wealthy benefactors enabled him to fund visiting physicists, mostly young ones, from other countries. Among them were Oskar Klein, who turned Theodor Kaluza's classical five-dimensional field theory into a quantum one, and Douglas Hartree, who developed numerical methods for solving the Schrödinger equation.

Although "birth" appears in the book's title, most of the action takes place in 1923–27 when new observations of atomic spectra—notably the anomalous Zeeman effect—revealed the inadequacy of what became known as the old quantum theory as pioneered by Bohr, Max Planck, and Arnold Sommerfeld. Heisenberg, Pauli, Paul Dirac, and other young physicists saved the day with their bold extensions of the theory.

Melinda Baldwin's feature article on page 26 recounts how Ernest Rutherford used letters to *Nature* to raise his visibility while a young professor at McGill University in Montreal.

They did not do so in isolation. Besides passing through Bohr's institute and other centers of quantum research, such as Max Born's at the University of Göttingen, the physicists shared drafts of papers and corresponded with each other via mail. They were networked, to use a modern term.

I spent my postdoc years, 1988–90, at Japan's Institute of Space and Astronautical Science in Sagamihara, an industrial city outside Tokyo. The somewhat exotic choice was driven by opportunity. My field of research was x-ray astronomy. Because Earth's atmosphere is opaque to x rays, telescopes and detectors have to be mounted on spacecraft, which is expensive. I did my thesis on data from a European spacecraft, *EXOSAT*. The next x-ray astronomy spacecraft to be launched, *Ginga* in 1987, was Japanese.

My postdoc was funded by the Japan Society for the Promotion of Science (JSPS) as part of a program to attract foreigners to Japan. Candidates were selected by partner organizations in their home countries, in my case the UK's Royal Society. The JSPS occasionally hosted receptions for its Japan-based fellows. What struck me was the scarcity of Americans. "They prefer to stay in the US," a JSPS staffer explained to me. Indeed, the American postdocs I met as a graduate student at Cambridge University worried that their presence overseas would harm their prospects of a tenure-track position back home.

This past June the American Institute of Physics (the publisher of PHYSICS TODAY) released a report that sought to predict the impact of the COVID-19 pandemic on the physics enterprise. Postdocs, the report's authors concluded, were especially vulnerable, given their need for access to laboratories. "Separated from their research and scientific cohorts, these young scientists will have difficulty resuming their previous career paths."[2]

What connects the quantum postdocs of the 1920s, my postdoc of the 1980s, and the postdocs of COVID-19? One thing could be travel. The quantum postdocs and I went abroad for opportunities we couldn't get at home. Some countries are recovering from the pandemic more quickly than the US is. If you're a graduate student in the US, please at least consider applying for postdocs abroad. Without looking too hard, I found positions in strongly correlated quantum many-body systems at Aarhus University in Denmark, condensed-matter physics at the Chinese Academy of Sciences' Institute of Physics in Beijing, and active galaxies and galaxy formation at Seoul National University in South Korea.

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PT

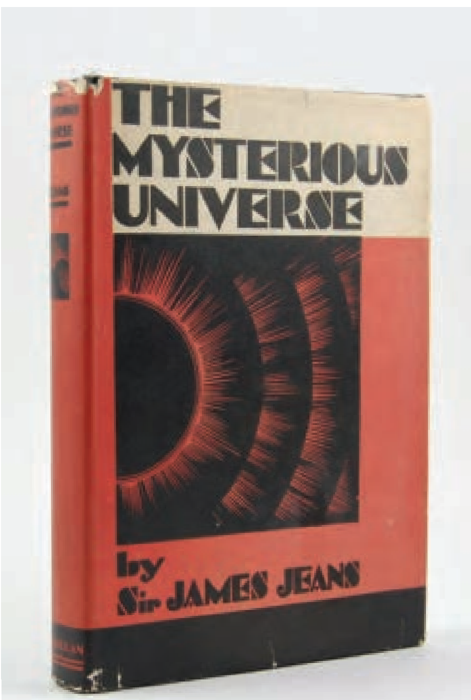
James Jeans's views on the nature of reality

Daniel Helsing's takedown of the views of James Jeans ("James Jeans and *The Mysterious Universe*," PHYSICS TODAY, November 2020, page 36) needs a rebuttal. The view that a real physical universe is "out there"—end of story—misses entirely the benefit of our huge and relatively recent mathematical insights into the nature of what seems to be reality, according to our evolved human senses.

We have achieved deeper insight only through our discovery of the immense power of often astonishingly simple mathematical equations that elucidate the nature of the so-called universe. That is profoundly yet almost trivially demonstrable! I offer an example: I expect Helsing would agree that the most mysterious thing about the universe is the nature not of matter or space but of time.

With Hermann Minkowski's 1908 insight into Einstein's 1905 special relativity, we humans achieved the almost unthinkable: a deep understanding of the utterly simple nature of time. For while $ds^2 = dx^2 + dy^2 + dz^2 + dt^2$ would describe a completely timeless Pythagorean universe having nothing but four space dimensions, Minkowski, bless him (*pace* Einstein), discerned that $ds^2 = dx^2 + dy^2 + dz^2 - dt^2$ actually describes the emptiest parts of *our* universe, which possesses three space dimensions but also has time. Yes, only a minus sign—but our greatest intellectual discovery ever.

Such equations were created solely because of the existence of the human mind, and they demonstrate that the universe itself is intrinsically mental in its nature. In my 2005 essay "The mental universe," I assist Jeans and Arthur Eddington in the Sisyphean task of educating the public on that point.[1] I also try to assist young students in seeing how simple the math is; for example, I concisely present special relativity at https://henry.pha.jhu.edu/2-pager.pdf.



LAURA MASSEY/ALEMBIC RARE BOOKS

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▶ **Helsing replies:** I did not intend a "takedown," as Richard Conn Henry claims, of James Jeans's idealistic interpretation of modern physics. Nor did I express the view that "a real physical universe is 'out there.' " Apart from exploring Jeans's inherently fascinating views and the reactions they provoked, I pointed to the historical dimensions of philosophical interpretations of physics, contemporary views included. I am agnostic on the question of the nature of ultimate reality—I do not know what is out there, and while I am certainly curious, I do not see how I will ever be in a position to know.

I respect and admire any scientist who works hard to advance our understanding of the universe and any popularizer who makes a genuine effort to interpret science philosophically—including James Jeans and the other popularizers I mention. Part of the process is cultivating an awareness of the historical embeddedness of our theories, interpretations, and worldviews, regardless of whether they tend toward idealism or naturalism.

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Nuclear is carbon-neutral

David Kramer stated in his news item "Hydrogen-powered aircraft may be getting a lift" (PHYSICS TODAY, December 2020, page 27) that "to be carbon-neutral, the hydrogen must be produced either with renewable energy or with natural gas equipped with carbon capture and storage." There is one other form of power production that is carbon-neutral and viable for use: nuclear.

I am curious whether Kramer omitted nuclear power by accident or by choice. Too often nuclear power is not considered for carbon-neutral power production, even though existing and advanced nuclear power technologies are widely accepted as carbon-neutral. Any serious discussion regarding either carbon-neutral energy production or hydrogen production should include nuclear power.

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▶ **Kramer replies:** The omission of nuclear power as a carbon-neutral power source was inadvertent, not deliberate.

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TV inspires future scientists

The article on *3-2-1 Contact* by Ingrid Ockert, in the January 2021 issue of PHYSICS TODAY (page 26), provided an interesting background of the innovative show. As a child, I watched the show regularly, and I received a *3-2-1 Contact*–branded optics exploration kit as a gift one Christmas. I clearly remember aligning the mirrors of a periscope and exploring color combinations with a spinning wheel.

Working as an optical engineer a few decades later, with the opportunity to contribute to such historic efforts as the *James Webb Space Telescope* currently scheduled to launch on Halloween of this year, I frequently think back to that influential kit and show. My sincere hope is that organizations such as PBS and Sesame Workshop continue to receive the funding necessary to inspire our future engineers and scientists.

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A note on dielectrophoresis

A story about dipole molecules in liquid (Physics Today, April 2020, page 17) has prompted me to share some of my own experiences.

When an electrically polarized object, like a dipole, is in a nonuniform electric field, it experiences a force. That phenomenon is known as dielectrophoresis. It is possible to create a field with constant, nonzero second derivative. A dipole particle in such a field would experience a constant force that can thus be made to move in a fixed direction under a constant force.

I created such a field in a shallow device I had made at glass manufacturer Owens-Illinois, my employer, and used yeast and blood cells to study it. The cells did not move unless the field had a frequency of at least 1 MHz. I did not try much higher frequencies. In 1975–76 I took my experiment to the hematology laboratory of Massachusetts General Hospital. Unfortunately, the hoped-for dispersion of velocities among cell types was not observed, and the study ended.

However, water molecules themselves have a dipole moment. When polarized light was passed vertically through the horizontal device, applying the 1 MHz field would switch the transparency on and off.

Apparently, the yeast or blood cells were passively carried along a current of water, driven by the nonuniform field. It is a mystery why there was no motion of the cells (yeast or blood) until the frequency was increased to 1 MHz. Perhaps clusters of water molecules, which are imagined to explain the high boiling point of water, are not dipoles, and the field at or above 1 MHz breaks up some of the aggregates, allowing the dipole moment of H^2O to be sensed.

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Chasing a power supply in Siberia

Arthur Liberman's Letter to the Editor on Cold War particle-physics collaborations (Physics Today, October 2020, page 12) reminded me of a visit I made in 1969 to Akademgorodok, a small research town near Novosibirsk, Siberia. At that time our Northeastern University research group had theoretically postulated, and done an initial experiment on, ρ–ω interference in the leptonic decay mode.[1] There were several interesting features to be experimentally or theoretically studied, and a flurry of work followed. We sought to do definitive experiments at the well-suited colliding-beams accelerator in Gersh Budker's research facilities in Akademgorodok.

During discussions with the facility's director, Veniamin Siderov, concerning the proposed experiments, we compared the structure of the Novosibirsk research group with that of the Northeastern group. The numbers that emerged gave significant insight to the hurdles faced by physics researchers in the Soviet Union.

Northeastern's high-energy research group consisted of five PhDs and seven support technicians. When I requested that Siderov provide comparable information about his facility, he replied that he had 2000 technicians. I assumed that he had misunderstood my question, but he actually did have that many technicians working for him. To help me understand the staggering difference, he described the procedure he would follow when he needed, for example, a power supply.

In the US one would simply go out and buy a power supply, but such devices were not available on the Soviet market, and Siderov had no access to hard currencies. He would have to set up a production line in a subgroup of his 2000 technicians, and they would produce perhaps 100 power supplies. He would then act as a vendor of the devices—for several years if need be—to support his technicians and make purchases of his own from other similar manufacturing centers. The amount of organization, energy, and manpower required to obtain a power supply was staggering.

I had come prepared to discuss the details of the proposed experiment, but Budker was already expert in the details of ρ–ω interference. Instead he wanted to discuss the proposed experimental setup—in particular, the number of photomultiplier tubes and power supplies. He agreed to make the accelerator available for the proposed experiment on one condition—that after completion of the measurements, the equipment would be left at his lab.

I carried that proposition back to my supporting agency, which had previously supplied support for Soviet experiments in the US. However, the arrangement was not approved; it amounted to the US paying for Soviet beam time while Soviet researchers got US beam time for free.

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How two planets likely acquired their backward orbits

It's challenging enough to figure out what exoplanetary systems look like today. Reconstructing their histories is more difficult still.

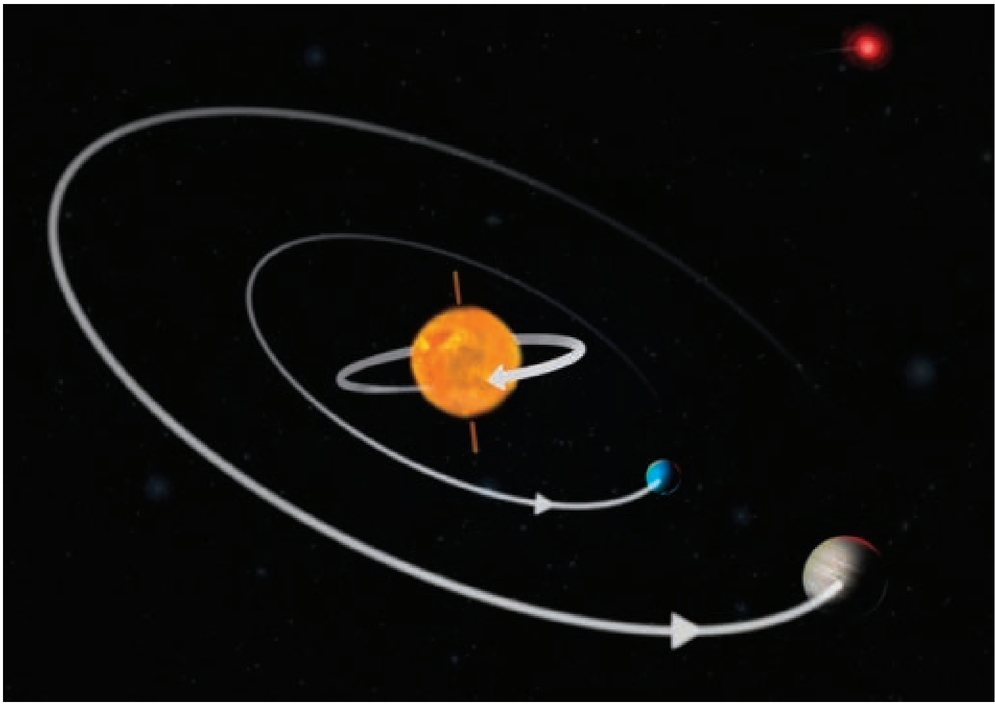

FIGURE 1. PLANETARY ORBITS in the K2-290 system are misaligned with their host star's spin, as illustrated in this artist's representation. The probable culprit is a companion red dwarf star, visible in the distance, whose gravitational influence disrupted the system before the planets emerged from the protoplanetary disk. (Image by Christoffer Grønne.)

All eight planets in our solar system orbit the Sun in the same direction, and none of their orbits lie more than a few degrees outside the Sun's equatorial plane. That alignment makes sense: All of the solar system's angular momentum came from the same place—the gravitational collapse of a much larger cloud of gas and dust—so it should all point in the same direction, right?

For most of scientific history, our solar system has been the only planetary system that astronomers could study. It was easy to assume that alignment must be inevitable. But over the past quarter century, as researchers have collected more and more observations of extrasolar planets, it's become clear that not all planetary systems are like our own. In particular, many exoplanets orbit in a different, or even opposite, direction to their host stars' spins.

Several theories have been proposed to explain those orbital misalignments, but testing them has been a challenge. Now, through their observations of the exoplanet system K2-290 (illustrated in figure 1), Simon Albrecht of Aarhus University in Denmark, his recent PhD student Maria Hjorth, and an international team of collaborators have found a tidy confirmation[1] of one mechanism[2] that was proposed in 2012: Because of the gravitational influence of an orbiting companion star, the protoplanetary disk is pulled out of alignment with the primary star's spin before the planets even form.

Observing orbits

Exoplanets are generally too faint to image directly. For the most part, their existence is known only through the effects they have on their host stars' light. If a planet has sufficient gravitational heft to pull its host star to and fro, it reveals itself through the periodic Doppler shifting of the star's spectral lines. That radial velocity method was responsible for most of the earliest exoplanet discoveries (see the article by Jonathan Lunine, Bruce Macintosh, and Stanton Peale, PHYSICS TODAY, May 2009, page 46), and it's most suitable for so-called hot Jupiters: giant gaseous planets that are so close to their host stars that they orbit every few days.

Most exoplanets discovered recently, on the other hand, are detected via the transit method—the periodic dimming of the host star by a planet passing directly across the line of sight (see PHYSICS TODAY, January 2014, page 10, and December 2019, page 17). That method, too, most readily detects hot Jupiters. But it's also suitable for spotting smaller, rocky planets with more Earthlike orbits.

With such indirect evidence of a planet's existence, it might seem impossible to learn anything about the direction of its orbit. But transit detections, in particular, reveal a wealth of subtle information. When a star spins on an axis that's not parallel to the line of sight, part of it moves toward Earth and part moves away; its light is thus partly blueshifted and partly redshifted. A planet transiting the star in the same direction as the spin blocks the blueshifted part first and the redshifted part second. For a planet orbiting in the opposite direction, the reverse is true.

That spectroscopic trick is called the Rossiter–McLaughlin effect, named after two astronomers who studied it in binary stars almost a century ago. Exoplanets block much less of their stars' light than other stars do, but with sophisticated enough instrumentation, their Rossiter–McLaughlin effect can also be detected.

The first exoplanets to be spectroscopically studied in that way were all hot Jupiters.[3] So when it came to light that

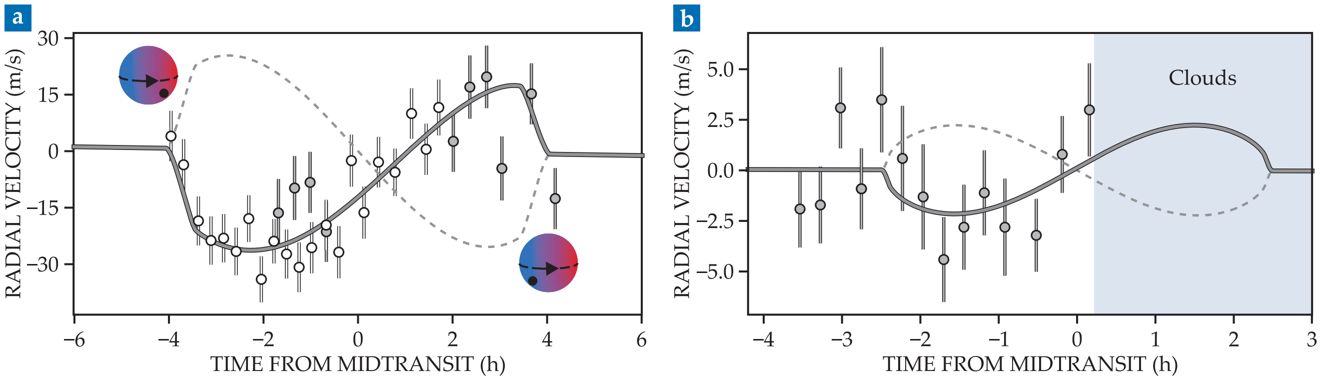

FIGURE 2. THE DIRECTION of a planet's orbit is revealed by the effective radial velocity—the redshift or blueshift—of the host star's spectral lines as the planet transits the star. **(a)** Two spectrographs recorded transits of the K2-290 system's larger planet (open and shaded circles). Both show redshifts followed by blueshifts, evidence that the planet orbits in the opposite direction of the star's spin. The solid curve is the best-fitting model, and the dashed curve is what would have been seen if the orbit and spin were aligned. **(b)** Only one transit of the smaller planet was recorded, and it was partially blocked by clouds. Still, that planet also appears to orbit backward. (Adapted from ref. 1.)

many of them were misaligned—by a few tens of degrees up to nearly a full 180°—researchers speculated that the mechanism responsible might be something specific to those planets' unusual sizes and orbits. "Hot Jupiters are already thought to be weird," says Princeton University's Josh Winn, a coauthor of the new paper, "because giant planets shouldn't be able to form so close to a star. So maybe the same process that put the planet there also tilted its orbit."

One theory is that the giant planets form in distant orbits—much like our own Jupiter—and then get kicked somehow into highly elliptical orbits.[4] Notably, the dynamical processes that can form such orbits can also amplify any small misalignment into a large one. As the Jupiters approach and retreat from their host stars, tidal forces pull the planets like taffy and dissipate their orbital energy as internal friction. As they lose energy, the planets settle into circular orbits close to, but misaligned from, their stars.

Finding misalignment

But the K2-290 system has no hot Jupiters. Its planets are a warm Jupiter, 11 times the diameter of Earth and with a period of 48 days, and a hot sub-Neptune, 3 times Earth's diameter and with a period of 9 days. The system also contains a red dwarf in a binary configuration with the primary star at a close enough separation to have influenced the planets' orbits.

"Most of the time, if there's a companion star, it's harder to detect and confirm the planetary system because the additional light complicates the search and confirmation of the planetary signal," says Albrecht. But the red dwarf in K2-290 is sufficiently faint and distant from its primary to stay out of the way most of the time. "So I pitched to Maria that we should study this system," he says.

Because both K2-290 planets transit the primary star, their orbital planes almost certainly coincide. (If they didn't, the intersection of the two planes would have to lie along the line of sight from Earth, which is unlikely.) But the researchers didn't yet know if the two planets orbit in the same direction, so they measured the Rossiter–McLaughlin effect for both.

For the larger planet, the measurement was straightforward. Many spectrographs around the world have the power to detect the subtle shifts in the stellar spectrum. The researchers observed two full transits of the planet with two different instruments: the High Accuracy Radial Velocity Planet Searcher–North in the Canary Islands and the High Dispersion Spectrograph in Hawaii. The data from both, plotted in figure 2a, clearly show the planet orbiting backward with respect to the star's spin.

The smaller planet posed a greater challenge. With less than 1/10 the cross-sectional area of the larger planet, it blocks much less of the star's light, and its effect on the spectrum is so slight that only a few instruments in the world can measure it. One of those is ESPRESSO, the Echelle Spectrograph for Rocky Exoplanets and Stable Spectroscopic Observations, which came online in 2018 at the Very Large Telescope in Chile. As the instrument's name suggests, it is designed for the study of small planets. Demand for observing time is high, but the researchers were able to fast-track an application to observe one transit of the smaller K2-290 planet.

"And it would have been great," says Albrecht, "except that clouds blocked the star for half of our observing time." Only with their precise knowledge of the orbital timing could the researchers conclude that the blueshift, shown in figure 2b, was from the first half of the transit, not the second, and that the smaller planet too was misaligned to the star's spin.

Resonance effect

The coplanar orbits rule out most proposed mechanisms, such as planet–planet scattering, that could have misaligned the system after the planets formed, because those processes would act differently on the two planets and give them different orbital planes.

But the discovery of the red dwarf companion allowed the researchers to test the postulated mechanism of primordial misalignment. As the planetary system is just beginning to coalesce, the theory goes, the protoplanetary disk is gravitationally torqued by both the binary companion star and the rotationally flattened primary star, and the disk in turn exerts a back-reaction torque on the star. The directions of those torques oscillate as the binary star orbits and the spin of the primary star precesses. As the disk disappears, the oscillation frequency due to the back-reaction torque slowly drifts.

When the frequencies come into resonance with one another, the two stars working together can tip the disk by a large angle in a short time. "The resonance can dramatically flip the disk even when the binary companion's orbit is only modestly misaligned with the primary star's spin," explains coauthor Rebekah Dawson of the Pennsylvania State University. "When you drive the system at just the right frequency, you get a big response."

Once the frequencies drift back out of resonance, the disk settles into a new orbital plane that's widely misaligned from its original plane. Although the companion star is still there, it's no longer as influential on the planetary alignment as it once was.

The researchers can't be sure of the system's original configuration, but they guessed several values for the initial disk–star orbital parameters, and they modeled each one. In every one of their simulations, the system found its way within a few million years to a configuration consistent with what is observed today. "There are lots of misaligned systems," says Dawson, "but in the others, we don't have such a smoking gun."

What's out there

The evidence from K2-290 doesn't mean that the primordial mechanism is responsible for all planetary misalignments. "There's probably more than one way to mess up a system," says Winn, "and we're just beginning to explore what's possible."

It's far too soon to tell what the most common misalignment mechanism is—or even how prevalent misaligned systems are. Exoplanet studies are still overwhelmingly dominated by the systems that are easiest to observe, whose formation and dynamics may not be representative of planetary systems in general. Hot Jupiters remain by far the easiest planets to study by any method, although powerful new spectrographs like ESPRESSO are starting to bring smaller planets under spectroscopic scrutiny. And multiplanet systems are rendered virtually invisible when the planets' orbits don't all lie in the same plane.

Still, the K2-290 observations pile on yet more evidence that planetary systems are diverse, and observations from our own well-studied solar system aren't necessarily universal or even typical. "We'd have developed a very different theory of solar-system formation," says Albrecht, "if, when Galileo looked at the Sun with his telescope, he'd seen the sunspots going the other way."

Johanna Miller

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A new look at the proton sea

The ensemble of particles that make up the proton manifests a puzzling asymmetry that continues to challenge theory and experiment alike.

Students of particle physics learn early that the proton is made of three quarks: two up and one down. But there must be more to the story than that. The proton's rest mass is 938 MeV. The three quarks, with masses of just a few MeV each, make up only a tiny fraction of that.

Where does the remaining mass come from? Much of it is the kinetic energy of the quarks—they're not at rest inside the proton, and special relativity dictates that their effective mass increases with speed. Most of the mass lies in the details of how the strong force holds the proton together.

Gluons, the carriers of the strong force, are themselves massless, but the energy of the gluon field contributes to the total proton mass. And the field can spawn fleeting pairs of quarks and antiquarks, known as the sea, as represented in figure 1.

At the energy scales encountered in everyday life, protons behave like self-contained particles, and the sea and the

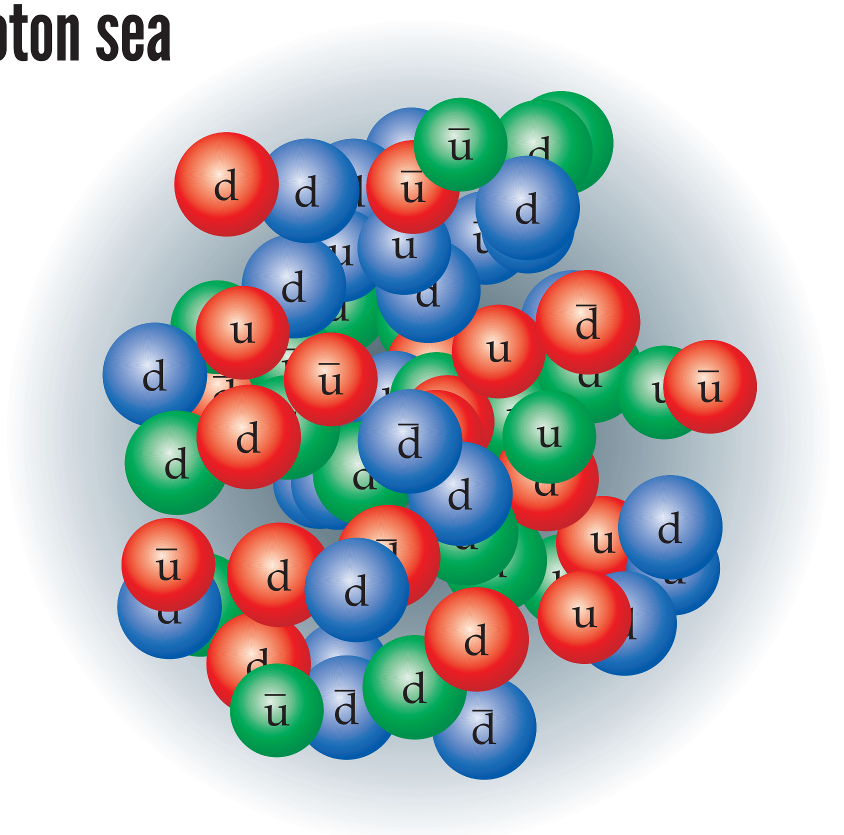

FIGURE 1. THE PROTON comprises not just two up quarks and a down quark but also a roiling sea of quark–antiquark pairs. The sea, which can't be accurately modeled by perturbative quantum chromodynamics, is an integral part of the proton's makeup and challenges theorists' understanding of how the strong force works. (Adapted by Donna Padian from an image by Paul Reimer.)

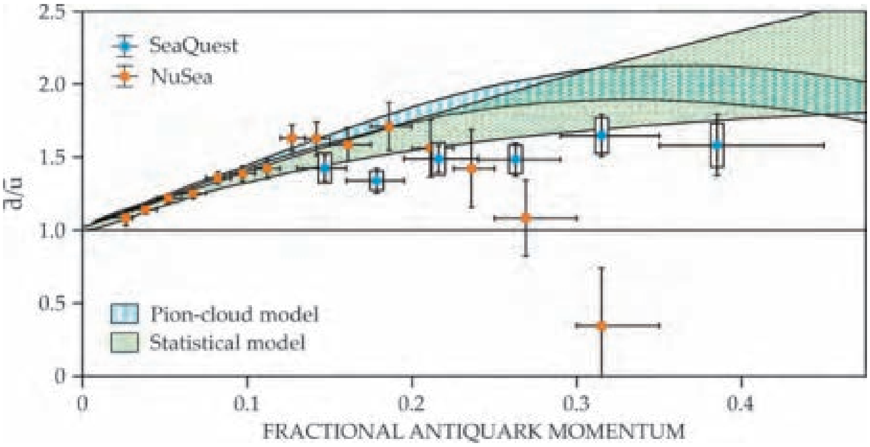

FIGURE 2. THE COMPOSITION of the proton's quark sea, characterized by the ratio between the numbers of down and up antiquarks, was probed 20 years ago by NuSea[2] and has now been further explored by SeaQuest.[1] The SeaQuest data, unlike the NuSea data, show a $\bar{d}/\bar{u}$ ratio that's always greater than 1, no matter what fraction of the proton's momentum an antiquark carries. That trend is a qualitatively better match to several theories, including the pion-cloud model[3] and a statistical model.[4] (Adapted from ref. 1.)

rest of their internal structure are mostly irrelevant. But at the high energies of particle accelerators, the reactions produced by a proton–proton collision really stem from collisions between the protons' component particles. Understanding the sea thus makes it possible to better predict what proton–proton colliders are capable of.

Now the SeaQuest experiment at Fermilab has released the results of the most thorough analysis of the sea to date.[1] The collaboration found that $\bar{d}$ antiquarks outnumber $\bar{u}$ antiquarks by about 50%. The result gives theorists a firmer foundation for their efforts to understand the inner workings of the proton, and it appears to help resolve a two-decade-old mystery left by the last experiment to study the sea.

Blow ye winds

The key to navigating the sea is to identify a particle reaction that could result only from sea quarks, not the original three valence quarks. In a collision between some combination of d and u quarks, there's no distinction between valence and sea quarks. But a collision that involves antiquarks must involve the sea. (Quarks of other flavors, such as strange and charm, also occasionally show up in the sea, but they're not SeaQuest's focus.)

One reaction for homing in on the sea antiquarks is the Drell–Yan process: In a pair of colliding protons, a quark from one annihilates with an antiquark from the other to produce a virtual photon, which promptly decays into a muon and antimuon.

An experiment to study the sea through the Drell–Yan process typically shoots a beam of high-energy protons into a stationary target made of liquid hydrogen; the muon–antimuon pairs keep traveling in the original direction of the beam, where they're then detected. That configuration is most sensitive to collisions involving antiquarks from the target and quarks from the beam, rather than the other way around. So by swapping between targets made of hydrogen and deuterium, the experimenters can measure the difference between the antiquark seas of the proton and the neutron—and thus, with some symmetry assumptions, the $\bar{d}/\bar{u}$ antiquark ratio for the proton.

Some 20 years ago, SeaQuest's intellectual precursor—NuSea, also at Fermilab—used that approach to study the sea.[2] The results, shown in orange in figure 2, left theorists a bit bewildered. NuSea found that, for the most part, down antiquarks outnumbered up antiquarks in the sea. But among those rare antiquarks that carried more than 30% of the proton's total momentum, the flavor imbalance reversed, and $\bar{u}$ outnumbered $\bar{d}$.

Across the line

That there should be any difference at all in the $\bar{d}$ and $\bar{u}$ numbers was initially a surprise. Gluon–quark interactions depend on energy and color—the strong force's analogue of electric charge—but not on flavor. Relative to the total energy available in the proton, the energy required to form a $u\bar{u}$ pair or a $d\bar{d}$ pair is nearly the same: The pairs should be produced in equal numbers. A more formal analysis using perturbative quantum chromodynamics, the simplest way of quantifying strong-force processes, gives the same answer.

To explain the $\bar{d}$ excess, theorists have developed more sophisticated models that incorporate additional phenomena. For example, Fermi statistics may play an outsized role: Quarks and antiquarks, being fermions, can't share quantum states with identical particles, so the presence of two up quarks in the proton already could significantly hinder the formation of a third.

Another idea, developed by Seattle University's Mary Alberg and the University of Washington's Gerald Miller, represents the sea quarks as a cloud of pions and other mesons that appear and disappear around the proton: At any given instant, the proton might really be a neutron (ddu) plus a positively charged pion ($u\bar{d}$)—or another proton (uud) plus a neutral pion (an equal superposition of $u\bar{u}$ and $d\bar{d}$). "This violates energy conservation," explains Alberg, "but it is allowed, for a fleeting moment, by the Heisenberg uncertainty principle." By adding up the contributions from all the possible channels, the theorists can model the composition of the sea.[3]

The theories can explain the overall $\bar{d}$ excess but not the $\bar{u}$ excess at high fractional momentum. There's no reason that Fermi statistics should ever favor the production of $u\bar{u}$ pairs over $d\bar{d}$ pairs. And the dominant $\bar{d}$ source in the pion-cloud model, the π^+–neutron channel, always dominates over any source of $\bar{u}$.

NuSea was unable to help resolve the mystery. Its $\bar{u}$ excess was seen only at the tail end of the data, and it wasn't possible to look any more closely. The experiment had been conducted on equipment that had been designed for another purpose, and it wasn't set up to capture the muon–antimuon pairs produced by antiquarks of high fractional momentum. As SeaQuest spokesperson Paul Reimer (who also worked on NuSea) puts it, "Just when the experiment was starting to show something interesting, it ran out of the ability to see anything."

Go to sea once more

Right away, the idea emerged for SeaQuest, a purpose-built experiment designed to detect events from high-fractional-momentum antiquarks, but the fruition of the project was long in coming. "The first proposal was in 1999," explains Reimer, "but Fermilab wasn't in a position to run the experiment at that time, so very little work was done until about 2009. The experiment was commissioned in 2012, and data collection ran from 2013 until 2017."

By then, Fermilab's Tevatron, whose 800 GeV proton beam supplied the protons for NuSea, had been shut down. SeaQuest's only option was to use the 120 GeV protons from the lab's main injector, which remains operational. But the energy reduction was actually an improvement: The Drell–Yan cross section is inversely related to the collision energy, whereas cross sections for various background processes are directly related to energy. Put all together, then, SeaQuest was almost 50 times as effective at studying sea quarks as NuSea was.

A major experimental challenge—and a big part of why SeaQuest's data analysis has taken so long—came from the fluctuating intensity of the main injector beam. To detect Drell–Yan events, researchers comb their data for muons and antimuons whose timing and speed indicate that they were produced in the same place at the same time. If too many protons arrive at the target at once, there's a chance that particles produced in separate reactions could look like they came from the same Drell–Yan event.

"We could have just thrown away all the data from when the beam intensity was too great," says Reimer, "but then we would have lost a lot of our statistics. So we had to find a way to deal with it and extrapolate down to what we would have seen at low intensity."

The results just released, shown in blue in figure 2, buck the NuSea trend and show a continued $\bar{d}$ excess at high fractional momentum. Although the data are qualitatively more consistent with the predictions of many models, including those shown in the figure in green and blue, it's not yet possible to say which theoretical explanation of the sea is most accurate.

Should the NuSea data thus be superseded by the more easily explained SeaQuest data? Reimer is hesitant to go that far. "We've found no reason to think that either data set is incorrect," he says. "All I can say is that the NuSea data are on the very edge of that experiment's acceptance, whereas SeaQuest was designed to study this region."

In search of more clues, SeaQuest is transforming into SpinQuest. The new experiment will study collisions of beam protons with spin-polarized targets, in the hope of better understanding how the proton gets its spin. The proton spin contains contributions from the spins of all the valence and sea quarks, all of their orbital angular momenta, and the gluons holding everything together. So why, with such an ever-fluctuating ensemble of components, is the proton's spin always ½?

Johanna Miller

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One frog species finds a solution to the cocktail party problem

A mechanism in the lungs of tree frogs helps filter incoming noise and other amphibian sounds from the calls of their own species.

When people attend large, noisy gatherings, hearing a conversation is often difficult. The so-called cocktail party problem also affects the green tree frog (pictured in figure 1) and other frogs in habitats teeming with the sounds of various animals and with anthropogenic sources of noise. Environmental background noise can reach volumes of 60–80 dB (relative to the standard sound-pressure-level reference), about the same amplitude as a vacuum cleaner. To be heard, tree frogs produce loud calls, often 100 dB in amplitude from 1 m away, an order of magnitude louder than the background noise.

Against the cacophony, frogs and other animals may, for example, incorrectly identify species-specific call patterns or struggle to locate sound sources. In exceptionally loud environments, other species abandon acoustic communication altogether and resort to visual cues, such as waving their legs. (For more about acoustic biology, see the article by Megan McKenna, PHYSICS TODAY, January 2020, page 28.)

If your goal is to study evolutionary adaptations that improve the signal-to-noise ratio of incoming acoustic information, frogs make interesting subjects. For about 200 million years, they've been

FIGURE 1. TREE FROGS, like the male pictured here, inflate their vocal sacs—the flexible membrane of skin below the mouth—to amplify their mating calls in noisy habitats. To hear those calls even better, members of the species reduce the volume of ambient noise by taking advantage of the anatomical connection between their lungs and tympanum, or eardrums, via the eustachian tubes and the glottis, shown in the inset. (Photo courtesy of Norman Lee; inset adapted from ref. 3.)

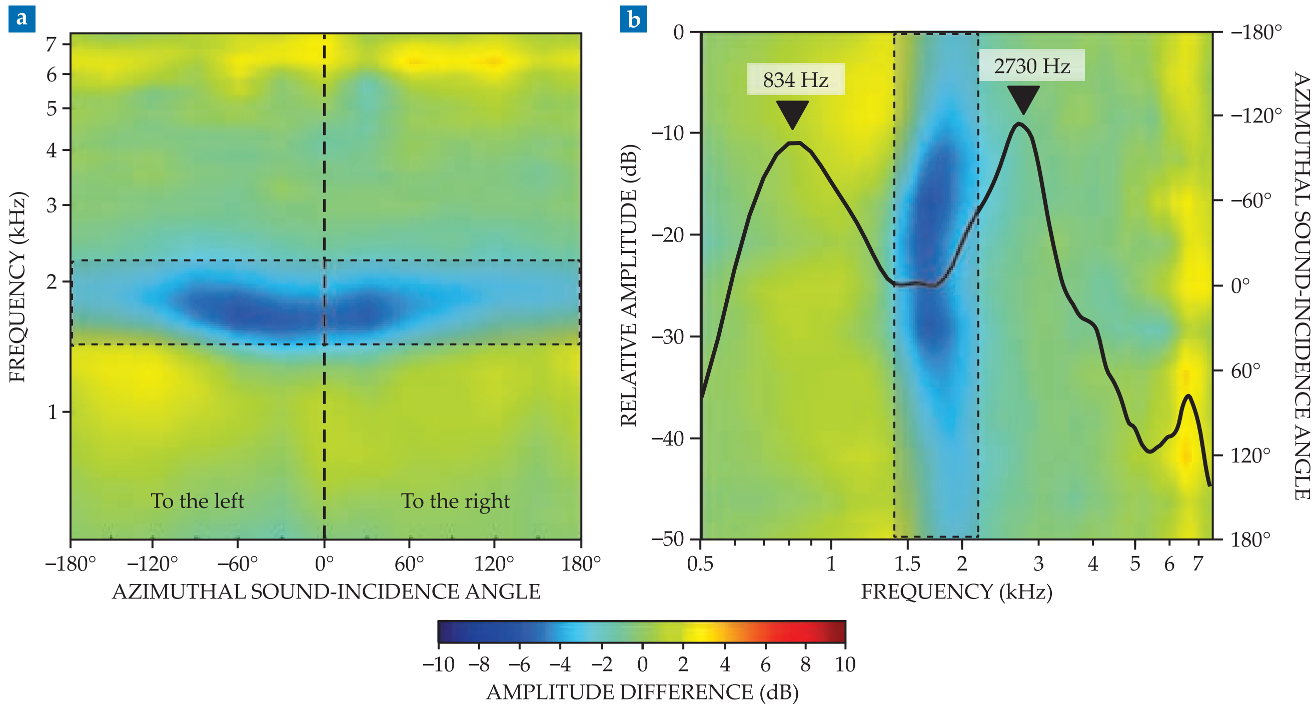

FIGURE 2. CANCELED NOISE. (a) Color variations show the average difference in amplitude of eardrum vibrations of 21 green tree frogs when their lungs are inflated and deflated. The vocalizations of several other frog species lie in the band (dashed region) where the greatest noise reduction occurred. **(b)** Superimposed on the rotated data from panel a are the mating calls of tree frogs (black line), which have average spectral peaks at 834 Hz and 2730 Hz. To better hear those calls, a lung-inflation evolutionary adaptation used by females enhances the spectral contrast between signal and noise by lowering the volume of the 1.4–2.2 kHz frequency band between the mating-call peaks. (Adapted from ref. 3.)

successfully vocalizing in noisy environments.[1] They and other amphibians have evolved a lung-to-ear sound-transmission pathway. The inset of figure 1 shows the airborne routes by which sound waves reach the internal surface of the tree frog's eardrum, or tympanum: directly through the eustachian tubes connected to the animal's mouth and the more meandering path from the lungs via the glottis opening.

Researchers have known about frogs' lung-to-ear anatomy for at least 30 years and have been studying how lungs may modulate the acoustic signals that reach the eardrum. Previous studies have shown that some frogs improve the directional sensitivity of a single eardrum at a select frequency range by inflating their lungs.[2]

Rather than solving the cocktail party problem by making their own calls louder than the background noise, at least one frog species is capable of improving their communication by reducing the volume of noise around them. Norman Lee of St Olaf College in Minnesota, Mark Bee of the University of Minnesota, and their colleagues have now found that when green tree frogs inflate their lungs, incoming acoustic signals from a biologically noisy frequency band are attenuated.[3] The practice enables female tree frogs with inflated lungs to better hear the mating calls of their male suitors.

Picking up vibrations

In previous studies, researchers sought to understand if the lungs could control sound-source localization in frogs. Most experiments explored how incoming sounds may affect the directional sensitivity of a single eardrum. Lee and his colleagues also wanted to study directionality and to tease out the contributions of sound impinging on the external and internal surfaces of a frog's ear. So they positioned a frequency-modulated acoustic stimulus at various locations around the frog and analyzed the amplitude of the resulting vibrations at the eardrum.

To measure whether having the lungs inflated affected the animal's ear vibrations, Lee and his colleagues used laser Doppler vibrometry. The method works by shining a laser on targets—in this case the frog's eardrum and the external body mass over the lungs—and then recording with a high-precision interferometer the frequency of the light that's scattered from the vibrating targets. The superposition of the incident laser and a reference laser beam aimed at a photodetector are then used to calculate the Doppler shift.

The results for a single eardrum showed that the lungs contributed a small improvement to the frog's directional hearing. But like humans and other vertebrates, frogs locate sources of sound by, among other ways, using the difference in loudness between the left and right ears (see the article by Bill Hartmann, Physics Today, November 1999, page 24).

When the data were analyzed from an organism-level perspective with two ears, the researchers found that the lung-inflation improvements in directionality at each eardrum canceled each other out. "That result was very striking," says Lee. "We thought if this lung input has nothing to do with improving directionality, then what might it be?"

Lowering the volume

To learn more, Lee and his colleagues analyzed the amplitude of the eardrum's vibrations at various frequencies and sound-incidence angles. "When we looked at the lungs' inflated and deflated states and took the difference, those plots really showed a pattern that was striking to us," says Lee. Figure 2a shows that difference: There's a pronounced loss in eardrum sensitivity between 1.4 kHz and 2.2 kHz. Rather than finding that the tree frogs used inflated lungs to amplify their own calls, the researchers found that the lung inflation reduces the volume of noise from other frog species.

An analysis of a data set of choruses of many species collected by the North American Amphibian Monitoring Program shows that many frogs use that frequency band for mating calls, even though the 1.4–2.2 kHz band is quite noisy. Figure 2b shows that the mating calls of green tree frogs have two local maximums in amplitude outside the range, at 834 Hz and 2730 Hz. Although the amplitude of the mating calls of green tree frogs peak on either side of the frequency range, the nearby noise makes finding a potential mate challenging.

That evolutionary pressure may have caused green tree frogs—and perhaps other frog species—to develop the noise-reducing adaptation. The inflated lungs of the tree frogs vibrate most strongly at the resonance frequency in the middle of the noisy 1.4–2.2 kHz band, which could help attenuate the noise there.

When comparing the new results with data from three other frog families that have a common 155-million-year-old ancestor, Lee and his colleagues found that all the frogs have a similar acoustic relationship: The lung resonance frequency is in a band that's bounded by mating-call spectral peaks on either side. Whether and how a frog's body size affects the usefulness of lung-mediated noise reduction remains to be answered.

Noise-canceling headphones

Lee and his colleagues have begun to investigate the mechanism behind the lung-inflation behavior with a generalized frog-physiology model. Amphibian ears have two sensory organs that process acoustic signals—the amphibian papilla and the basilar papilla. Each contains hair cells that mechanically transduce vibrations to electrical signals in auditory nerve fibers tuned to respond to specific frequencies. After simulating the frequency tuning of 161 individual fibers, the researchers found that the greatest reduction in eardrum sensitivity corresponds to the frequency range at which the amphibian and basilar papillae overlap.

The vibrations from the inflated lungs may decrease the response of the nerve fibers in that overlapped frequency range. Inflated lungs may also limit the possibility of two-tone rate suppression, in which sound in a particular frequency range can suppress auditory responses to sound at a lower frequency range. In tree frogs, sound energy from 1.4 kHz to 2.2 kHz can suppress the response of nerve fibers tuned to the mating calls heard at lower frequencies.

Lee and his colleagues aren't entirely sure yet of the precise relationship between the inflated lungs and the reduction of the eardrum response at a select frequency range, but they suspect it may be similar to the destructive interference used in noise-canceling headphones. The technology uses small microphones to record external ambient noise; signal processors then emit out-of-phase sound waves that destructively interfere with the incoming noise.

The researchers hypothesize that for tree frogs, the inflated lungs act analogously to the headphones' microphones. Then the phase of the acoustic signal is somehow modulated inside the body so that it arrives at the eardrum out of phase with the sound frequencies impinging on the frog's body. The situation is a bit more complicated because of another sound source, which arrives at the eardrum internally via the opposite ear, but the researchers are keen to figure it out. Lee says, "We think we can get at this question with a combination of additional laser measurements and modeling."

Alex Lopatka

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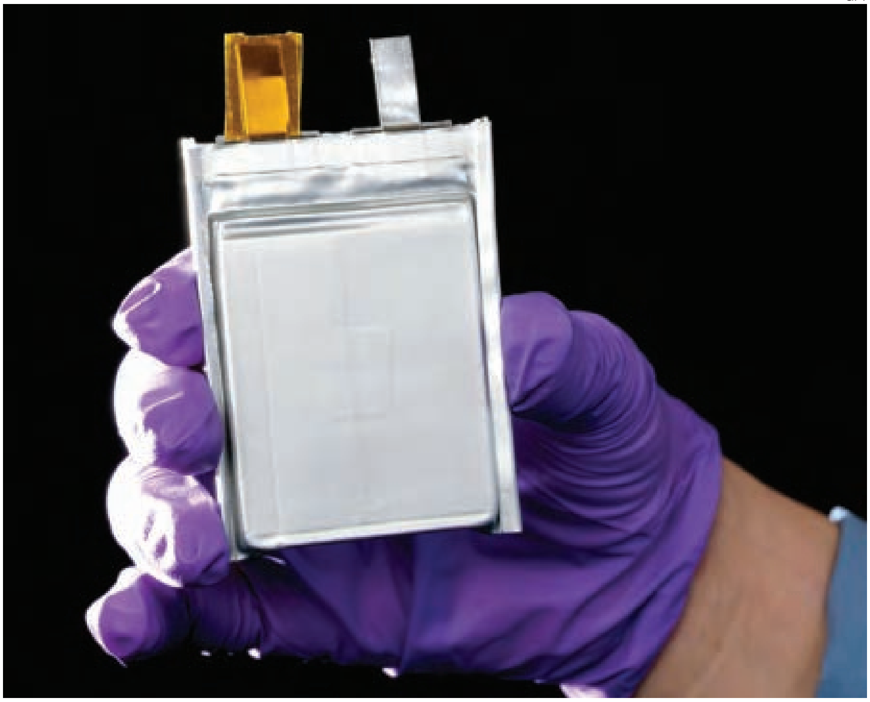
Fears of a lithium supply crunch may be overblown

Unexploited lithium deposits lie throughout the world, but investment in new mines is lagging.



GM

A PROTOTYPE lithium-metal battery developed by GM. In March 2021 the automaker announced a joint development agreement with SES, a lithium-metal battery startup.

As the world moves to decarbonize transportation and the Biden administration pushes for greater adoption of electric vehicles (EVs), an explosion in demand for lithium for EV batteries may outstrip existing and currently planned supply sources. New deposits around the world and new technologies to extract the light metal are likely to fill the gap, however, and it's possible that cobalt and nickel supplies will become a greater constraint on expanded EV battery production.

According to market analysis firm Benchmark Mineral Intelligence, a deficit of 26 000 tons in lithium supply will develop this year and will widen to 1.1 million tons by 2030. By then, global demand is expected to surge to more than five times today's levels, to 2.4 million tons of lithium carbonate equivalent (LCE), the industry's standard unit of production (see table, page 21). The World Bank last year provided a somewhat less bullish outlook for the light metal but said that a fivefold increase in lithium demand by 2050 will be necessary if the world is to limit global temperatures to 2 °C above their preindustrial level.

Benchmark product director Andrew Miller says the forecast shortage takes into account current mines and mining projects that are known to be in development. "However, lithium is not scarce, so the question is how quickly resources can be developed or accelerated to meet these requirements," he says.

Roderick Eggert, an economics professor at the Colorado School of Mines, agrees. "There is a significant amount of unused mining capacity, principally in Australia, that should allow growth in demand over the next few years to be met without a dramatic increase in price."

President Biden's $2 trillion jobs and infrastructure package, announced on 31 March, reserves $174 billion to stimulate the US market for EVs. The prodigious sum underscores the surge in demand that lies ahead for the lightest metal. Nearly all the growth in lithium consumption in the next decade will be attributable to EV batteries, Miller and others say. Some growth in demand for electric utility-scale storage batteries is expected during the latter part of the decade. In the longer term, other types of battery chemistry, such as flow batteries now in the R&D phase, will likely compete with lithium for large-scale storage applications where weight and size are less important.

Although specifics haven't been released, Biden's EV plan would seek to secure domestic automakers' supply chains, beginning with the raw materials, and to stimulate more EV battery manufacturing in the US. But Eggert says a better strategy would be to diversify US lithium sources globally. Self-sufficiency would be much more costly, he says. "It's less of an issue of will there be enough and more of an issue of will there be a diversity of sources brought into production in a time frame that matches the growth in demand."

Western Australia now supplies around 60% of the world's lithium from five mines containing an igneous rock known as spodumene. Most of the remaining global supply comes from salt flats in Argentina, Bolivia, and Chile, in the form of brines that contain high concentrations of the light metal. The brine is pumped up from the ground and put into manmade ponds, where the lithium salts are concentrated via evaporation. "There are a lot of undeveloped resources from both Australia and South America, and they will compete against one another," says Eggert.

The sole US mine, Nevada's Silver Peak, is a brine operation. Its owner, Albemarle Corp, recently announced plans to double production there. The

Lithium Market Balances
(Tons of lithium carbonate equivalent)

Market Balance (+Surplus / −Deficit)	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Demand	268 362	300 429	340 662	429 484	584 989	722 701	899 622	1 078 407	1 296 650	1 542 268	1 814 107	2 123 076	2 379 817
Supply	278 508	323 988	343 712	403 340	461 953	563 375	711 683	871 891	987 377	1 107 227	1 168 865	1 207 852	1 274 742
Market balance	10 146	23 559	3 050	−26 144	−123 035	−159 326	−187 939	−206 515	−309 274	−435 040	−645 242	−915 224	−1 105 075

LITHIUM DEMAND will begin to outstrip supply beginning this year and the imbalance will grow rapidly in the absence of further mine development, according to market analysis firm Benchmark Mineral Intelligence. (Figures may have rounding errors.)

amounts were not disclosed.

As with many other critical minerals, China has an outsized hand in the global lithium supply chain. In addition to the lithium mined domestically, China processes almost all Australian raw material to lithium carbonate and lithium hydroxide, the compounds used in the manufacture of cathodes for lithium-ion batteries. Three companies, Japan's Panasonic, South Korea's LG Chem, and China's Contemporary Amperex Technology Co Limited (CATL), produced around three-quarters of all EV batteries in 2020.

A diversity of new sources

The supply base for lithium is expected to diversify over the next decade, even as South American and Australian output increases. As of 2020, brine-based lithium sources were in various stages of development in Argentina, Bolivia, Chile, China, and the US, and mineral-based lithium sources were being developed in Africa, Australia, South America, Canada, and Europe, according to the US Geological Survey.

In addition, new mining techniques and types of deposits are expected to supplement traditional sources. Sedimentary clay deposits are being evaluated in the Southwest US, including at Thacker Pass in Nevada, the world's second-largest prospective new source, according to *MINE* magazine. Thacker's owner, Lithium Americas, estimates the holding could yield enough lithium to make 60 000 tons annually of LCE for 46 years. Australia's Hawkstone Mining, owner of the Big Sandy sedimentary clay prospect in Arizona, says its mine could produce 50 000 tons of LCE annually for 40 years. The mine could be operating by 2025, says Doug Pitts, Hawkstone's US general manager.

A sedimentary clay deposit in Sonora, Mexico, the world's largest lithium project in development, contains an estimated 4.5 million tons of LCE, according to *MINE*. Five of the world's other top 10 mining projects are in Western Australia. The other two are in Quebec and Zimbabwe.

Another potential new source of lithium is superheated brines brought up from deep underground in the production of geothermal energy. In the US, recent interest has focused on the shores of California's Salton Sea, where a handful of companies now operate geothermal plants. The California Energy Commission has awarded $16 million in grants over the past two years to explore the feasibility of piggybacking lithium extraction operations onto those facilities. One awardee, the renewables subsidiary Berkshire Hathaway Energy, operates 10 geothermal plants in the region, which is sometimes called Lithium Valley. If successful, the company says it could produce 90 000 tons of LCE per year—roughly one-quarter of current global demand.

Eggert says that the amounts of lithium from geothermal operations will be nontrivial, "but my impression is that these are dilute sources compared to conventional [mining]." The process hasn't been demonstrated at a commercial scale. What's more, geothermal energy and the extraction of lithium from brines raise environmental concerns, particularly given existing pollution in the Salton Sea. With the infrastructure already mostly built, however, geothermal brines have the potential to quickly become a significant supply source, Miller says. And, as with the clay deposits, geothermal is particularly attractive to US consumers who want to source their material locally.

Standard Lithium, of Vancouver, Canada, is developing a technology it claims can extract up to 90% of lithium from oil-field brines without the need for the evaporation ponds of the conventional evaporative process. The company plans to produce 21 000 tons of LCE per year using the byproduct of bromine production by the German company Lanxess in southern Arkansas.

In southern California, mining giant Rio Tinto's US Borax division is evaluating the recovery of lithium from wastes generated from past borate mining. The company reports its lithium–borate deposit in Serbia is a large undeveloped mineral resource with a potential for 50 000 tons of LCE a year. Spodumene has been mined in North Carolina in the past, and Piedmont Lithium and Albemarle Corp are considering restarting operations there.

Investors have been somewhat hesitant to commit to new mines due to doubts over the duration of the boom in lithium demand, says Eggert. New battery technologies could begin to supplant lithium ion in 15 years. Investors are reluctant to fund a production facility that will have a lifetime of several decades when the technology's future is uncertain beyond 20 years, he says.

Higher-value elements

Other components of the lithium battery are also facing a supply crunch. Surprisingly, the light metal accounts for just 4% by weight of the minerals used in a typical lithium ion cell. Graphite used in the anode accounts for more than half the total mass, and 19% is nickel. Most problematic, at 6%, is cobalt. Not only is it rare and expensive, but most of the world's supply is mined in the Democratic Republic of the Congo, where child labor and other human rights violations are endemic.

Manufacturers of EV batteries have been working to minimize or replace cobalt with different combinations of other transition metals, mainly nickel and manganese, says George Crabtree, director of the Joint Center for Energy Storage Research at Argonne National Laboratory. But some cobalt remains desirable to stabilize the cathode, improve battery life, and enhance EV performance. The cathodes of the first EVs, including Tesla's original Roadster, were made of lithium cobalt oxide, which contributed to the car's high cost.

Most of today's EV cathodes are lithium nickel manganese cobalt oxide, containing much smaller amounts of cobalt. Elon Musk recently reported that Tesla Model Threes sold in China are equipped with cobalt-free lithium iron phosphate cathodes. That chemistry has mostly been limited to power tools because of its lower energy density. (For a discussion of lithium-ion battery chemistry, see the article by Héctor D. Abruña, Yasuyuki Kiya, and Jay C. Henderson, PHYSICS TODAY, December 2008, page 43.)

Given its combination of high energy density and light weight, the lithium-ion battery is expected to dominate for at least the next decade. "Lithium ion is obviously the best battery we've ever had," says Crabtree. But the battery has evolved and will continue to do so. Recent advances suggest that some EVs could require as much as twice the lithium as today's versions. GM and Singapore-based SES, for example, are developing a solid lithium anode to replace graphite. The anticipated increase in energy density should enhance range and potentially reduce charging time, GM says. The partners will build a high-capacity manufacturing line in Woburn, Massachusetts, for a pre-production battery by 2023.

A LITHIUM BRINE operation at the Salinas Grandes salt flats in Argentina. Around 30% of the world supply of lithium is from South American brines.

QuantumScape, of San Jose, California, is developing lithium-metal batteries in partnership with Volkswagen. Their design would also eliminate the liquid organic electrolyte that is a feature of all current lithium-ion cells. A solid electrolyte would put an end to the infrequent battery fires caused by thermal runaway reactions.

Some research indicates that silicon graphite composites have a storage capacity about half to three-quarters that of pure lithium, says Crabtree.

Recycling not a factor

Limited recycling of lithium-ion batteries is under way, but the economics are not attractive enough for widespread adoption, says Jeff Spangenberger, group leader of materials recycling at Argonne. Recycling can be accomplished using pyrometallurgical or hydrometallurgical processes.

If recycling were to take hold, cobalt, not lithium, would be the driver, he says. The less cobalt contained in EV batteries, the less attractive are the economics of recycling them. With their high cobalt content, consumer electronics are much more valuable per given weight, but the challenge of collecting cellphones and laptops on a mass scale has stood in the way.

Nitash Balsara, a University of California, Berkeley, chemical engineer, says regulations may be necessary to stimulate recycling. That was the case with lead–acid batteries, nearly all of which have long been recycled. "We didn't know how to do that until we were forced to do it," he says. "It's important enough, and the time is now to develop the processes."

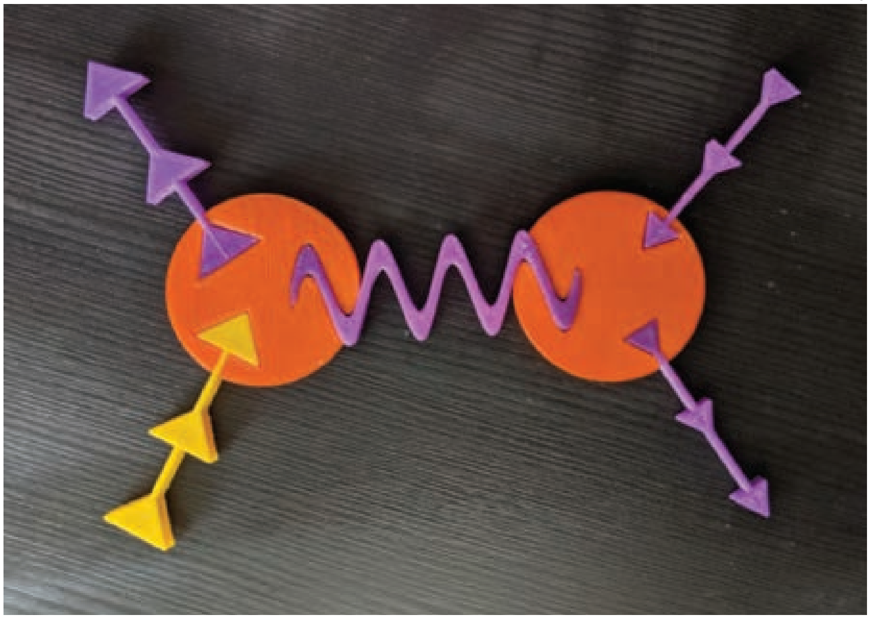
A Department of Energy–supported program known as the ReCell Center is developing direct recycling technology aimed at recovering, regenerating, and reusing lithium-ion battery components without melting them down or otherwise changing their chemical structure.

David Kramer

Hackathons catch on for creativity, education, and networking

Physics and astronomy communities take a page from data-science and tech worlds to hold events of feverish teamwork.

FLIP TANEDO



SNAP-TOGETHER, 3D-printed Feynman diagrams got their start in 2017 at a public Science Hack Day in San Francisco, where Flip Tanedo (assistant professor of theoretical physics at the University of California, Riverside), Matt Bellis (associate professor of physics at Siena College), and Willow Hagen (a graduate student at Carnegie Mellon University) made prototypes. In search of a teaching tool, the hackers were inspired by Tinkertoy.

In November 2019, 25 teams of students assembled at Argonne National Laboratory to take part in the CyberForce competition to defend and bolster energy infrastructure. An additional 79 teams met at nine other Department of Energy labs. The teams—consisting of four to six undergraduate and graduate students mostly in computer science and engineering—had eight hours to fend off cyberattacks by more experienced teams on simulated systems.

For DOE, the competition's aim is to build up the pipeline of future cybersecurity engineers for the energy industry. "It's wonderful to see the wow factor when things click for them," says Amanda Joyce, an Argonne cybersecurity expert who coordinates the annual competition. The lab has hired a handful of people through the event since it began five years ago.

David Hogg, a group leader for astronomical data at the Flatiron Institute and a physics professor at New York University, laments the typical format of scientific meetings: "All these amazing scientists from around the world are in the same location. But for most of the meeting, they sit quietly in their seats, not speaking to each other. That is the worst use of their time." Daniela Huppenkothen, an astronomer at the SRON Netherlands Institute for Space Research in Utrecht, shares that conviction. In 2014 she and Hogg joined some colleagues to launch Astro Hack Week. The annual five-day event brings 40–70 people together for tutorials and hacking. Scientists in other disciplines have created spin-offs, including Geo Hack Week and Neuro Hack Week.

At a well-run hackathon, says Huppenkothen, "there is a sense of energy and excitement. You take yourself out of your day-to-day routine and try to make progress on something else." Time scales are long in science, she continues. "The Astro Hack Week is very effective in reminding me of why science is exciting."

Hackathons come in many shapes and sizes, from traditional all-nighters to recurrent weekly gatherings. They can be run by civic groups, companies, or academic entities. The tasks may be focused or open-ended, and the balance of collaboration versus competition varies. Hacking events typically involve coding, but they can also focus on solving social problems, policymaking, or crafting. Nearly all consist of a burst of intense work on something outside the participants' usual activities. Common goals include working together, building community, and emerging with tangible outcomes. In the sciences, hackathons are often intentionally educational.

Pitch, hack, present

Many hackathons start with participants pitching ideas and perhaps stating their areas of expertise. The participants form teams and go to work; at the end, the teams present their results.

That's how the annual McGill University physics department hackathon works. The 24-hour event attracts high school and college students. The only restriction is that projects have to be related to the physical sciences, says Nicholas Vieira, a master's student in astronomy who led the organizing team for the department's virtual event last fall. The organizers provide suggestions, like "develop a tool that could be used to teach introductory physics" or "make something that proves the Earth is not flat." Mentors are important for the hackathon, he says. They help when people are struggling to come up with ideas or as they work.

"The ability to work in a team and use your imagination is probably more useful for later graduate studies—and work in any field, really—than cranking out assignments," says Vieira. Among the projects that have come out of past McGill physics hackathons are a program that takes both route and elevation into account to minimize fuel usage for driving in a city and a web app that lets the user play with a magnetic pendulum. For in-person events, says Vieira, the organizers reserve space and provide food, and people can stay and hack through the night. In 2019, 150 people participated. The 2020 event was virtual due to COVID-19 and attracted 200 competitors.

At MIT's second annual quantum computing hackathon earlier this year, companies D-Wave and IonQ made their quantum computers available and offered tutorials on their technologies. "We had more than 200 participants in 29 countries across 12 time zones," says Madison Sutula, an MIT doctoral student in electrical engineering and computer science and co-organizer of the event. "The purpose is to introduce people to developing and running code on real quantum hardware," she says.

Quantum computing is in its infancy, and events like the MIT hackathon "help grow the workforce and spark new lines of inquiry," says Matthew Keesan, vice president for product development at IonQ. "Getting to write code that shoots lasers at individual ions [with the IonQ quantum computer] is cool. It's exciting." Among the winning projects this year were several games and a program that generated a song. "Prizes can be fun," he says, "but the camaraderie of a hackathon is the real reward."

Thousands of Microsoft employees take part in the company's annual hack week. That's far too many for everyone to pitch and present in person. Instead, ideas and teams are assembled online in advance. "One year I did a throwaway fun thing, related to visualizing air traffic in augmented reality," says Jonathan Fay, a software engineer at the company. "The next year I did a project in computer vision that dramatically sped up key calculations. It was an algorithm that eliminated entire classifications of false matches." The algorithm was based on an insight he hadn't had time to pursue, and it led to cost savings for the company, he says.

When people do passion projects, or just have the opportunity to do something different, Fay says, "their ability to focus and explore and enjoy is enhanced. That can be really effective."

The benefits of departing from routine cut across all forms of hackathons. At the 2010 winter meeting of the American Astronomical Society (AAS), James Davenport noticed sticky notes and scribbles on whiteboards accumulating around the conference center. They were for the Hack Together Day being planned for the last day of the meeting.

EMMANUEL NGONGA

THE WINNING TEAM at the hybrid remote–on-site hackathon hosted last September by the University of Zambia used Twitter data to analyze whether people view COVID-19 as a hoax. From left, lecturer Habatwa Mweene, dean of natural sciences Onesmus Munyati, and the winning student team of Esther Mungalaba, Mudenda Sakala, Emmanuel Hansingo, and Clemens Chama.

"The guerrilla hype made it exciting and intriguing," he says.

The hack day itself was "transformative," says Davenport, who at the time was a second-year graduate student. "The mantra was 'do something, create something, learn something.'" People coded. But they also cut up their cloth posters and sewed tote bags and items of clothing. "The event had a radical bohemian attitude. For a graduate student, it was empowering," says Davenport, now a research assistant professor at the University of Washington and an organizer of the annual AAS Hack Together Day.

A close cousin of the hackathon is the sprint, where people dedicate several days to jointly explore data, such as from a particular mission or telescope. Ana Bonaca, a postdoc at the Center for Astrophysics | Harvard & Smithsonian, has been an organizer for sprints on data from *Gaia*, the European Space Agency observatory that is measuring precise positions and motions of nearly 2 billion stars. "The peer pressure and being held accountable is energizing," she says. Similar events have been organized around NASA's *Transiting Exoplanet Survey Satellite* and to prepare to analyze data related to dark matter and dark energy from the Vera C. Rubin Observatory.

At the Space Telescope Science Institute in Baltimore, Maryland, astronomer Erik Tollerud has co-organized a handful of in-house hackathons that paired software engineers with scientists to work on selected projects. "The scientists know what they want, and the engineers are better at writing and documenting code," says Tollerud. "The results were polished, published, and used."

Hacking for education

In the days leading up to Astro Hack Week every year, SRON's Huppenkothen has nightmares that no one stands up to pitch ideas. "But that never happens," she says. The event takes a broad approach to both topics and outcomes, and people end up working on apps, machine learning, websites, and more. The daily tutorials are largely guided by what the participants want to learn, and may involve data analysis techniques or machine learning. "Data science as a field is developing rapidly, and academia has been lagging," she says. "We use the tutorials and hacking as a vehicle to quickly expose people to new ideas."

Sergei Gleyzer, a high-energy experimentalist at the University of Alabama, has begun to incorporate hackathons into a machine learning class he teaches. "Each task has a science driver, and each emphasizes a different aspect of machine learning," he says. One task is to separate the Higgs boson signal from noise in simulated data from the Large Hadron Collider. Another is to predict the strength and shape of interactions between nuclear spins in an NMR spin-echo experiment. The problems are ones Gleyzer has posed in more traditional hackathons, but in the class setting students are given more time since they cannot free up their schedules just to hack.

Hackathons are a regular feature at LUT University in Lappeenranta, Finland, where students get course credit for them. As many as 10 hackathons a year are held, with participation ranging from 10 to 130 students. Usually they have a theme, often determined by local companies that "want to prepare a future workforce," says Jari Porras, a professor of software engineering. Recent hot topics have included remote-controlled industrial locks, game development, and optimization of waste collection.

In the course of a hackathon, Porras says, teams produce a proof of concept. Some of the ideas have been taken into production, and students have taken jobs with the sponsoring companies. The companies also hold hackathons for each other as a means to seek subcontractors. For students, though, "we get technology companies to sponsor a hackathon, and the students learn content we don't cover in traditional courses." Through hackathons, he adds, "we are teaching teamwork, pitching, and presenting—all important soft skills."

Nikhita Madhanpall is based in South Africa and runs educational hackathons for the Development in Africa with Radio Astronomy Big Data project. "The aim is to provide initial exposure to data science, with the hope to have an impact on socioeconomic development," says Madhanpall. The hackathons focus on health, agriculture, and astronomy. Tutorials are provided, and because the participants are mostly novices, the challenges are specific. "We use a new data set and participants have to be creative," she says.

In one event in Mozambique, the tutorial involved machine learning and image analysis related to Hurricane Maria, which devastated Puerto Rico in 2017. For the hacking part, participants put their new skills to use on satellite

IQUISE

MIT'S FIRST ANNUAL quantum computing hackathon in January 2020 drew 55 participants. This year, more than 900 people applied for 219 slots in the virtual event.

data to analyze flood effects from a local 2019 cyclone. For a 2020 hackathon, the University of Zambia hosted a mixed remote and on-site event. Participants got tutorials on how to gather, clean up, and use data from Twitter to perform sentiment analysis. They then were tasked with doing a Twitter-based project related to COVID-19.

"People in Africa are desperately hungry for knowledge about artificial intelligence and machine learning," says Madhanpall. "They know about it and they don't want to be left behind." The main motivations are the skills and learning, she says. "But the prizes are important to drive everyone to work hard." Past prizes, she says, have included hard drives, tablets, and subscriptions to online courses.

Diversifying tech fields

Siân Brooke is a fellow in computational social science at the London School of Economics and Political Science. For her PhD at Oxford University, she studied—and participated in—hackathons to explore how the culture of programming creates barriers to women entering tech fields. The hackathons were "dominated by young, socially awkward white men. They went to meet people like themselves," says Brooke. "That reinforces who goes into tech. Hackathons need to make a good effort to encourage diversity. They should have a code of conduct, and they should show that they enforce it."

Brooke dismisses the notion that emphasizing collaboration over competition is more attractive to female would-be participants. "We get chastised for being competitive," she says, "but given the opportunity, women are incredibly competitive."

The organizers of Astro Hack Week and some other events use algorithms to help select a diverse set of participants from the always large pool of applicants; last year Astro Hack Week was oversubscribed by nearly a factor of five. "We try to create a balance across discipline, geography, career stage, gender, and other categories," says Huppenkothen. Another measure to make hackathons more inclusive is avoiding all-nighters, which may be seen as unsafe for women, are inconvenient for people with families, and are unpleasant for many people.

Some organizers have experimented with all-female hackathons. Neale Pickett, a Los Alamos National Laboratory scientist involved in DOE cybersecurity hackathons, has organized events for high school girls. Madhanpall is planning an all-female competition in Africa, where typically the applicant and participant pools are 20–30% female, she says. And the teams on the mixed-gender hackathons cannot have a woman alone with men on a team because, she says, "from experience, women find it easier to voice opinions or contribute when there are at least two women."

Toni Feder PT

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Ernest Rutherford's AMBITIONS

Melinda Baldwin

One of the pioneers of radioactivity research, Rutherford feared his work would be overlooked—and changed his publishing strategies to make sure it wasn't.

At the turn of the 20th century, Ernest Rutherford (see figure 1) was a rising star in the fast-moving field of radioactivity physics. As a member of Cambridge University's storied Cavendish Laboratory in the 1890s, Rutherford had discovered alpha and beta radiation, coauthored papers with the legendary J. J. Thomson, and developed a reputation for designing simple yet ingenious experiments. In 1898, at age 27, he left the Cavendish for a professorship at McGill University in Montreal. Rutherford continued his remarkable record in Canada, churning out paper after paper that explored different types of emissions from radioactive elements.

Yet a March 1901 letter from Rutherford to his mentor Thomson reveals that Rutherford was deeply dissatisfied with the state of his career—and particularly unhappy with the location of his job. In the early 20th century, the most important physics laboratories in the world were concentrated in Europe; by comparison, North American institutions were scrappy upstarts at best and irrelevant backwaters at worst. Rutherford felt isolated and frustrated by his distance from the centers of the physics world. "After the years in the Cavendish I feel myself rather out of things scientific, and greatly miss the opportunities of meeting men interested in Physics," he told Thomson. "I think that this feeling of isolation is the great drawback to colonial appointments."[1] He asked Thomson to let him know if any professorships were likely to open up in the UK. But Thomson had no positions to recommend; a move seemed unlikely.

Rutherford's distance from other major physics laboratories was especially worrisome given how competitive radioactivity research was in the early 1900s. Other researchers were working on the same questions as Rutherford, and he worried that his work would be ignored or overlooked

The Cavendish Laboratory at Cambridge University.
(Image from Bjanka Kadic/Alamy Stock Photo.)

because of his separation from the European physics community. To avoid that fate, Rutherford revamped his publishing strategies. He began looking for ways to ensure that his discoveries would get into print faster than those of rival scientists and be seen by colleagues in Europe. Rutherford's efforts not only secured his future in the field, they also shaped the rise of one of the 20th century's most influential scientific journals, *Nature*.

Rutherford's training

Born on 30 August 1871 on New Zealand's South Island, Rutherford was the fourth child of James, a Scottish-born wheelwright, and Martha, an English-born schoolteacher. They brought their children up in a relatively remote area, but they took pains to ensure that their children received a good education. Rutherford quickly distinguished himself as a talented student with a gift for physics and mathematics. In 1894, after earning his BSc from New Zealand's Canterbury College (now the University of Canterbury), Rutherford applied for and won an 1851 Exhibition Scholarship from the British Crown. Awarded to support doctoral and postdoctoral work, the scholarships were some of the most prestigious in the UK. Rutherford happened to graduate in the first year the competition was open to students born in the colonies.[2] He chose to continue his work in physics at the Cavendish Laboratory under the supervision of Thomson, who was known for his work on cathode rays.

Thomson took a special interest in Rutherford. He and his wife, Rose, looked for potential lodgings on Rutherford's behalf before his arrival. Once Rutherford reached Cambridge, Thomson took care to introduce the young New Zealander to longtime residents and fellow newcomers. He was intrigued by Rutherford's scientific work and offered him support and advice on his experiments. In a letter home to his parents, Rutherford wrote that "I admire Thomson quite as much as I thought I would, which is saying a great deal."[3]

Despite Thomson's congeniality, Rutherford did not find his laboratory entirely welcoming. The Englishmen working at the Cavendish treated Rutherford as an outsider and an interloper. In his letters home, Rutherford complained that he was ostracized and mocked by his colleagues, and that they attempted to place obstacles in his way, such as preventing him from using the laboratory's equipment. Rutherford also struggled with the distance from his fiancée, Mary Newton, who was still living in New Zealand.

Nevertheless, Rutherford quickly made his scientific mark studying the transmission and detection of radio waves. He had developed a novel radio-wave detector back in New Zealand and brought it with him to Cambridge. After only six months, he prepared a paper on the subject for the Royal Society of London. Meanwhile, Thomson grew more and more impressed with his protégé's talent and promoted Rutherford's work to his colleagues in the physics world. Even though Rutherford initially faced a chilly welcome from fellow junior colleagues, his talents and Thomson's mentorship soon helped him find a place in the UK's physics community.

Röntgen rays and radioactivity

Rutherford's time at the Cavendish coincided with a remarkable period of discovery in the physics world. In 1895 physicist Wilhelm Conrad Röntgen noticed an interesting phenomenon while experimenting with a vacuum discharge tube: When he placed his hand between the tube and a screen coated with barium platinocyanide, the darkened image of the bones in his hand appeared on the screen. It quickly became apparent that Röntgen had discovered a new kind of wave, and "Röntgen rays" became a scientific and popular sensation. Most Anglophone scientists eventually adopted Röntgen's preferred name for his discovery, "x rays."

FIGURE 1. A PORTRAIT of Ernest Rutherford in 1908. (Courtesy of the Library of Congress, Prints and Photographs Division, George Grantham Bain Collection, LC-B2-707-6.)

One of the many scientists inspired to study Röntgen's new phenomenon was Henri Becquerel, a professor at the prestigious École Polytechnique in Paris. Becquerel was interested in whether naturally phosphorescent minerals also produced x rays or emitted other unknown rays. In March 1896 he reported an unusual finding to the French Academy of Sciences: One night, he placed uranyl potassium sulfate in a drawer with wrapped photographic plates, and by the next morning, a silhouetted image of the salts was visible on them. Subsequent experiments revealed that the salts developed photographic plates even when the salts had not been exposed to sunlight—meaning that the production of what Becquerel termed "uranium rays" was not linked to the salt's phosphorescence.

The new discoveries sparked Rutherford's scientific imagi-

FIGURE 2. ORIGINAL ENTRANCE to the Macdonald Physics Building (now the Macdonald-Stewart Library Building) at McGill University. (Photo by Selbymay/Wikimedia Commons/CC BY-SA 3.0.)

nation. He and Thomson collaborated on an influential paper, "On the passage of electricity through gases exposed to Röntgen rays," published in 1896 in the British monthly journal *Philosophical Magazine*. However, it was Becquerel's discovery that most intrigued Rutherford, and he turned his attention to studying the mysterious emanations from uranium salts.

Although Becquerel's discovery attracted far less immediate interest than Röntgen's, Rutherford was not the only physicist who saw the emanations' potential. Marie Skłodowska Curie, working in her husband Pierre's laboratory at the École Municipale de Physique et de Chimie Industrielles in Paris, took up the study of Becquerel's uranium rays. She soon discovered that several materials—most famously, pitchblende—also emitted uranium rays. Curie adopted the term "radioactivity" instead of uranium rays to describe the phenomenon she was studying. In 1898 the Curies and chemist Gustave Bémont announced the discovery of two new elements, polonium (named for Marie Curie's native Poland) and radium, both of which were hundreds of times more radioactive than uranium.

Rutherford's "colonial appointment"

Discovery after discovery flowed from the Curies' Paris lab, and Rutherford soon had one of his own to add. In 1898 he demonstrated the existence of two distinct types of uranium rays, which he called "alpha" and "beta." Alpha rays were positively charged and readily absorbed by most substances, but beta rays were negatively charged and could pass through metal unhindered. His experiment was elegant in its simplicity: He covered a piece of uranium with an increasing number of thin aluminum sheets and measured the uranium's ability to ionize gas after each successive layer was added. The positively charged alpha rays could not pass through more than 3 layers of foil, but beta rays were able to ionize gas through more than 12.

That same year, Rutherford was hired as a professor of physics at McGill. The appointment came as something of a surprise. Despite Thomson's enthusiastic recommendation, Rutherford knew there would be fierce competition for the job and was uncertain of his chances. McGill had one of the best-equipped research laboratories in the world, the Macdonald Physics Building (see figures 2 and 3), which received international attention when it opened in 1893 for its architecture, enviable library, expensive collection of experimental equipment, and the generous endowment of Can$150 000 meant to pay for the building's maintenance.[4] "There would probably be big competition for it, all over England," he wrote to Newton on 22 April 1898. "I think it is extremely doubtful that I will compete for it."[5]

But McGill chose Rutherford, and for the second time in his young life, he packed up his belongings and moved to a new continent. Rutherford quickly resumed his work on radioactivity with the help of two significant collaborators: Harriet Brooks, his first graduate student, and chemist Frederick Soddy, who joined him at McGill from Oxford University in 1900. Rutherford and Brooks began investigating the particles and rays being emitted by radioactive elements.[6]

Building on that work, Rutherford and Soddy in 1903 published a paper showing that radioactivity was the result of atomic disintegration. Old-guard physicists such as Lord Kelvin had dismissed the idea that radioactivity could change one element into another and said it was no better than alchemy. But Rutherford and Soddy convinced all but the most determined naysayers that radioactive atoms did indeed change their elemental identity after releasing alpha, beta, and gamma rays. They used the Macdonald Building's liquid-air machine—a state-of-the-art piece of equipment available to only a handful of laboratories at the time—to cool the emanations from radium and thorium into liquids. As Rutherford and Soddy demonstrated, the liquefied emanations had different elemental identities from radium and thorium. That work earned Rutherford and Soddy each a Nobel Prize in Chemistry: Rutherford in 1908 and Soddy in 1921.

The major disadvantage of Rutherford's job at McGill was its location. Although he found productive collaborators in Soddy and Brooks, the young physicist felt far from the centers of the physics universe. All the expensive equipment in the world was not enough to replace the sense of intellectual community he had experienced at the Cavendish—and soon both

Brooks and Soddy left Montreal for the UK. Rutherford arranged for his protégé Brooks to take a fellowship at the Cavendish Laboratory in 1901, which reflected his belief that a physicist had to work in the UK or Europe to truly matter in physics. Brooks did return to Montreal in 1903, but by that time Soddy had left for a position at University College London.

Intellectual isolation was not the only perceived drawback of Rutherford's "colonial appointment"—he also feared being beaten to the punch by the Curies. He didn't want to be just another physicist trailing the Parisian couple in the quest to learn about radioactivity; he wanted to be in the lead. A letter Rutherford wrote to his mother reveals both his competitive spirit and his desire to publish his work quickly: "I have to keep going as there are always people on my track. I have to publish my present work as rapidly as possible in order to keep in the race. The best sprinters in this road of investigation are Becquerel and the Curies in Paris who have done a great deal of very important work in the subject of radioactive bodies during the last few years."[7]

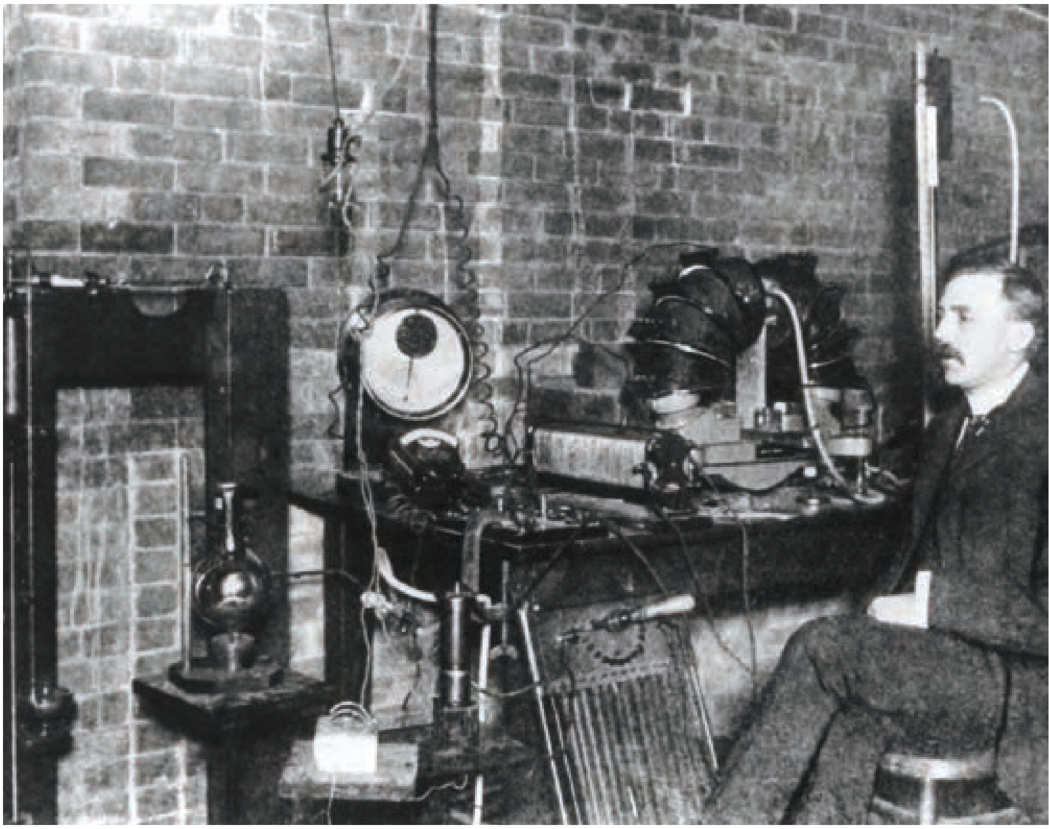

FIGURE 3. ERNEST RUTHERFORD in his laboratory in the Macdonald Physics Building at McGill University, 1905. (Courtesy of McGill University, Rutherford Museum, the AIP Emilio Segrè Visual Archives.)

But taking the lead in a scientific race with "sprinters" like Becquerel and the Curies was difficult, and Rutherford often found himself falling behind. In November 1899, for example, he was preparing a paper for *Philosophical Magazine* outlining how radioactive thorium could induce radioactivity in other substances, a phenomenon he called "excited radioactivity." But the Curies had been working on the same phenomenon, and their work reached print first. When Rutherford's paper appeared in the February 1900 issue of *Philosophical Magazine*, it ended with a morose footnote acknowledging that the Parisians had been first to publish: "As this paper was passing through the press the *Comptes Rendus* of Nov. 6th was received, which contains a paper by Curie and a note by Becquerel on the radiation excited in bodies by radium and polonium."[8]

Being scooped was a blow to both Rutherford's career ambitions and his ego. He placed much of the blame on his location. Because he was far from where the most widely read physics journals were published, Rutherford often had to wait a month or more for his articles to cross the Atlantic Ocean and reach the editorial offices and then another month or more for those journals to send back page proofs. Those delays added up. His early work with Brooks, for example, was conducted in 1899–1900 but did not make it into print until 1902. When competing against "sprinters" like Becquerel and the Curies, who could get their manuscripts to the top-tier *Comptes Rendus de l'Académie des Sciences* in a matter of days, that simply would not do. Rutherford began searching for a way to get his work into print as quickly as possible, and he soon set his sights on one of the UK's most widely read scientific periodicals: the weekly magazine *Nature*.

Rutherford and *Nature*

In 1900 *Nature* (see figure 4) was just over 30 years old and still under the editorship of its founder, astronomer Norman Lockyer. In its first decades of existence, *Nature* had made its mark as a host for scientific disputes. The magazine's weekly publication schedule—and the speed of the 19th-century Royal Mail—made *Nature*'s Letters to the Editor column an ideal platform for arguments between scientists. British readers intrigued by a discussion in that week's *Nature* could dash off a letter, mail it to *Nature*'s London offices, and expect to see their response in print the following week. In the late 19th century, the section was filled with discussions and debates about scientific issues ranging from the age of Earth to the latest evolutionary theories.

The explosion of interest in x rays inspired *Nature*'s readers to use the column for a new purpose: the announcement of exciting new research results. Specialist weeklies like *Nature* and its competitors *The Electrician* and *Chemical News* were able to capitalize on the intense interest in Röntgen's discovery because of their publication speed. They offered researchers a forum where preliminary observations and theories about the nature of the rays could reach an audience of scientific specialists within a week of submission and thus minimize the chances that other researchers would beat them to the punch. *Nature*'s pages were soon filled with letters from physicists who had

FIGURE 4. TITLE PAGE of an issue of *Nature* from 1896, during the age of early radioactivity research. (Courtesy of the Wenner Collection, AIP Niels Bohr Library and Archives.)

tried something new with x rays and wanted to report their findings. Most famously, *Nature* printed the first English translation of Röntgen's paper and the first x-ray photograph taken in England.[9]

Prior to being scooped by the Curies in 1899, Rutherford had not contributed to *Nature*, perhaps because he had focused on publishing lengthy papers in prestigious venues such as the Royal Society's journals. That would soon change. Rutherford contributed more than a dozen short letters to *Nature* between 1901 and 1908 on subjects such as the heating effects of radioactivity, the amount of helium emanating from radium, the dependence of radioactivity on the concentration of radioactive materials, and the electrical charge on the alpha rays emitted from radium. He continued directing papers to *Philosophical Magazine* and *Proceedings of the Royal Society of London* as well, but he saved those publications for longer write-ups of his best work. Promising preliminary results were sent to *Nature* to prevent the kind of disappointment he had experienced with excited radioactivity.

Interestingly, Rutherford's desire to publish quickly did not lead him to seek out other weeklies besides *Nature*. He and Soddy coauthored a multipart article on thorium emanations[10] for *Chemical News* in 1902, but after Soddy left McGill, Rutherford ceased to contribute articles to that journal, and he never became a regular contributor to *The Electrician*. That choice seems to have stemmed from Rutherford's strong sense of himself as a physicist. *Chemical News* catered to Britain's chemists; *The Electrician* aimed itself at an audience of engineers and industrial scientists. But Rutherford always considered himself a physicist, not an engineer or chemist. He was famously baffled when he received the Nobel Prize in Chemistry rather than his preferred discipline.

North American journals did not play a large role in Rutherford's publishing strategy. He did not send his work to the US weekly *Science*, which had a correspondence column like *Nature*'s and whose New York editorial offices were closer to Montreal than *Nature*'s London offices. He seems to have rejected the idea of publishing in Canadian journals, and he never attempted to fight the Curies on their own turf by publishing in France.

Rutherford's Britain-focused publishing strategy suggests that in addition to concerns about priority, he sought to reach a specific national audience. Publishing in British journals retained the advantage of publishing in Rutherford's native language, English, and it also increased the likelihood that his work would be noticed by British physicists seeking a new colleague. Notably, Rutherford turned down offers of physics professorships from Victoria University College in New Zealand, the University of Western Australia, and Columbia University in New York, indicating that his goal was not simply to leave McGill but to move back to the UK.[11]

Rutherford's choice of *Nature* shaped not only his professional trajectory but *Nature* itself. The practice of publishing quickly to secure priority was not new to science; the *Comptes Rendus*, for instance, had long been a place where French scientists could get their work into print quickly. But *Nature* was not a major site for priority claims until x rays and radioactivity. Furthermore, Rutherford's frequent contributions took *Nature* from a journal that had been only peripheral to the world of radioactivity—little was in it about the Curies and their work, for example—to a publication that was required reading for anyone working on the topic.

Rutherford's contributions also helped expand *Nature*'s international influence. In the 19th century, it was a journal by and for members of the British scientific community; it found a small audience in the US but had few subscribers in European scientific centers. Its contributors were almost entirely British. By 1910, however, physicists worldwide were reading *Nature* and sending their work to the journal. In the correspondence between Rutherford and US physicist Bertram Borden Boltwood, for example, both men frequently mentioned *Nature* as a place to print their own articles and an important source of information about others' research.

Boltwood was arguably the most important radioactivity physicist in the US at that time, and like Rutherford, he struggled with the disadvantages of being at a distance from major research centers like Paris and Cambridge. *Nature* proved invaluable as a source of pertinent abstracts and as a place to publish his work. He had a habit of sending preliminary results both to US journals and to *Nature*, as he mentioned in a 1906 letter to Rutherford: "I have sent off a brief communication to the Editor of Nature and a note for the December number of the Am. Jour. [*American Journal of Science*]."[12] Rutherford's letters also refer to sending early results to *Nature*; in October 1906 he wrote, "I have done a few expts. [experiments] recently which show that the emanations are completely absorbed in cocoanut [*sic*] charcoal at ordinary temperatures. . . . You will see an account in Nature of the same in a week or so."[13]

Other international radioactivity scientists followed Rutherford and Boltwood into the pages of *Nature*. The most notable among them was Otto Hahn, a future Nobel Prize recipient (for the discovery of uranium fission), who worked at McGill with Rutherford in 1905–6. Like Rutherford and other Anglophone colleagues, Hahn soon adopted the practice of writing to *Nature* about interesting preliminary results.

FIGURE 5. CAVENDISH LABORATORY group photo from 1934, including James Chadwick (front row, third from left), J. J. Thomson (front row, sixth from left), and Ernest Rutherford (front row, seventh from left). Photograph by Hills and Saunders, Cambridge. (Courtesy of Cavendish Laboratory, Cambridge University, the AIP Emilio Segrè Visual Archives, Bainbridge Collection.)

Rutherford's ambitions realized

Rutherford's publishing strategy paid off. In December 1906 he wrote to his mother to tell her that he had been offered a position in the UK: "I have received the offer of the Physics Chair at Manchester. I think it quite likely I shall accept. I think it is a wise move for a variety of reasons. I shall receive a better salary and be director of the laboratory and what is most important to me, will be nearer the centre of things scientifically."[14]

At the University of Manchester, Rutherford resumed his work on alpha particles, hoping to find a way to determine if they were composed of helium or hydrogen atoms. In 1908 he successfully trapped enough alpha particles to analyze them spectroscopically; the spectrum showed that they were indeed helium atoms, as Rutherford had long suspected. In 1908–9, Rutherford collaborated with his visiting colleague Hans Geiger and an undergraduate named Ernest Marsden to aim a stream of alpha particles at a metal foil. To their surprise, a small percentage of the particles deflected back at them rather than passing easily through the foil as they had expected. That finding led to a revolution in atomic theory. Thomson's old "plum pudding" model of the atom, which depicted positive and negative charge spread evenly throughout it like raisins in a dessert, was soon replaced with the nuclear model of the atom, in which positive charge was concentrated in a dense center.

Rutherford continued serving as a mentor to young physicists while at Manchester. He tried to persuade Brooks to come to the UK with him, but she decided to remain in Montreal after marrying in 1907. His protégés at Manchester included many notable physicists, among them Henry Moseley, who discovered that each element has a characteristic atomic number; James Chadwick, who discovered the neutron; and Niels Bohr, who revolutionized atomic theory and became one of the most influential figures in quantum physics.

In 1919, after the end of World War I, Rutherford received an even more desirable offer: To return to the Cavendish Laboratory as its new director (see figure 5). He brought Chadwick with him, and the pair studied radioactive disintegration in the 1920s. Despite his deep knowledge of radioactive decay and atomic structures, Rutherford famously dismissed as a pipe dream the idea of splitting the atom. He did not live to see Hahn, Fritz Straßmann, and Lise Meitner prove him wrong; in 1937 he died unexpectedly following surgery for hernia complications.

Rutherford left behind an impressive legacy. His work on radioactivity and atomic structure helped revolutionize the way physicists understood the world, and he mentored some of the 20th century's most influential members of the field. Rutherford also shaped the landscape of scientific publishing. Following his example, scientists from diverse disciplines across the world adopted the practice of announcing exciting results in a letter to the editor in *Nature*.[15] The British weekly might not have become one of the world's most sought-after publications had it not been for Rutherford and his dream of returning to the UK.

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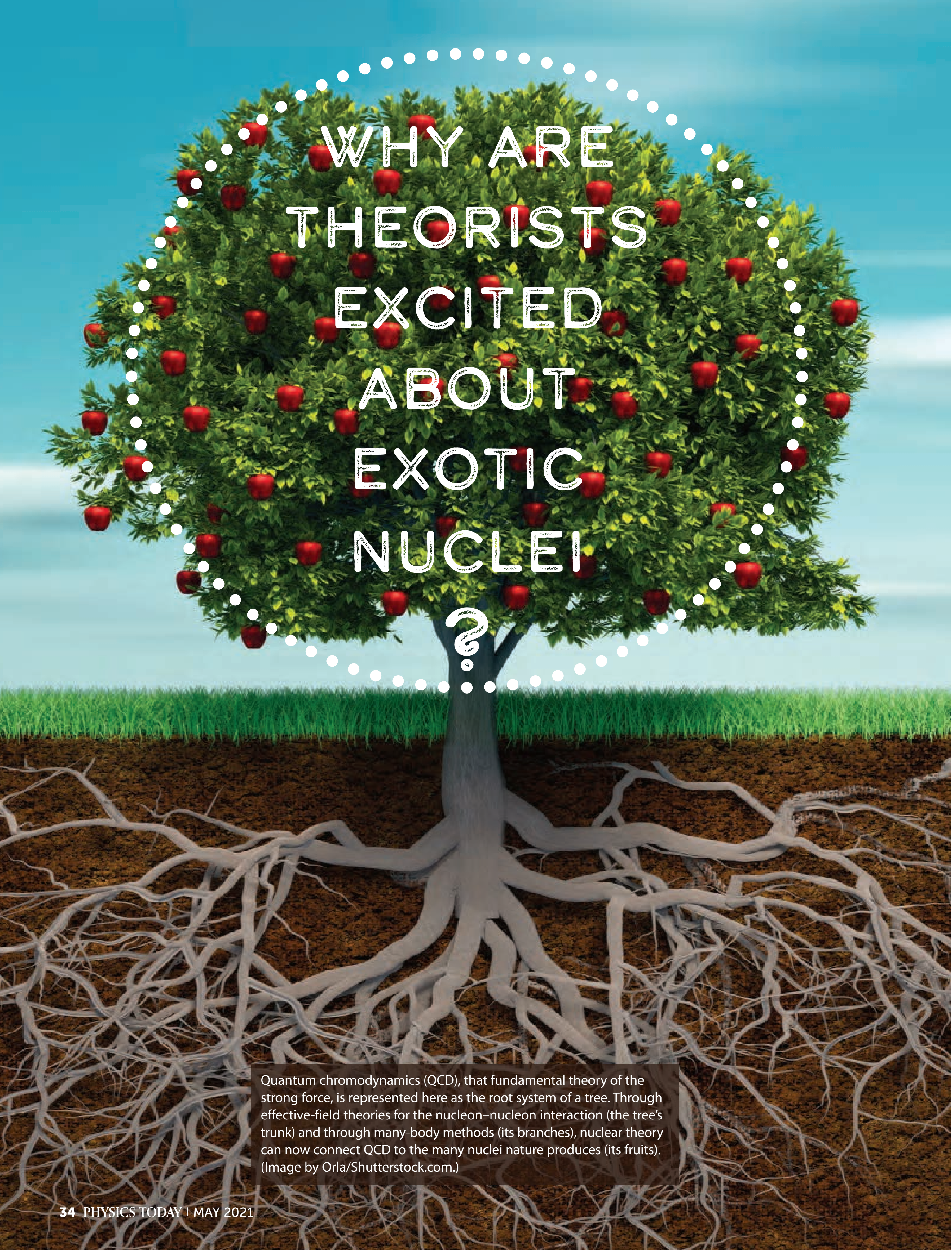
WHY ARE THEORISTS EXCITED ABOUT EXOTIC NUCLEI?



Quantum chromodynamics (QCD), that fundamental theory of the strong force, is represented here as the root system of a tree. Through effective-field theories for the nucleon–nucleon interaction (the tree's trunk) and through many-body methods (its branches), nuclear theory can now connect QCD to the many nuclei nature produces (its fruits). (Image by Orla/Shutterstock.com.)

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The limits of nuclear stability provide deep insights into the fundamental force responsible for the presence of matter.

Nuclei are at the heart of all palpable matter.[1] Although we understand the properties of things we touch every day—from the carbon in our bodies to the lanthanum in our cell phones—so much more may be revealed by investigating elements at the limits of their stability. Those limits become apparent when too many neutrons or protons are added to a nucleus. Matter falls apart in different ways, by emitting particles and radiation, say, or by fissioning into much lighter elements. Indeed, the world's elements seem to be finely tuned as a subtle interplay of components of the nuclear force. Those components can either hold a nucleus together or doom it to nonexistence.

Collectively known as nucleons, neutrons and protons form the building blocks of nuclei. A nuclear isotope is characterized by a mass number A and charge Z; each isotope contains Z protons and $N = A - Z$ neutrons. A few hundred isotopes exist naturally on Earth. Many thousands of others are short-lived and are constantly being created in numerous corners of the universe.

Nuclear physics has always been an essential component of astrophysical phenomena. Roughly half of the heavy elements found in our solar system originate from chain reactions triggered by neutron star mergers or the violent collapse of massive stars. Exotic nuclei are created, if only for an instant. A major ambition of our generation is to understand where and how heavy matter forms.[2] Exotic neutron-rich nuclei are an essential piece of that puzzle.

Discerning the properties of nuclei and their reactions constitutes the research field known as low-energy nuclear physics. At state-of-the-art facilities, rare-isotope beams are produced by purifying the shower of products of violent nuclear collisions between stable nuclei. Those isotopes are then either stopped in traps for high-precision measurements of their basic properties, such as mass and radius, or sent to beamlines, where they interact with target nuclei to produce various reactions that provide crucial information about the underlying force.

Despite the massive undertaking—from planning and executing the experiments to interpreting their results—those experiments are most often designed to study one single isotope. Over the past five decades, researchers have measured hundreds of isotopes to fill in the so-called nuclear chart. Critics often complain that what's done in low-energy nuclear physics amounts to mere stamp collecting. But the process is an important step to understanding how the world works: Simple patterns emerge from the chart, outlined in figure 1; and from those patterns, we gather deep insights into the nuclear force and predict new phenomena.

The theorists' dream is to understand all the manifestations of nuclear matter as it originates from fundamental forces—strong, weak, electromagnetic, and gravitational. Nuclei are primarily a consequence of the strong and electromagnetic forces. But as its name implies, the strong force is so strong that in many instances it cannot be treated as a perturbation. Quantum chromodynamics (QCD) explains how quarks come together in triples to form neutrons and protons. Because a perturbative approach to QCD is not applicable to neutrons, protons, or nuclei, large-scale numerical computations are required, in which quarks are placed on a lattice acted upon by the QCD Lagrangian. (See the article by Carleton DeTar and Steven Gottlieb, PHYSICS TODAY, February 2004, page 45.)

Why don't theorists calculate the properties of carbon-12 as a 36-quark problem or those of uranium-238 as a 714-quark problem? That would be a more direct approach. But the computations required to solve a problem with even half a dozen quarks would take years using the largest supercomputer in the US. Evidently, simulating the vast majority of nuclei directly from QCD will remain a dream for the future.

Fortunately an alternative to QCD exists. The energy scale of quarks is orders of magnitude higher than the energies required to determine the properties of nuclei, and there are well-controlled ways to connect the force between quarks with the force between neutrons and protons. And through that connection, the theorists' dream may become reality.

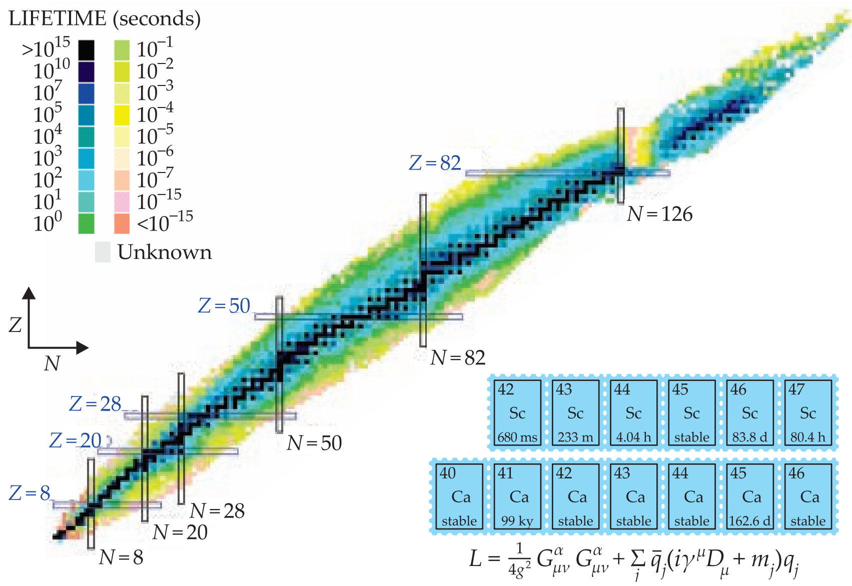

FIGURE 1. NUCLEAR CHART of isotopes, plotted by atomic number Z and neutron number N and color coded according to the isotopes' lifetimes. The inset shows a detail of the calcium and scandium isotopic chains. The nuclear force is a consequence of the quantum chromodynamic Lagrangian L. Identifying the patterns that emerge from the isotopic chains yields a deeper understanding of the nuclear force. (Image by Donna Padian.)

Connecting to the root

Nuclear theorists have long known that they do not need to explicitly include quarks in models to describe nuclear properties. Simply taking neutrons and protons as the building blocks is enough to reproduce many features of known isotopes.

The effective force between neutrons and protons was traditionally determined through fits to a large body of nucleon–nucleon (NN) data. Thanks to close collaborations between theorists and experimentalists over the decades, those fits had improved enough by the end of the 1990s that the resulting NN interactions perfectly described all relevant few-nucleon properties.[3] Even so, no connection had been established between the fundamental theory of QCD and the NN interaction from which nuclei emerge. What was needed was a path to bridge the effective NN interaction to fundamental interactions between quarks and gluons. Only through that transformation could nuclear theory have a chance of evolving from a descriptive to a predictive science.

The path toward bridging nuclei with QCD was first introduced by Ubirajara (Bira) van Kolck and collaborators using effective-field theory.[4] Imagine you have an image with enormous resolution, but all you really need to know is whether a giant gorilla sits at the center of the image. To that end, a low-resolution picture would suffice. Effective-field theory is the tool a nuclear physicist would use to controllably blur the picture, reduce its complexity, and make the problem computationally tractable.

Effective-field theory averages out QCD interactions' short-range components not relevant to the physics of nuclei, and it provides a form of the NN force using parameters that can be determined directly from QCD. The resulting NN force can then be used to solve the nuclear many-body problem and calculate all relevant nuclear properties.

Limits of stability

Not all is settled in nuclear-force land. In the limits of stability, theory encounters the most stringent tests. Such encounters are why theorists should be excited about studies with exotic nuclei. Those nuclei have the answers; they detect when the theory is wrong.

Were there no Coulomb force, nuclei would come together in pairs of neutrons and protons, because the interaction between those nucleons is slightly more attractive than either the neutron–neutron interaction or the proton–proton interaction. Because of the Coulomb repulsion between protons, as the system gets heavier, it needs more neutrons to provide the glue that keeps the matter together. For example, the most stable carbon isotope is ^{12}C, with six neutrons and six protons, whereas the most stable lead isotope is ^{208}Pb, with 126 neutrons and 82 protons.

Nature produces isotopes with an asymmetry of neutrons and protons much larger than ^{208}Pb's. But when the imbalance becomes too large, the nucleus becomes unstable and decays, either through nucleon emission or beta decay. In both cases nature tries to restore the system's stability with that decay. The limits of stability, often referred to as the drip line, are determined by the last isotope, for which there is a bound state in a given isotopic chain.

Strange things can happen at those limits: Nuclei, often thought of as compact objects, can develop halos and extended neutron skins (see, for example, reference 5). Lithium-11 is one famous example. It is composed of a tightly bound core (lithium-9) and two valence neutrons, which spend most of their time away from the core and resemble a halo. An example of an extended neutron skin is found in neutron-rich tin isotopes. Their valence neutron probability distribution extends farther from the nuclear center than the proton distribution, such that at the surface of the nucleus only neutrons exist.

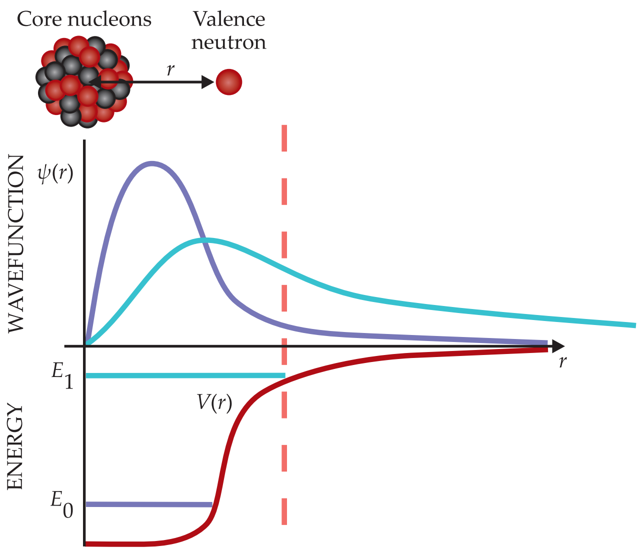

FIGURE 2. EXOTIC NUCLEI are quantum states at the limit of stability. The potential $V(r)$ between a nucleus's core and a valence neutron a distance r from the center is sketched in red. Classically, the neutron would not be able to move outside the classically allowed region (vertical dashed line). In stable nuclei, the valence neutron is well bound: Its energy E_0 is typically about −7 MeV and its wavefunction (purple curve) dies quickly outside that region. The valence nucleon for a nucleus at the limits of stability is loosely bound: Its energy E_1 is typically about −0.1 MeV and its wavefunction (blue curve) extends well beyond the classically allowed region. (Image by Donna Padian.)

Nuclei are quantum systems, and to a large extent one can describe them by solving the nonrelativistic Schrödinger equation. In the so-called valley of stability, the likelihood of finding a valence neutron far from the center of mass of the nucleus is close to zero. But that is not the case for nuclei at the limits of stability. Figure 2 contrasts a wavefunction of a valence neutron in a stable nucleus with one in an unstable, loosely bound nucleus.

In unstable isotopes, the valence neutron lives most of its life in the classically forbidden region, far from the nuclear center of mass. And it exhibits a characteristically long tail in its wavefunction. Those long tails strongly imprint themselves on the nucleons' binding energies, radii, deformations, and electromagnetic responses.

In the early days of rare-isotope facilities, studies at the limit of stability posed several challenges for theory. First, theorists needed far greater precision in their calculations. The average energy per nucleon in ^{12}C and ^{208}Pb is about 7 MeV. However, if we look at the last bound isotope in an isotopic chain, the typical energy that binds each valence nucleon is about 0.1 MeV. For studying stable nuclei, a theory with the precision of 1 MeV is good enough. But when studying nuclei at the limits of stability, theorists need that precision to improve by an order of magnitude.

Second, the traditional methods in many-body nuclear physics simply could not capture long tails in the wavefunction and fell short in their predictions. In the past decade, efforts to develop many-body methods that can deal with loosely bound systems have exploded. It used to be common for theorists to expand the nuclear wavefunction into harmonic-oscillator basis states—functions that fall off much faster than the known exponential dependence with radius—to exploit their analytic advantages. But a revolution has recently taken place, with theorists introducing different bases to capture the long tails.

What's more, with the enormous increase in computational power, many-body methods have improved the scaling of computation time with mass number. At the turn of the millennium, the largest *ab initio* many-body calculation could only calculate the properties of nuclei up to ^{12}C. But today, *ab initio* methods can compute ^{132}Sn, an extraordinary feat.[6] And the precision of the most competitive many-body *ab initio* approaches is now nearing the 0.1 MeV standard.

The impressive progress in many-body methods has uncovered shortcomings in our understanding of the NN force. Although the precision has increased, the mismatch to experiment at the limits of stability reveals a lack of accuracy in the interaction. It appears the blurry picture mentioned earlier is too blurry to pick out the details one needs for barely bound systems. As it turns out, exactly at the limits of stability is where small components of the NN force—those that are not significant for stable systems—become key.

Because the interaction is now rooted in QCD through effective field theory, ways now exist to improve the accuracy with which the interaction is calculated. But the improvement comes at the cost of some technical complications embodied in higher-order forces. Nevertheless, a courageous bunch of theorists are tackling that work.

Probing nuclei with reactions

Ever since Ernest Rutherford's gold-foil experiment, scientists have used reactions to study nuclear properties. Now, more than ever, that tool is essential. The rare isotopes we are interested in are unstable and will decay away if made into targets. Fortunately, isotope factories are able to generate them in a beam. Those isotopes then interact with a target that serves as a probe.

Nuclear reactions are versatile tools because they offer various knobs to turn.[7] On one hand, the energy at which the reaction takes place and the scattering angles that are measured serve to adjust the penetrability of the beam. The energy and angle variability allow experimentalists to scan a nucleus in a way akin to tomography. As in positron emission tomography (PET) scans, researchers may be able to create a three-dimensional image of the nucleus.

On the other hand, depending on the choice of the particle measured in the detector, one gets different information. When, for example, the halo nucleus beryllium-11 collides with a ^{12}C target, many things may happen at the same time. Most of the time the ^{11}Be nucleus—composed of a well-bound ^{10}Be core and a valence neutron in a radially extended orbital—passes through the target unscathed. But when ^{11}Be does react, it may remain in its ground state and yet suffer an elastically scattered deflection. Or it may undergo an inelastic excitation, break up into fragments, gain mass by picking up nucleons from the target, or even fuse with the target.

The type of detector that's used determines the reaction channel to be studied and the properties that can be extracted. For example, to measure inelastic scattering, researchers examine the radiation from the de-excitation; from it they can extract the probability that the transition between states in the halo nucleus will occur.

Like nuclei themselves, nuclear reactions are ruled by quantum mechanics. As depicted in figure 3, the simple picture for nuclear scattering consists of an incoming wave that impinges on a target nucleus. The field generated by that target nucleus distorts the incoming wave, and from that distortion one can determine properties of the nucleus. The part of the wave deflected in the near side of the collision interferes with the part deflected on the far side in a way that, to first order, is analogous to the diffraction of light. The resulting pattern gives a measure of the range of the relevant interaction.

Because the original wave can give rise to many other reaction channels, the intensity of the incoming wave will be reduced.[7] We can think about the reaction process as being driven by another sort of effective interaction—that between the two reacting nuclei. That interaction is referred to as the optical potential, as it contains an imaginary component that removes flux from the incoming wave. The process is analogous to what happens when light is absorbed as it travels through a medium.

The fundamental theory for nuclear reactions is QCD. However, studying the reaction of ^{11}Be and ^{12}C isotopes from the perspective of QCD is a daunting pursuit. The same effective-field theories discussed earlier can help address the many-body scattering problem at hand. Such *ab initio* efforts to simulate nuclear reactions are ongoing, but they're limited to light systems.[8] For heavier systems, another level of simplification is required: casting the problem as a few-body problem and introducing the above-mentioned optical potential.

Although the theory that connects quark degrees of freedom to nucleon degrees of freedom is clean and straightforward, albeit technologically challenging, the theory that goes from the nucleon–nucleon interaction to the nucleus–nucleus interaction is less controlled and still largely phenomenological. One of the greatest challenges in low-energy nuclear physics is to make a formal connection to QCD, so that reaction theory can become less dependent on data. In that respect, much work remains to be done.[9]

Theory crosses borders

The physics of nuclei sits at the crossroads of many different research fields—from astrophysics to fundamental particle physics and from chemistry to condensed-matter physics. Theory plays a key role in establishing connections between those fields.

An important example of that interdisciplinarity is the research in fundamental symmetries at the interface between nuclear physics and high-energy physics. The quest for neutrinoless double beta decay, which tells us whether a neutrino is its own antiparticle, will involve a giant detector (see PHYSICS TODAY, January 2010, page 20). Accurate theoretical predictions for the nuclear-structure properties of the relevant detecting

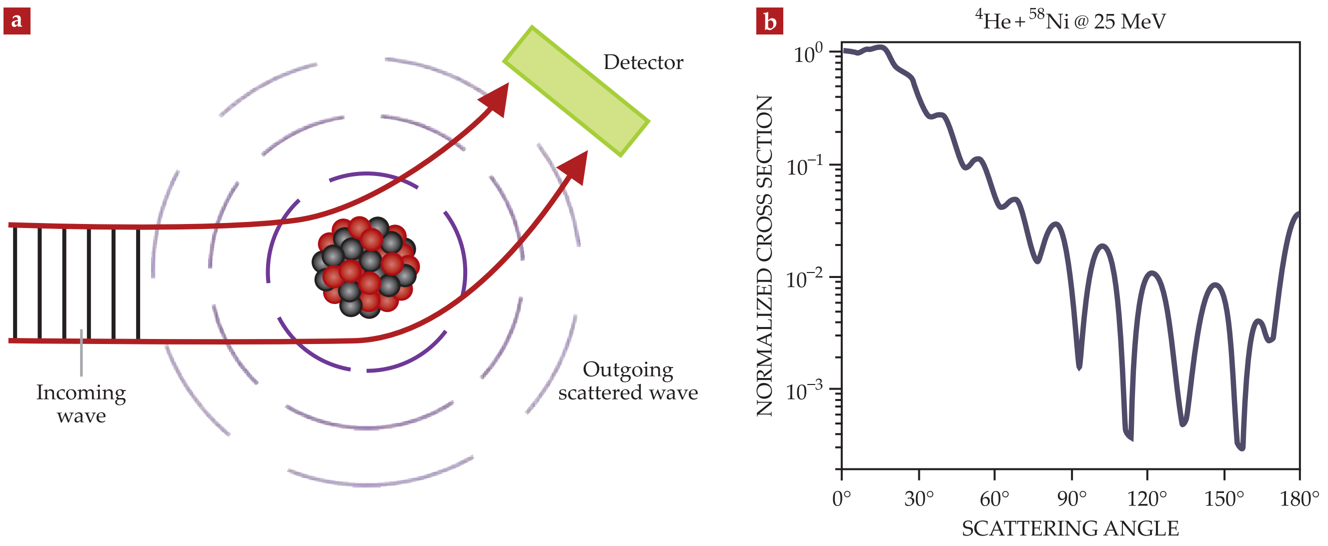

FIGURE 3. ELASTIC SCATTERING of a nucleus off a target is best described using waves: **(a)** Part of the incoming beam is deflected on the near side of the target, whereas other parts are deflected on the far side. Because their paths differ, they have accumulated different phases by the time they reach the detector. **(b)** The result at the detector is an interference pattern that's directly related to the size of the target nucleus. (Image by Donna Padian.)

isotopes will be an essential ingredient for the experiment's success.

In many respects, nuclei can serve as test beds of new physics beyond the standard model. One example involving rare isotopes has to do with baryon asymmetry in the universe. The asymmetry can be explored by searching for permanent electric dipole moments[10] in such pear-shaped nuclei as radium-225 and protactinium-229. (See the article by Norval Fortson, Patrick Sandars, and Steve Barr, PHYSICS TODAY, June 2003, page 33.)

The nuclear connection that has received the most public attention is astrophysics. Since the first 10 seconds in the history of the cosmos, nuclei have shaped our universe. Nuclear reactions are the fuel for large astronomical objects, and through those reactions the universe has synthesized the matter that pervades our lives. Nucleosynthesis, the chain reactions by which nuclei are produced, occurs in stars and explosive environments such as supernovae and neutron star mergers. In such extreme environments, nucleosynthesis steps through many neutron-rich and proton-rich nuclei, and thus their properties are important inputs to large-scale astrophysical simulations.

An illustration of the deep intersection between nuclear physics and astrophysics is the first detection of gravitational waves and their electromagnetic counterpart from the neutron-star merger GW170817. The electromagnetic signal offered an independent constraint on the equation of state of neutron stars.[11] The merger caused shivers in both the gravitational and nuclear communities. Often, reactions of astrophysical interest cannot be measured directly, and indirect reactions must be used to probe the same information.[12,13]

The technical challenges in the theory of nuclei also cut across fields. Nuclei are complex systems from which simple phenomena emerge, just as in molecular physics.[14] So it should be no surprise that similar phenomena—halos, Efimov states, deformation, phase transitions, and others—occur in the two fields. Likewise, many-body methods are widely applied both in chemistry and in nuclear physics; few-body methods that describe reactions with molecules can also be used to study reactions of nuclei at the limits of stability. With efforts to make nuclear theory more predictive, the field has been learning from statistics to quantify uncertainties and to help with experimental design.[15]

Beyond stability

The mass frontier and the asymmetry frontier are both important in the theory of nuclei. As Z goes beyond around 100, at some point the Coulomb repulsion becomes so strong that no matter how many neutrons are used to glue a particular nucleus together, it becomes energetically more advantageous for the isotope to either emit alpha particles or break apart and decay into lighter nuclei. As theorists move toward ever larger neutron–proton asymmetry, they also eventually reach a limit in which valence nucleons are no longer able to stay attached to the core nucleus. In both cases, theory needs to deal with the effects of the continuum—the range of unbound states that exist above a particle threshold.

THE PHYSICS OF NUCLEI SITS AT THE CROSSROADS OF MANY DIFFERENT RESEARCH FIELDS—FROM ASTROPHYSICS TO FUNDAMENTAL PARTICLE PHYSICS AND FROM CHEMISTRY TO CONDENSED-MATTER PHYSICS.

Many large-mass isotopes are of interest to our society. The mercury found in thermometers and barometers; the lead found in weights and batteries; and ^{238}U, the main fuel in reactors, all spring to mind. Oganesson, the heaviest element in the periodic table, has $Z = 118$ and a lifetime of less than a millisecond. Because of exponential growth in the computational cost in *ab initio* many-body methods, theories for describing it and other heavy systems rely on density functionals (see the article by Andrew Zangwill, PHYSICS TODAY, July 2015, page 34).

Although informed by theory, the functionals are typically fitted to experimental masses and other data. The models predict an island of stability of superheavy nuclei. (See the article by Yuri T. Oganessian and Krzysztof P. Rykaczewski, PHYSICS TODAY, August 2015, page 32.) Although the location of those superheavy elements on the nuclear chart is uncertain, they should reside above copernicium-112 on the neutron-rich side, around $N \approx 184$. The problem with phenomenological density functional theories is that, despite their validity in regions where data exist, they become unreliable in extrapolating to regions where no data exist. Although the path is complex, here, too, theorists are trying to connect the density functionals to more fundamental theories.

The second frontier concerns the neutron–proton asymmetry. For light nuclei, the most stable isotopes have a neutron-to-proton ratio (N/Z) around one. With their increasing Coulomb repulsion, heavier isotopes, such as ^{208}Pb, reach $N/Z = 1.5$. But near the limits of stability are exotic nuclei such as helium-8 ($N/Z = 3$) and ^{9}C ($N/Z = 0.5$); long isotopic chains, such as Sn, which has 32 isotopes; and neutron stars, the most perplexing form of nuclear matter that exists, with N/Z of about 20. Precisely predicting the maximum number of neutrons that can be added to a stable nucleus while keeping the system bound is one of the greatest challenges for *ab initio* many-body theories, especially for systems whose Z exceeds 20.

For nuclei with Z less than 20, the limits of stability have produced halos, in which valence nucleons hang around a central core nucleus in the classically forbidden region, as discussed earlier. Because the halo nucleons are decorrelated from the rest of the nucleus, few-body theories—in which nuclei are composed of a core nucleus with few valence nucleons—are often adequate to describe their properties.

When the attraction obtained by adding another neutron to an isotopic chain is not enough to keep it bound, the nucleus steps into the positive energy domain. States beyond the limits of stability are sometimes elusive for theory, particularly if they have short lifetimes. Examples of those states include the tetra-

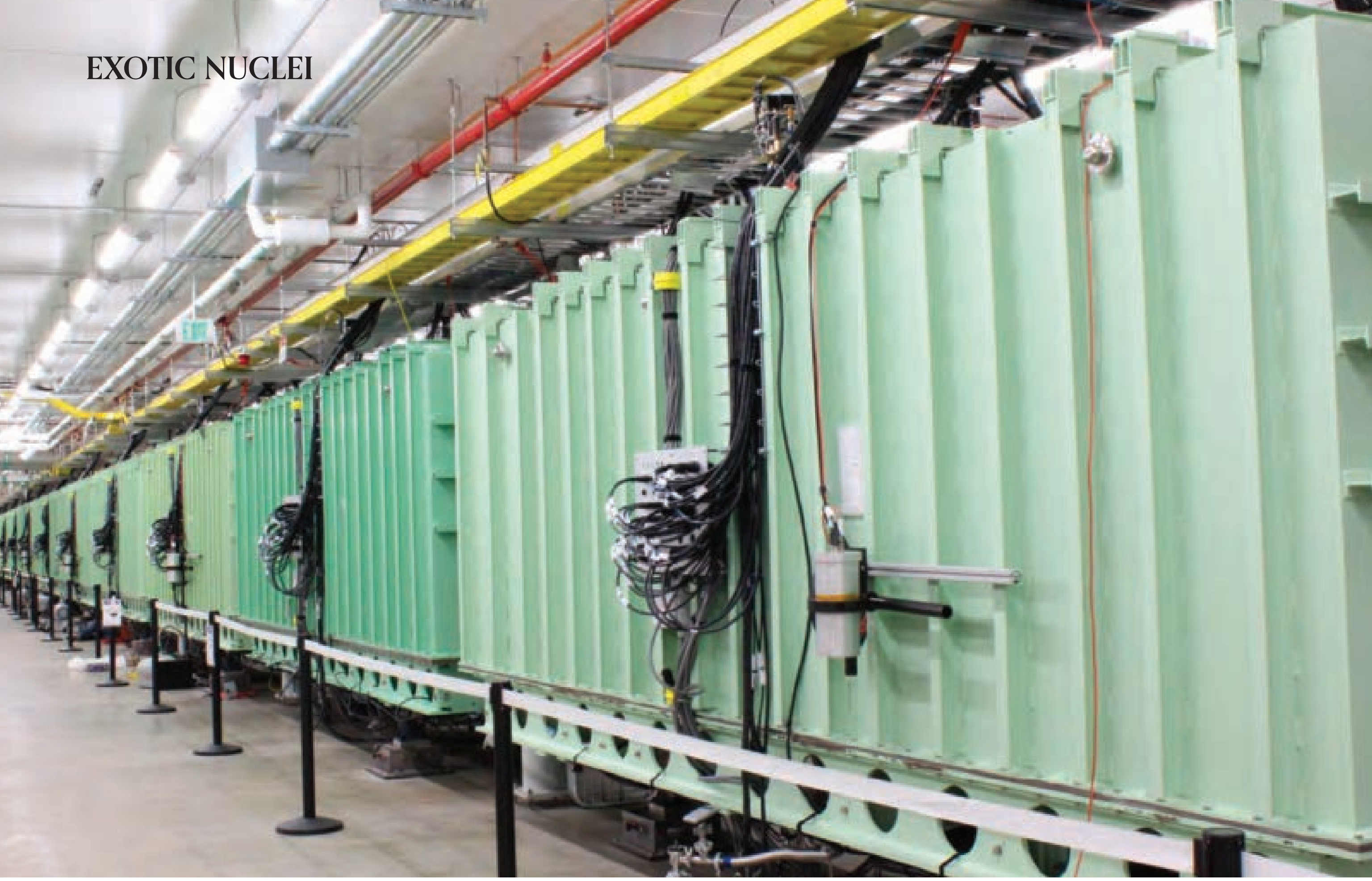

FIGURE 4. THE FACILITY for Rare Isotope Beams is taking shape as the highest-energy superconducting heavy-ion linear accelerator in the world. When it begins operating in 2022, the facility will be able to accelerate all ions from hydrogen to uranium to at least 200 MeV/nucleon and produce thousands of rare isotopes by in-beam fragmentation. (Courtesy of the Facility for Rare Isotope Beams.)

neutron,[16] a hypothetical stable cluster of four neutrons; the ^{10}He resonance ($N/Z = 5$); and two-neutron radioactivity[17] in ^{16}Be.

New facilities

Around the world, technology to study rare isotopes has been advancing rapidly. Many isotopes have been discovered since the Rare Isotope Beam Factory began its operation a decade ago at the RIKEN National Science Institute in Japan. But nuclear physicists are most excited for the start of operations at the Facility for Rare Isotope Beams (FRIB) next year at Michigan State University.[18] That facility, partly shown in figure 4, is expected to produce nearly 80% of all the isotopes predicted by density functional theory, including many on the neutron dripline.

A linear accelerator bent into three segments, FRIB accelerates a heavy-ion primary beam up to half the speed of light. Many different isotopes can be formed in the violent collisions between nuclei in the beam and nuclei in the production target. The rare isotopes of interest will be separated and either guided directly into the relevant high-energy experimental halls, or stopped and reaccelerated to the low-energy beamlines.

Nuclear facilities have been producing rare isotopes for decades. Unique about FRIB is the 400 kW power of the accelerator. The increase in power expands the accelerator's reach into exotic areas: The machine will be able to explore the properties of long isotopic chains, such as the Sn isotopes, and thus allow theorists to test their understanding of the NN interaction and its dependence on neutron–proton asymmetry. With the beam's intensity, FRIB will be able to measure several reaction channels simultaneously and more accurately than could be done before. Along the way, FRIB will likely unveil some unexpected phenomena to keep theorists scratching their heads.

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Inducing new material properties with HYBRID LIGHT–MATTER STATES

Cyriaque Genet, Jérôme Faist, and Thomas W. Ebbesen

Even in the absence of light, coupling cavities with molecules and materials can modify their chemical reactivity, conductivity, and more.

The link between light, matter, and vacuum has been a subject of discussion since antiquity. The conceptual revolution that started in the 1920s with quantum mechanics and led to the development of quantum electrodynamics (QED) changed our understanding of light–matter interactions—particularly the role of vacuum, the space through which light propagates.

In the 1970s a series of milestone experiments by atomic physicists showed that optical cavities could fundamentally modify the spontaneous emission of photons from excited atoms by either enhancing or suppressing it. The effect had already been predicted by Edward Purcell in 1947 and is best understood by considering that a cavity modifies the density of optical states of vacuum. Atoms can emit light only into available optical states. In a cavity the density of those states is altered, and therefore so is the probability of photon emission. Such a system can even enter a regime in which a spontaneously emitted photon is periodically reabsorbed by the atom itself; the resonant frequency of that exchange is known as the Rabi frequency. (For more on cavity QED, see the article by Serge Haroche and Daniel Kleppner, PHYSICS TODAY, January 1989, page 24.)

Such periodic energy exchange naturally results in the formation of hybrid states known as polaritonic states. Their nature, a kind of half-photonic and half-matter chimera, raises the prospect of changing material properties. The most striking aspect of the so-called strong-coupling regime is that the existence of the polaritonic states does not require the cavity to be initially populated with photons. In other words, the coupling can occur with an electronic, vibrational, or other material transition and proceeds via the zero-point fluctuations of the electromagnetic energy inside the cavity.

The optical excitation of such a coupled system by a light source results in the formation of a polariton—a quasiparticle formed when a photon is coupled to a matter excitation. Exciton polaritons have attracted a lot of interest for their ability to, among other things, form condensates that exhibit superfluidity and host vortices (see the article by David Snoke and Peter Littlewood, PHYSICS TODAY, August 2010, page 42).

Here, in contrast, we consider the situation in which coupled systems are not optically excited. Numerous studies over

A microfluidic Fabry–Perot optical cavity for doing quantum electrodynamic chemistry. (Photo courtesy of Thomas W. Ebbesen.)

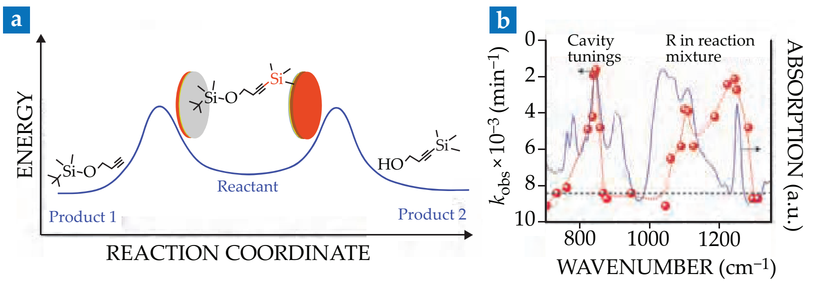


FIGURE 1. CHEMICAL REACTION biasing. **(a)** When the reactant *tert*-butyldimethyl{[4-(trimethylsilyl)but-3-yn-1-yl]oxy}silane is attacked by a fluoride ion, one of two products emerges. If the reaction proceeds in a cavity, it can be biased toward the normally unfavored product by tuning the cavity's resonance to match the vibrational frequency of one of the molecule's bonds. **(b)** The overall reaction rate k_{obs} (red dots) dips when the cavity is coupled to the reactant's silicon–carbon bond (842 cm^{-1}), silicon–oxygen bond (1110 cm^{-1}), or silicon–methyl bond (1250 cm^{-1}). The reactant's IR absorption spectrum (blue line) has the corresponding maxima. (Adapted from ref. 4.)

the past decade have shown that, surprisingly, material properties can be significantly modified under such conditions. In the following sections, we give a few examples of recent findings in chemistry and condensed-matter physics that illustrate the potential of strong coupling in the absence of light to control the properties of matter.

Cavity chemistry

The demonstration that strong coupling to an electronic transition can modify a photochemical reaction has stimulated many theoretical studies.[1] They have shown, for instance, that the experimental observations could be explained by the formation of a polaritonic potential-energy surface (PES) that modifies the internal dynamics and the reactivity landscape.[2]

Polaritonic states are not limited to electronic transitions; they can also be made by coupling a cavity mode with a molecular vibrational transition. Such vibrational strong coupling (VSC) yields a new type of state, the so-called vibropolaritonic state, which has remarkably strong effects on chemical reactivity. Molecular vibrational transitions have relatively high frequencies ω_ν, which are fixed by the bond strength f (typically on the order of 10^3 N/m) and by the tiny atomic masses involved in the vibrations. Their resonances are characterized by small Boltzmann factors, $n_\nu \sim e^{-\hbar\omega_\nu/k_BT} \sim 10^{-4}$, which describe the probability of being in an excited state. Such molecular modes are therefore in their ground states, even at room temperature.[3]

Chemistry experiments under VSC can be run inside microfluidic optical cavities (see opening image) that are tuned to the IR vibrational bands of the solute, the solvent, or both. A simple Fabry–Perot cavity comprises two mirrors that are separated by a thin polymer spacer, typically about 10 μm thick. The cavity's frequency ω_c can be fine-tuned to a given vibrational transition simply by squeezing the spacer with a screwdriver and monitoring the spectrum with a standard Fourier-transform IR spectrophotometer. The two reactions described below illustrate the consequences of VSC on chemistry.

Most chemical reactions lead to several products because of the complexity of the PES of the reactivity landscape. For practical purposes—lowering cost, reducing waste, and minimizing purification steps—much effort is put into finding ways to selectively orient a reaction toward the desired product, and thus achieve the highest yields. The requisite biasing has traditionally been done by chemical means, such as through the choice of reaction pathway, catalyst, and solvent.

A study of a simple reaction with two possible outcomes, shown schematically in figure 1a, demonstrated that VSC could produce similar biasing toward a particular product. In the absence of VSC, the proportion of product 1 to product 2 was 60:40; under VSC, it became 20:80. That shift reflects modifications in the relative barrier heights.[4] The inversion of the selectivity occurred only when three of the numerous vibrational modes were coupled by tuning the cavity across the various vibrations (see figure 1b). The vibrations corresponded to the silicon–carbon, silicon–oxygen, and the silicon–methyl stretching modes that are associated, not surprisingly, with the bonds being broken in the reaction. Tunable VSC can thus provide information on the mechanism of the reaction.

As can also be seen in figure 1b, VSC slowed down the reaction rates for both products by changing the energy-barrier heights leading to each one. Temperature studies measuring the enthalpy and entropy of activation showed surprisingly large changes in those values, typically an order of magnitude greater than energy associated with the resonant frequency shifts caused by VSC, which are on the order of k_BT. In other

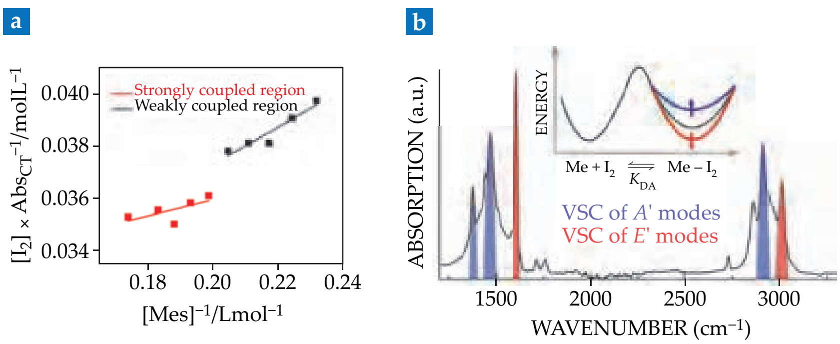


FIGURE 2. SYMMETRY and vibrational strong coupling (VSC). **(a)** The highly symmetric molecule mesitylene can react with iodine through a charge-transfer complexation reaction. A so-called Benesi–Hildebrand plot reflecting the change in the inverse mesitylene concentration versus the charge-transfer complex's absorption reveals an abrupt shift when the coupling transitions from weak to strong. **(b)** An IR absorption spectrum of mesitylene shows its vibrational modes. They can be grouped by the symmetry classes they belong to, *E'* (red) and *A'* (blue). Coupling a cavity to those modes shifts the equilibrium landscape of the mesitylene–I_2 complexation process (inset). Under VSC of the *E'* modes, the equilibrium constant K_{DA} increases and the complex is favored; VSC of the *A'* modes favors the reactants. (Adapted from ref. 6.)

Theoretical concepts of light–matter strong coupling

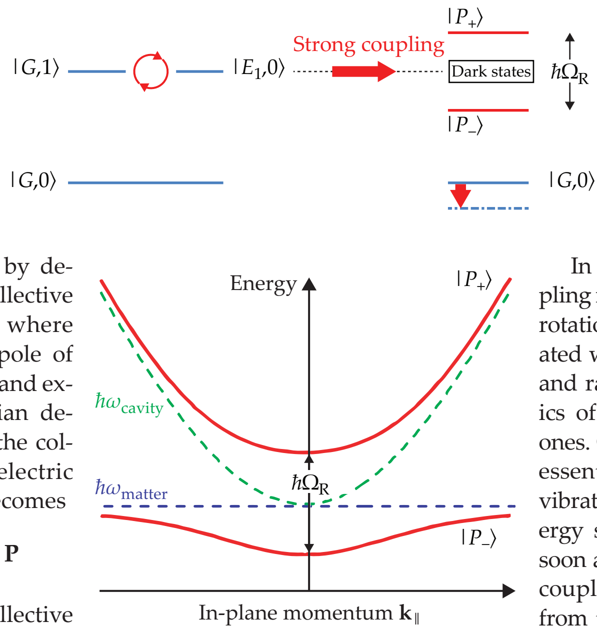
Confining a material in an optical cavity can produce new hybrid light–matter states. When the rate of energy exchange between the material and the cavity—the Rabi frequency—is faster than any dissipative process, the system reaches what's known as the strong-coupling regime. Although strong coupling is difficult to achieve with single entities such as atoms, increasing the number of entities N that are collectively coupled to an optical mode facilitates the process by enhancing the energy exchange.

The energetic structure of a strongly coupled light–matter system can be derived simply by describing the matter part as a collective dipole moment, $\mathbf{P} = \sum \mathbf{p}_i$, where $\mathbf{p}_i = \langle e_i|\mathbf{d}|g_i\rangle$ is the transition dipole of one emitter between ground $|g_i\rangle$ and excited $|e_i\rangle$ states. The Hamiltonian describing the coupling between the collective dipole $\mathbf{P}$ and the electric displacement $\mathbf{D}$ of the mode[2] becomes

$$H = H_{\text{cav}} + H_{\text{matter}} - \frac{1}{\varepsilon_0}\,\mathbf{D}\cdot\mathbf{P}$$

In the above framework, the collective ground state for the coupled system is defined as $|G,0\rangle = |g_1, \ldots, g_N\rangle|0\rangle$ with all the emitters in their ground states and no photon, $|0\rangle$, in the cavity. The polaritonic states, $P_\pm = (|G,1\rangle \pm |E_1,0\rangle)/\sqrt{2}$, are formed from the symmetric and antisymmetric superposition of the matter's ground state with one photon, $|G,1\rangle$, and the matter's first excited state with no photon, $|E_1,0\rangle$. They are separated by the enhanced Rabi splitting energy, $\hbar\Omega_R = 2\hbar\Omega\sqrt{N}$, where $\hbar\Omega$ is the interaction strength of a single entity with the vacuum field of the cavity, as illustrated at the top of the figure.

The symmetry of the Hamiltonian



implies that when N oscillators couple to one optical mode, the Hamiltonian has $N + 1$ solutions. Two of them, P_+ and P_-, couple to the light field; that leaves $N - 1$ states, the so-called dark states that don't couple to the light field but are nevertheless collective and can influence the properties of the coupled system. They should not be confused with uncoupled entities in the cavity, such as those whose dipole moments are oriented perpendicular to the cavity field.

The dispersive behavior of a Fabry–Perot cavity has consequences for the properties of cavity-coupled materials at room temperature. Experiments have shown that it is important to induce strong coupling at the bottom of the dispersion band—the energy versus in-plane momentum plot at the bottom of the figure—to observe changes in material properties.

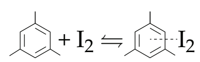
In the case of electronic strong coupling involving molecules, the role of the rotational–vibrational reservoirs associated with each electronic level is crucial and radically differentiates the dynamics of inorganic systems from organic ones. Organic molecules' relaxations are essentially driven by the rotational–vibrational reservoir in the thermal energy scale (k_BT), which implies that as soon as $\hbar\Omega_R > k_BT$, the relaxations of the coupled system cannot be estimated from those of the uncoupled molecular states. Those relaxations occur in a so-called non-Markovian regime, which contributes to some surprising features of the polaritonic states, such as their unexpectedly long lifetimes. (For more on non-Markovian polariton dynamics, see A. Canaguier-Durand et al., *Eur. Phys. J. D* **69**, 24, 2015.)

words, the simple modification of the vibrational frequency spectrum induced by VSC cannot fully account for the experimental observations.

Large activation-energy changes have been systematically seen in all reactions studied to date, regardless of whether VSC decelerates or catalyzes the reaction. Some other fundamental aspect must therefore be involved.[5] The most likely candidate is symmetry, which has been known to play a key role in chemical reactivity since the seminal work of Kenichi Fukui, Robert Woodward, Roald Hoffmann, and Richard Bader in the mid 20th century. (Fukui and Hoffmann shared the Nobel Prize in Chemistry for their work on chemical reactivity; see PHYSICS TODAY, December 1981, page 20.) Symmetry correlations between reactants and products determine the PES of the reactivity landscape and thus affect the products and rates of reactions. The symmetry of the vibrations can also help favor certain pathways over others.

Tilting the balance

A simple charge-transfer complexation reaction between the highly symmetrical mesitylene molecule and iodide illustrates the interplay between VSC and symmetry:[6]



The charge-transfer complex has a distinct absorption band in the UV that can be monitored to extract the kinetic equilibrium constant K_{DA} of the system. The dramatic modifications caused by strong coupling are surprisingly clear: Figure 2a shows an abrupt change in slope, which is reminiscent of a phase transition and reflects changes in both the complex's absorption and the system's K_{DA} when the coupling goes from weak to strong.

When the cavity is tuned across the vibrational bands of mesitylene to induce VSC, the ground-state landscape tilts either toward or away from the product. Notably, the direction of the tilt depends on the symmetry class of the vibration to which the cavity is coupled, as illustrated in figure 2b. The type of vibration, its frequency, and the energy-spectrum shift caused by coupling appear to have little or no impact on the reactivity landscape.

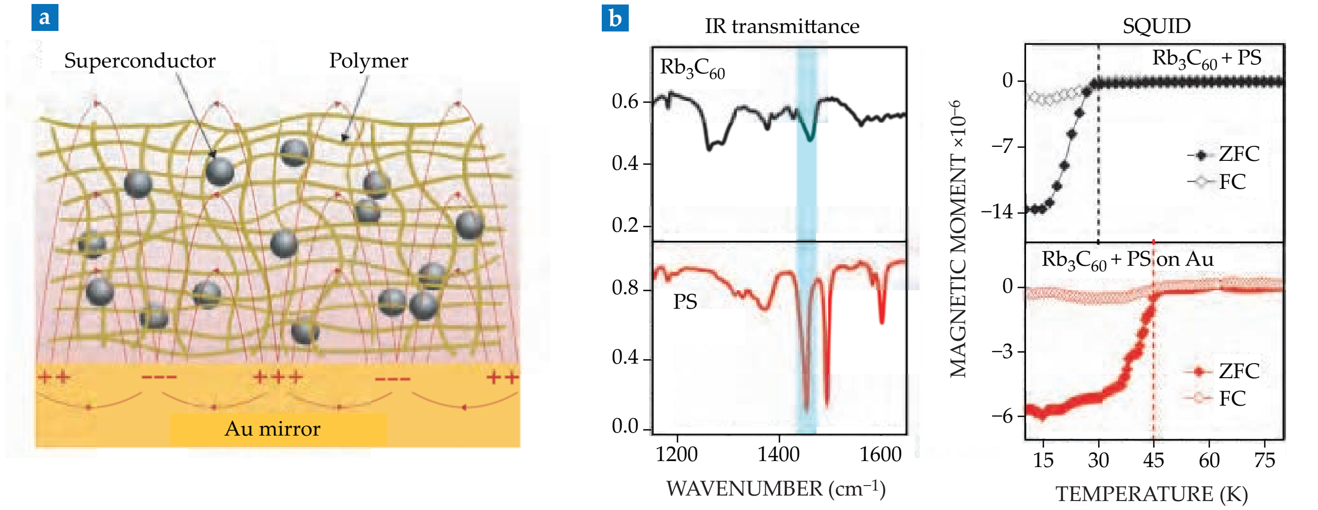


FIGURE 3. SUPERCONDUCTIVITY enhanced by plasmons. **(a)** Coupling the IR absorption band of Rb_3C_{60} nanoparticles to the surface-plasmon modes of a gold mirror can enhance the compound's superconducting properties. A polymer matrix is needed to mediate the coupling. **(b)** Although Rb_3C_{60} absorbs only weakly in the IR, polystyrene (PS) has an overlapping vibrational band that absorbs strongly at the same wavelength and facilitates cooperative coupling. Measurements of the polymer–particle complex's magnetic moment under zero-field-cooled (ZFC) and field-cooled (FC) conditions reveal an increase in the superconductor's critical temperature with surface-plasmon coupling from 30 K to 45 K, and the gaps between the FC and ZFC curves indicate the Meissner effect. (Adapted from ref. 11.)

Although reactivity landscapes can be complex and involve many factors, such as the solvent's properties and steric hindrance, knowing that symmetry affects chemical reactions under VSC should help researchers predict the outcomes of chemical reactions. VSC could even be used to study larger molecules whose symmetries are not as well defined.

Chemistry under VSC, also known as QED chemistry and polaritonic chemistry, is a new approach to the field and simple to implement; it can be done on any chemistry bench in most labs with just a few tools (see the opening image). It is even relatively simple to massively parallelize the microfluidic optical cavities for industrial purposes. The VSC approach is not limited to chemistry. Enzyme activity can also be modified by simply coupling the stretching modes of H_2O, which would open the door to applications to biological systems.[7] Furthermore, since more than one type of molecule can couple to a given cavity mode, it is possible to, for example, quantum mechanically entangle two molecules to the same mode and modify processes such as energy transfer between molecules.[8]

High concentrations of molecules are necessary to achieve strong coupling with cavity modes. Experiments have therefore been limited because chemical reactions are, by contrast, usually carried out in relatively dilute solutions. One way to overcome that problem is by involving the abundant solvent molecules. If the solute and solvent have an overlapping vibrational mode, the cavity can strongly couple to it. For example, putting *para*-nitrophenyl acetate and a solvent that shares its C–O stretching mode together in a Fabry–Perot cavity increased the rate of a solvolysis reaction by an order of magnitude, even though only the solvent was present at a sufficiently high concentration for strong coupling.[9] Theory shows that intermolecular vibrational interactions can indeed mediate such cooperative effects.[10] They are also critical to enhancing the electron–phonon scattering that affects the quantum properties of certain materials, such as superconductors, under strong coupling.

Superconductivity

The shift in molecular vibrational frequencies induced by strong coupling leads naturally to the question of whether phonon-driven solid-state phenomena, such as superconductivity, can be modified in the VSC regime. The challenge of exploring that question lies in the fact that superconductors' IR absorption bands are typically weak and therefore difficult to strongly couple.

The cooperative effect discussed above for solutes and solvents has been used to overcome that limitation. One such experiment tested the well-known superconductor Rb_3C_{60}, whose Cooper pairing is driven by phonons, under VSC.[11] A powder made up of superconductor particles, approximately 200 nm in size, was dispersed in various polymers with different vibrational bands. Spin coating those solutions on gold films (see figure 3a) strongly coupled the samples to the surface plasmons of the metal film. A SQUID (superconducting quantum interference device) magnetometer measured both the critical temperature T_c of each sample and the Meissner effect, a signature of superconductivity.

Of the several polymers tested, only polystyrene had strong vibrational bands that were resonant with the superconductor (see figure 3b). That sample reached the cooperative VSC regime and displayed not only a distinct increase in T_c, from 30 K to 45 K (see figure 3b), but also a clear Meissner effect. In view of the poor signal-to-noise ratio, many samples were tested to confirm the shift in T_c. The increase can be attributed to an enhancement of the electron–phonon coupling discussed above. Further experiments that fully characterize Rb_3C_{60}'s superconducting properties and studies of other superconductors are needed to provide further insight into the consequences of strong coupling on superconductivity.

Electronic transport

When the Rabi frequency of a light–matter system is near the

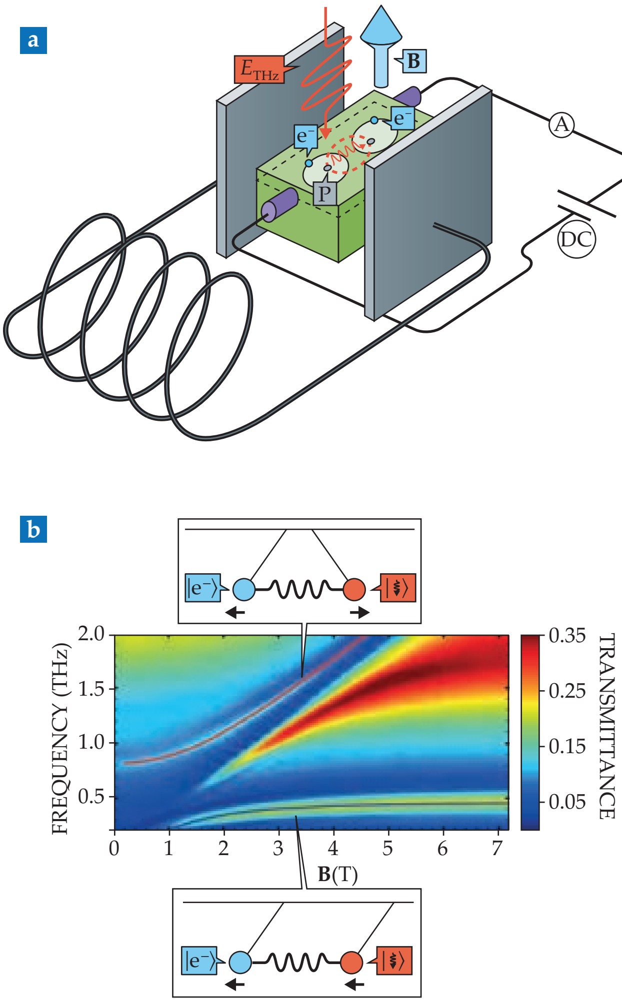


FIGURE 4. STRONG COUPLING in an experimental platform. **(a)** When electrons are trapped inside a heterojunction (green) and subjected to a perpendicular magnetic field **B**, they perform cyclotron orbits. Those orbits can then couple to the vacuum-electric-field fluctuations inside an electronic resonator (here an inductance–capacitance resonant circuit) of deep-subwavelength dimension to create collective excitations of the electron–cavity system known as polaritons. The polaritons can be probed either optically (as shown schematically by the wavy red arrow labeled E_{THz}) or by electrical transport (shown by the ammeter). **(b)** A polaritonic state can be understood as a coupled electron–photon mode whose resonant frequency, shown here in a color plot of the terahertz transmission, is tuned by a magnetic field. Similar to coupled classical pendula, the states exhibit in-phase and out-of-phase resonances. (Adapted from C. Maissen et al., *Phys. Rev. B* **90**, 205309, 2014.)

resonant frequency of the empty cavity, the system enters the ultrastrong-coupling (USC) regime. It can then exhibit some striking features: Its ground state, for example, becomes modified and contains virtual photons.[12] The transition from strong to ultrastrong coupling is naturally gradual, as is the modification of the ground state. We want to probe those changes using electronic transport.

Ultrastrong light–matter coupling can be achieved by engineering both the electronic excitations and the cavity. As already discussed in the context of the chemical reactions, coupling a collective excitation of many dipoles, rather than that of a single atom, to an optical cavity can help the system reach the strong-coupling regime (see the box on page 45). So can a properly designed resonator—for instance, a cavity where the electric field is confined in a deep-subwavelength-sized volume. That level of confinement can be achieved by replacing a Fabry–Perot cavity with an electronic inductance–capacitance resonant circuit.

Using a cavity of deep-subwavelength size greatly enhances the strength of the vacuum-electric-field fluctuations because the same zero-point energy of the electric field, half a quantum, must be squeezed in a smaller volume. Such cavities are most easily fabricated in the terahertz-frequency region, where metals have a very large and negative value of their dielectric function that enables tight confinement of an electric field.

The exploration of the USC regime was predicted to be achievable in two-dimensional electron systems coupled to terahertz cavities,[12] and that prediction was borne out experimentally.[13] In particular, a ratio of order unity between the Rabi frequency of a light–matter system and the resonant frequency of the empty cavity was observed in experiments in which researchers exploited the cyclotron resonance of a 2D electron gas as the matter excitation.[14,15]

Figure 4a illustrates the principle of such a system's operation: A high-mobility 2D electron gas confined by a semiconductor heterostructure is subjected to a strong perpendicular magnetic field **B**. The resulting Lorentz force bends the electron trajectories into quantized cyclotron orbits, and the system displays an equidistant ladder of states, so-called Landau levels, whose spacing is proportional to the field strength B.

Optical transitions between the Landau levels occur in the terahertz-frequency range and can be coupled to an inductive–capacitive circuit of deep-subwavelength dimension; the circuit's capacitor serves as the cavity. The polaritonic states—cavity photons strongly coupled to the cooperative motion of the cyclotrons—appear as resonances that tune with the magnetic field as the Landau level spacing is brought in and out of resonance with the cavity. When the system is probed by an external terahertz excitation, one resonance appears at a frequency higher than that of the bare resonator and another appears at a lower frequency, similar to what happens with a pair of coupled classical oscillators (see figure 4b).

The system illustrated in figure 4 can be used to investigate how light–matter coupling might affect electronic transport. Magneto-transport in a 2D electron system with very low disorder exhibits a rich phenomenology that includes, most famously, the integer and fractional quantum Hall effects. (For more on integer quantum Hall effects, see the article by Joseph Avron, Daniel Osadchy, and Ruedi Seiler, PHYSICS TODAY, August 2003, page 38; on fractional quantum Hall effects, see PHYSICS TODAY, July 1983, page 19.) That richness, however, reflects the theoretical complexity of combining electronic transport and quantum optics, which can make such systems challenging to study.

Initial experiments performed under a weak terahertz illumination that slightly increased the occupation of the polaritonic state showed the role such a state played in the electron-

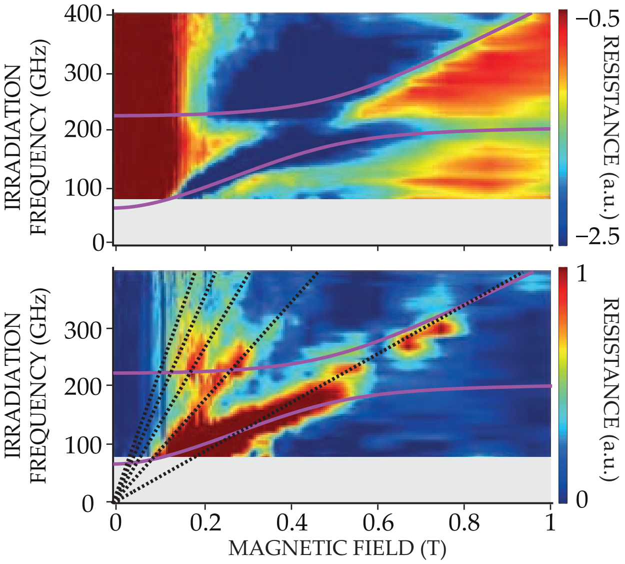


FIGURE 5. MAGNETO-TRANSPORT under weak terahertz illumination. The color plots reveal the change in resistance of a two-dimensional electron gas when probed in the manner illustrated schematically in figure 4. The top graph shows the resistance change for magnetic fields that cause transport to occur in extended states that form polaritons (purple lines). In the lower graph, the Fermi level lies in the localized states that do not participate in the polaritons; the resistance maxima therefore follow the dispersion of the Landau levels (black dashed lines). (Figure adapted from ref. 15.)

transport properties of the 2D electron gas (see figure 5). In the semiclassical limit—at which the presence of the Landau levels has not yet produced the quantized resistance steps characteristic of the integer quantum Hall effect—electron transport was found to be sensitive to the presence of the polaritons when the Fermi level coincided with a Landau level and transport was therefore dominated by extended states. In contrast, when the Fermi level lay between Landau levels in the localized states responsible for the quantum Hall conductance, transport was immune to the presence of the polaritons. The small extent of the states' wavefunctions caused the states to couple only weakly to the polaritons.

The experiments discussed above were conducted at millikelvin temperatures in ultrapure semiconductor heterostructures to minimize the impact of disorder and thermal excitation on the electrons' motions. However, the effects of polaritonic states on transport have also been studied in a completely different regime.[16] In room-temperature organic semiconductors, electronic transport is typically dominated by short-range site-to-site hopping. Experiments have shown that strong coupling can produce a striking increase in charge mobility in the organic material, where collective coupling causes the polaritonic states to be delocalized. The experiments show the potential for increasing carrier transport by polaritonic means: One could imagine building a transistor in which an external modulation of the cavity vacuum electric field would control the current.

Symmetry and beyond

The examples in this article make clear the enormous potential to modify and control material properties—even ground-state ones—by inducing hybrid light–matter states. Still, despite the simplicity of the coupling process, many of the underlying fundamental changes associated with strong coupling remain poorly understood. Experiments suggest the whole behavior of a coupled system switches, as if it has formed a new state of matter driven by the redefinition of its energy levels.

In the extreme case of USC, a forbidden bandgap appears and all the energy levels are shifted. Vibrational USC provides a practical way to generate polaritonic states with smaller linewidths than those of either the bare optical transition or the molecular vibration, which indicates longer-lived hybrid states. The dynamics of bond breaking in the ground state could therefore be radically modified, yet the potential impact of USC on chemistry remains to be explored.

The impact of symmetry in strongly coupled solid-state systems has yet to be examined. Beyond modifying transport properties, strong coupling also appears to be a promising route for controlling phase transitions—not just by tuning familiar ones, such as in superconductivity, but also by inducing new ones. For example, Yuto Ashida (at the University of Tokyo) and collaborators recently proposed a method for turning a paraelectric material into a ferroelectric one.[17]

In the terahertz regime, weak interactions such as intermolecular forces strongly influence the macroscopic properties of many materials and molecular systems. Strong coupling in those systems may open the door to controlling and enforcing new self-assembly processes.[18] It could also act on biological architectures and affect their functions. Chirality is an important property in those cases, and it needs to be explored in the context of strong coupling, material properties, and chemical reactivity.

Controlling material properties with polaritonic states is an unusually multidisciplinary endeavor, which explains the excitement and broad interest it has recently generated and the new perspectives it has opened. There will no doubt be many more surprises.

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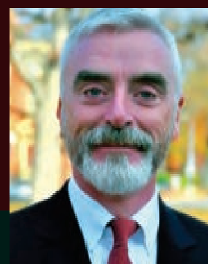
2020 ANNUAL REPORT

We all know that 2020 has been an extraordinary year. A year filled with challenges but also opportunities. A year in which the whole team here at the American Institute of Physics has delivered success to the 10 societies and associations in our federation and provided leadership within the broader physical sciences community.



Michael H. Moloney, PhD
Chief Executive Officer

Like all of you, every single member of our staff and every volunteer in our community has been greatly impacted by the COVID-19 Pandemic. The pandemic propelled AIP and its staff to think creatively across all departments as to how we achieve our mission, serve our audiences and continue to deliver excellence to the physical sciences community. I am so proud of how our organization was able to mobilize early on in 2020 to minimize disruption to our work — and in some cases flourish in new, exciting ways — which you can read about in the AIP 2020 Annual Report at the URL below.

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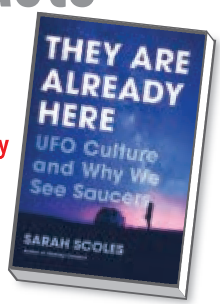
A view northwest along Nevada State Route 375, officially designated as the Extraterrestrial Highway due to its proximity to the US Air Force base commonly known as Area 51.

An ethnography of extraterrestrial enthusiasts

Despite years of research into the history of UFO studies, I've never seen a flying saucer. Neither has science journalist Sarah Scoles, author of *They Are Already Here: UFO Culture and Why We See Saucers*. But many people claim to have seen UFOs, and those witnesses stand by their experiences with a fervor that would make the Vatican envious. What motivates their devotion? What causes witnesses to attach such deep significance to the sightings and the places where they occur?

Scoles sets out to answer those questions in *They Are Already Here*. She is no stranger to subcultures exploring possible extraterrestrial life; her first book, *Making Contact: Jill Tarter and the Search for Extraterrestrial Intelligence* (2017), examined a major figure in the scientific field devoted to that mission. In *They Are Already Here*, Scoles sets aside the perspectives of traditional scientists and focuses instead on the experiences of average Americans in and around some of the most well-known sites in modern UFO lore. Along the way, she explores the expectations, assumptions, politics, and cultures that lie beneath peoples' UFO sightings.

They Are Already Here
UFO Culture and Why We See Saucers
Sarah Scoles
Pegasus Books, 2020. $27.95



The book begins by describing the 2017 *New York Times* exposé of the Pentagon's "secret" UFO investigations, which were officially known as the Advanced Aerospace Threat Identification Program. In the chapters that follow, Scoles introduces her audience to a wide array of places and people. We are taken to Area 51, Roswell, and the annual meeting of the International UFO Congress. We spend time with billionaire ranchers and with those barely making ends meet. We learn about studies of UFO phenomena by institutions like the US Air Force and outsiders like Tom DeLonge, the former Blink-182 front man turned UFO prophet. And we are introduced to organizations investigating UFO phenomena, like the Mutual UFO Network. The book ends where it began: with a sense of wonder at the strangeness of the universe.

They Are Already Here is more of a memoir than a study in history, sociology, or science. It tells the stories of people Scoles met on a pilgrimage through the American West to many of the hot spots of 20th- and 21st-century UFO lore. The author moves abruptly from theme to theme, place to place, and person to person. Although this stylistic choice sometimes makes for a disjointed reading experience, it accurately represents what it is like to work with such a colorful, diverse group of skeptics and believers. The result is a series of vignettes that offer a glimpse into the lives and beliefs of those in the UFO subculture.

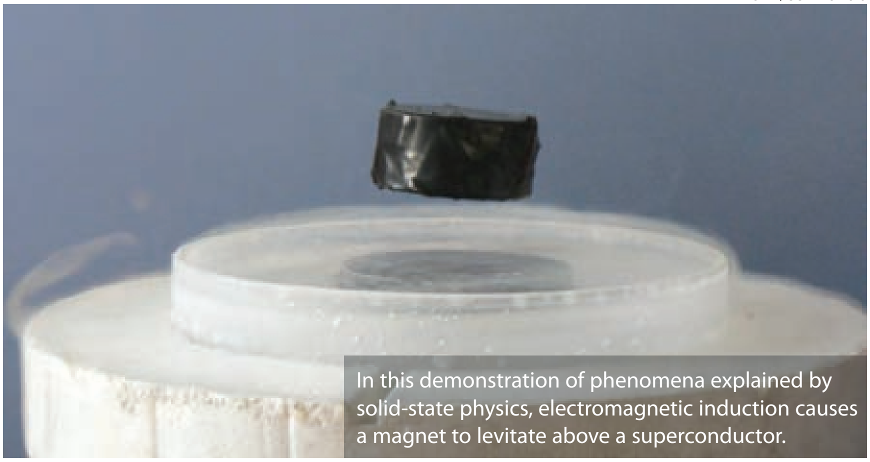
For this reason, *They Are Already Here* doesn't accomplish what it sets out to do. Scoles states in the introduction that the book is an effort to understand the nexus between UFOs and "the cultural, sociological, economic, political, and religious environments of whatever spot they inhabit in spacetime." She wants to understand the socially and culturally contingent ways in which UFO sightings create meaning for witnesses, and why those experiences imbue UFOs themselves with such lasting power. Those of us who have engaged in serious academic study of 20th-century UFO phenomena will tell you what an ambitious project that is.

In the end, readers of Scoles's book do not gain much insight into why people continue to believe that UFOs exist and are extraterrestrial in origin. Although we get a sense of the wide variety of beliefs held by witnesses, the book provides very little insight into how or why their positions and attitudes differ. Similarly, Scoles paints a rich picture of the spectrum of groups dedicated to studying UFO phenomena but doesn't explain how these organizations were founded.

Despite those flaws, the book is a fun trip. *They Are Already Here* is a quick read, which is fortunate because it's hard to put down. The text's style and narrative benefit from Scoles's journalistic training. She is generous and sincere with her subjects, who might otherwise be easily cast off as bizarre crackpots. The book is an immersive experience, and although it may not offer much in the way of analysis, it does more to humanize UFO witnesses than most other recent entries in the field.

Kate Dorsch
University of Pennsylvania
Philadelphia

MAI-LINH DOAN/CC BY-SA 3.0



In this demonstration of phenomena explained by solid-state physics, electromagnetic induction causes a magnet to levitate above a superconductor.

An interdisciplinary approach to solid-state physics

Although solid-state physics has evolved into a highly interdisciplinary field, it is typically taught differently by physicists, chemists, and engineers. *Quantum Theory of Materials*, a new graduate-level textbook on the physics of crystalline solids, attempts to bridge varying approaches and provide a comprehensive picture for that broad audience.

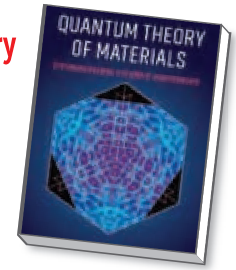
Written by two leaders in the field, Efthimios Kaxiras and John Joannopoulos, the book features a clear exposition of solid-state physics' fundamental theoretical principles, an excellent account of modern computational approaches and applications, and a first-rate introduction to modern topological concepts and their role in shaping the dynamics of Bloch electrons. Because of the authors' clarity, focus on basic principles, and thoughtful choice of examples, *Quantum Theory of Materials* serves as a top-notch introduction to solid-state physics not only for physicists but also for chemists, engineers, and materials scientists.

Solids are complex many-body systems, but their properties are often explained by single-particle or quasiparticle models. In *Quantum Theory of Materials*, the authors discuss with pedagogical clarity the physical principles behind that major simplification without going into complicated technical details. They then describe the emergence of collective excitations, such as excitons, phonons, plasmons, and magnons, and explore the essential effects of the interactions between those collective excitations and quasiparticles. One of those effects—superconductivity—is outlined elegantly in the text.

The chapter on electron dynamics and topological constraints differentiates the book from most existing textbooks because the most important developments in those subfields occurred in the past three decades. It gives a nice pedagogical introduction to the important role played in condensed-matter physics by Berry phases and such related concepts as curvature, connection, and Chern numbers. Similarly, it discusses the role of those concepts in the quantum Hall effect, the microscopic theory of dielectric polarization, and the emerging field of Dirac materials.

Quantum Theory of Materials is a welcome addition to the current crop of solid-state physics textbooks. It has a slightly more advanced mathematical level than the classic *Solid State Physics* (1976) by Neil Ashcroft and N. David Mermin, and it includes significant new material that was not available when that text was written. Modern concepts such as Berry phases and related notions are included in some recent graduate-level textbooks, such as *Fundamentals of Condensed Matter Physics* (2016) by Marvin Cohen and Steven Louie and *Solid State Physics* (2nd ed., 2013) by Giuseppe Grosso and Giuseppe Pastori Parravicini, but those two excellent textbooks require knowledge of more advanced mathematics and are specifically tailored for physicists.

Quantum Theory of Materials
Efthimios Kaxiras and John D. Joannopoulos
Cambridge U. Press, 2019. $89.99



Unlike the aforementioned books, *Quantum Theory of Materials* provides a comprehensive treatment of the subject that is appropriate for a wide interdisciplinary audience. For example, it covers group theory and symmetry in more detail than most solid-state-physics textbooks. Those topics are usually presented in more specialized physics classes, but they are often ignored in engineering and chemistry.

At the same time, the text includes a useful introductory chapter explaining how chemical bonds relate to atomic properties and how vastly different materials result from various bonding interactions. That is a popular subject in chemistry but often receives little attention in physics. Similarly, physicists often use the more abstract formulation of electronic structure theory in reciprocal space, whereas chemists use the more intuitive orbital formulation in real space. The close interrelation of the two approaches is stressed throughout the book.

Every chapter is supplemented by well-chosen problems to help readers better understand the subject. The appendices include concise overviews of basic background material, including mathematical tools and essential concepts from classical electrodynamics, quantum mechanics, thermodynamics, and statistical mechanics.

It is impossible to cover all the important facets of a discipline as diverse as condensed-matter physics in a single textbook. Notably, Kaxiras and Joannopoulos chose not to discuss the effects of disorder on material properties or include an introduction to the physics of liquids and glasses. Those topics would be of interest to the book's audience, and the authors should think about adding such a chapter in a future edition. Nevertheless, *Quantum Theory of Materials* will likely be widely adopted at many universities.

Roberto Car
Princeton University
Princeton, New Jersey

NEW BOOKS & MEDIA

Women of Arecibo

Women in Astronomy

AAS Committee on the Status of Women in Astronomy, 2021

The collapse of the 305-meter radio telescope at Arecibo Observatory last December continues to affect the astronomy community. Women astronomers share their stories and memories of Arecibo in a new series on the *Women in Astronomy* blog, maintained by the American Astronomical Society's Committee on the Status of Women in Astronomy. The series adds a gender-based dimension to the many eulogies for the legendary observatory. The first entry, by postdoc Allison Smith, describes how the famous observatory served as a "beacon" to her during graduate school; it was while working there that she first gained confidence as an astronomer. Smith, who was at the observatory when it collapsed, hopes that the astronomy community will replace it with a new instrument. —RD

The Mission

A True Story

David W. Brown

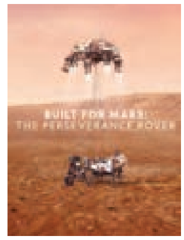
Custom House, 2021. $35.00

Centered on the 17-year effort to develop a spacecraft to study Jupiter's icy moon Europa, *The Mission* relates the story of the *Europa Clipper*, also known as the *Europa Multiple Flyby Mission*. After a brief biography of project scientist Robert Pappalardo, journalist David W. Brown launches into an intriguing narrative that involves NASA, the US government, and the political hurdles scientists faced to get a space mission—particularly one not destined for Mars—from concept to approval. Once a pipe dream, the *Europa Clipper* is now set to launch in 2024. -CC

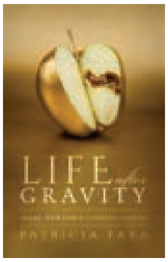
Built for Mars

The Perseverance Rover

National Geographic, 2021



In February, the rover *Perseverance* successfully landed on the Martian surface. The probe managed a daring entry into the atmosphere and is now surviving under harsh surface conditions. How did NASA take the lessons learned from its 2011 rover *Curiosity* and apply them to *Perseverance*? National Geographic's *Built for Mars* documentary delves into this question by following a team of technicians and designers as they build, test, and launch *Perseverance* to the red planet. We see the stress of technicians as they carefully "drill a hole into an instrument worth millions of dollars," and we learn about the rover's small helicopter, its reentry parachute, and the extreme measures taken to reduce contamination of the spacecraft before its launch. Any budding technologist will find *Built for Mars* fascinating; it is available now on National Geographic's website. —PKG



Life After Gravity

Isaac Newton's London Career

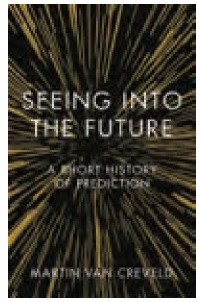
Patricia Fara
Oxford U. Press, 2021. $32.95

Historian of science Patricia Fara explores lesser-known facets of Isaac Newton's later life in this new book on his career as a high-ranking civil servant at the Royal Mint in early modern London. It turns out, for example, that Newton's hatred of Catholicism drove his support of Protestant monarchs King William III and Queen Anne in the 1690s and 1700s. He feared the return of the Stuart dynasty, a Catholic branch of the royal family that William had overthrown in 1688. In addition to recounting Newton's role in political intrigue in the British court, Fara also explores less savory aspects of his career, such as his financial losses in the collapse of the South Sea Company, which played a large role in the transatlantic slave trade (see PHYSICS TODAY, July 2020, page 30). Well-written, engaging, and timely, *Life After Gravity* casts a critical eye on one of the most famous figures in the history of physics. —RD

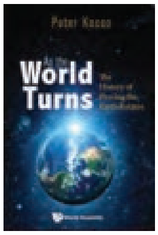
Seeing into the Future

A Short History of Prediction

Martin van Creveld
Reaktion Books, 2020. $24.00



What will the weather be like tomorrow, next week, or next year? Will there be another war, famine, or global pandemic? Will the stock market rise or fall? In *Seeing into the Future*, military historian and theorist Martin van Creveld provides an overview of some of the myriad methods humans have devised over the millennia to foretell what is to come, from the ancients' use of prophecy and astrology to today's mathematical algorithms. In addition to delving into when, where, why, and how those techniques originated, he discusses such questions as why prediction is so difficult, whether modern humans are any better at making predictions than our ancestors were, and whether knowing the future is a good thing. —CC



As the World Turns

The History of Proving the Earth Rotates

Peter Kosso
World Scientific, 2020. $58.00

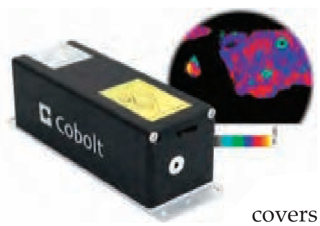
Until the development of the space program in the latter half of the 20th century, humans had no way to leave Earth and directly observe whether it rotates. So how did Nicolaus Copernicus, Galileo Galilei, Isaac Newton, and other early scientists determine that it does? Philosopher of science Peter Kosso addresses the question by delving into the history of humans' study of Earth and the heavens, from the time of the ancient Greeks to the present day. His thought-provoking discussion explores the difference between appearance and reality, the nature of scientific evidence and method, and the apparent dichotomy between the propositions that Earth moves and that all motion is, ultimately, relative. —CC PT

NEW PRODUCTS

Focus on analytical equipment, spectroscopy, and spectrometry

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 its description. Please send all new product submissions to ptpub@aip.org.

Andreas Mandelis



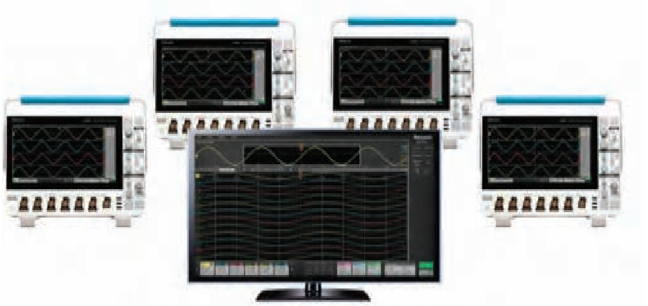
Stabilized 488 nm laser for Raman spectroscopy

Hübner Photonics has added model 08-NLD 488 nm to its Cobolt 08-01 series of high-performance, single-frequency, narrow-linewidth lasers. The series, which covers the broad 405- to 1064-nm range, is designed to meet the requirements of high-resolution Raman spectroscopy applications. The 08-NLD 488 nm offers high wavelength stability of less than 1 pm (over 8 h, ±3 °C), spectral bandwidth of less than 1 pm, and spectral purity of greater than 40 dB. It features fully integrated electronics in a single compact package and delivers 40 mW output power. Cobolt lasers are manufactured using proprietary HTCure technology. According to the company, the resulting hermetically sealed package improves the lasers' reliability under varying environmental conditions. ***Hübner Photonics Inc**, 2635 N 1st St, Ste 202, San Jose, CA 95134, https://hubner-photonics.com*

High-purity water analyzer

The TOC-1000e online total organic carbon analyzer from Shimadzu Scientific Instruments provides high sensitivity and low detection limits, which can reach 0.1 μg/L. It is suitable for industries that require highly purified water, including pharmaceuticals, semiconductors, food and beverages, and precision equipment manufacturing. According to the company, the TOC-1000e analyzer is the first to use a mercury-free excimer lamp in the smallest and lightest casing available. The excimer lamps emit high-energy 172-nm-wavelength light by inducing a dielectric barrier discharge within a xenon gas. New Active-Path technology transfers energy from the lamp to the sample. It efficiently irradiates the sample inside the lamp with UV light to reliably oxidize organic matter. ***Shimadzu Scientific Instruments Inc**, 7102 Riverwood Dr, Columbia, MD 21046, www.shimadzu.com*

Software for multiple-scope analysis

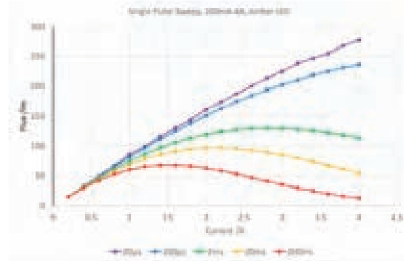


To facilitate research during the COVID-19 pandemic, Tektronix has enhanced its TekScope PC software to allow users to remotely view and analyze data from up to 32 channels from multiple scopes simultaneously in the same interface. The company claims that unlike other available software, the Multi-Scope Analysis feature on TekScope lets users remotely control the acquisition settings on all scopes, rather than requiring them to set up each scope individually. Because up to 32 channels can be debugged together, the high-resolution solution can catch very fast glitches across many channels at once, and analysis is accelerated. TekScope is compatible with data taken from all Tektronix scopes, so users can leverage Tektronix's familiar user interface and analysis features no matter which scope they use. ***Tektronix Inc***, *14150 SW Karl Braun Dr, PO Box 500, Beaverton, OR 97077, www.tek.com*

Integrated test instrument

Keysight has launched its portfolio of Smart Bench Essentials (SBE) laboratory products, which includes four instruments—a triple-output power supply, an arbitrary function generator, a digital multimeter, and an oscilloscope. They are linked by a single graphical interface with data management and analysis capabilities. The reliable, capable SBE products are suitable for university teaching laboratories, which require an environment conducive to sharing and maximizing learning. They can facilitate the blending of remote and in-person learning technologies, a trend accelerated by the COVID-19 pandemic. Their compactness and stackability make them suitable for designing and testing products in small manufacturing businesses. Keysight's PathWave BenchVue application software complements the SBE series, which also offers the optional PathWave Remote Access Lab and PathWave Lab Manager software. ***Keysight Technologies Inc***, *1400 Fountaingrove Pkwy, Santa Rosa, CA 95403-1738, www.keysight.com*

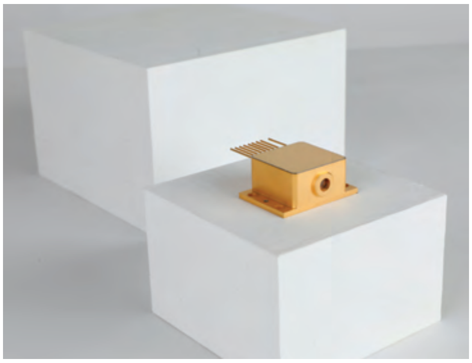
Testing high-power LEDs



According to Instrument Systems, optical measurement accuracy for high-power LEDs in advanced LED package designs requires spectroradiometers with minimum measurement times in the microsecond range and precise triggering to ensure the LED is correctly powered during the short integration time. The company's CAS 125 spectroradiometer with a CMOS sensor and specially tailored readout electronics for time-optimized control delivers minimum exposure times of 0.01 ms. An input/output interface permits synchronization with pulsed current sources or source measure units with hardware trigger capability. Exact synchronization reduces heating and minimizes total measurement time. Integral sensor temperature stabilization ensures a dark current behavior independent of ambient conditions for long-term stability even in environments with unstable temperatures. The CAS 125 is suitable for characterization of high-current-density LEDs, high-power LEDs with reduced heat-dissipation capability, and high-luminance LEDs. ***Instrument Systems Optische Messtechnik GmbH****, Kastenbauerstr 2, 81677 Munich, Germany, www.instrumentsystems.com*

Microfocus x-ray source

According to Excillum, at 700 W its MetalJet E1 delivers 10 times as much x-ray flux across a broad spectral range as a 30 W conventional tungsten-and-solid-anode microfocus source with the same 30 μm spot size. In the spectral range of 24–29 keV, where the characteristic emission lines of indium and tin are present, the flux advantage is as high as 70 times. The MetalJet E1 delivers 24 keV indium $K\alpha$ emission for high-energy analytical applications, which makes it a suitable source for any microfocus application requiring shorter exposure times, higher throughput, or better signal-to-noise ratio. Despite running at a high thermal load, the MetalJet E1 does not require external water cooling. It can be operated remotely from any computer and maintains a positional stability of below 1 μm during continuous long-term operation. Applications include inspection and quality assurance in semiconductor, electronics, and battery manufacturing. ***Excillum AB****, Jan Stenbecks Torg 17, 164 40 Kista, Sweden, www.excillum.com*

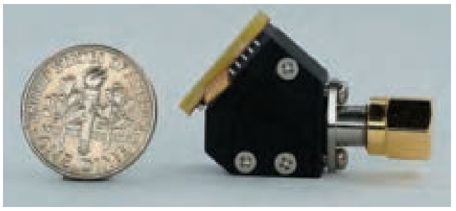


QCLs for gas detection

Photonic Solutions' series of narrow-linewidth Fabry–Perot quantum cascade lasers (QCLs) is now available in wavelengths from 10 μm to 17 μm, suitable for gas-detection applications. The uniMir lasers are manufactured by mirSense of Palaiseau, France, in high heat-load and turnkey configurations. The rugged, ultracompact QCLs produce up to 10 mW CW output power. The QCLs optimized for 10–17 μm operation are based on a new class of single-mode, distributed-feedback QCLs that use different III–V semiconductor materials to fabricate the active region of the lasers. Very tight linewidth drives high-sensitivity gas sensing. The QCLs enable mid-IR absorption spectroscopy to address the important class of aromatics known as BTEX (benzene, toluene, ethylbenzene, and xylenes). The detection of those toxic volatile organic compounds is important for environmental monitoring and safety. ***Photonic Solutions Ltd***, *Unit 2.2 Quantum Ct, Research Ave S, Heriot-Watt University Research Park, Edinburgh EH14 4AP, UK, www.photonicsolutions.co.uk*

High-sensitivity trace-element analysis

Spectro Analytical Instruments, a unit of Ametek's Materials Analysis Division, has introduced the third version of its Spectrogreen analyzer for inductively coupled plasma optical emission spectrometry. The Spectrogreen TI features Spectro's twin interface, which automatically combines both axial and radial plasma views (looking both across and from end to end). It optimizes sensitivity, linearity, and dynamic range while avoiding matrix effects such as easily ionizable elements. The Spectrogreen TI delivers reliable, accurate analyses of trace and higher concentrations of elements in challenging matrices, such as certain wastewaters, soils, and sludges and organic, high-salt, and metal samples. It is suitable for routine elemental analyses in agronomy, consumer product safety, and environmental, pharmaceutical, chemical, petrochemical, and food applications. ***Spectro Analytical Instruments Inc***, *91 McKee Dr, Mahwah, NJ 07430, www.spectro.com*



Ultracompact spectrometer modules

The latest addition to the Ibsen Photonics platform of ultracompact spectrometers is the Pebble VIS-NIR OEM model, which measures only 20 × 15 × 8 mm. At its core is a highly effective transmission grating manufactured by Ibsen. A key benefit of using a transmission grating inside Pebble is a high resolution of 8 nm across the full 500–1100 nm wavelength range. With a fast, very sensitive 256-pixel CMOS detector array and a large numerical aperture of 0.22 (low f-number of *f*/2.2), Pebble provides very high sensitivity for such a small spectrometer. Its pure transmission-based optics ensure good thermal stability and make it suitable for real-time measurements in the field. The cost-effective Pebble is suitable for use by integrators of handheld and portable multispectral instruments for biophotonics, medical, food, and precision agriculture applications based on fluorescence or absorbance measurements. ***Ibsen Photonics A/S**, Ryttermarken 17, DK-3520 Farum, Denmark, https://ibsen.com*

Small molecule analysis

Waters Corporation has released its Acquity RDa detector, a time-of-flight mass spectrometer (MS) for small molecule analysis in academia, pharmaceuticals, food, and forensics. Specific applications include impurity and food contaminant analysis, forced degradation studies, lipid screening, natural products and drug profiling, and general accurate-mass measurements. The compact Acquity RDa detector is quick to deploy and easy to operate. It features SmartMS technology that lets users accurately identify analytes and evaluate outcomes with robust, reliable workflows for routine applications. The detector operates on waters_connect, an open software platform that provides a complete audit trail for acquisition, processing, and reporting of data. It enables high standards of data integrity and compliance to 21 CFR Part 11 requirements. ***Waters Corporation**, 34 Maple St, Milford, MA 01757, www.waters.com*

High-performance FLIM system

The new generation of the Becker & Hickl DCS-120 fluorescence-lifetime imaging microscopy (FLIM) system features high temporal resolution, timing reproducibility, spatial resolution, and sensitivity. Its photon efficiency is nearly ideal, the company says. Fluorescence lifetimes can be detected down to 10 ps, and the decay data can be resolved into 4096 time channels, with a minimum time bin width of 405 fs. Pixel numbers as high as 4096 × 4096 are available. The system is offered in a confocal version with excitation by picosecond diode lasers or in a two-photon version with a titanium:sapphire or a femtosecond fiber laser. The DCS-120 FLIM system uses fast scanning by galvanometer mirrors, confocal or non-descanned detection, and FLIM by the company's multidimensional time-correlated single-photon counting technique. Data acquisition functions include precision dual-channel, multiwavelength, and time-series FLIM; laser wavelength multiplexing; and phosphorescence lifetime imaging. Data analysis is performed by next-generation SPCImage NG software. Applications of the new DCS-120 system include molecular imaging in live cells and tissues, protein-interaction experiments by fluorescence resonance energy transfer, and cancer cell identification. ***Becker & Hickl GmbH**, Nunsdorfer Ring 7-9, 12277 Berlin, Germany, www.becker-hickl.com* PT

Arthur Ashkin

Arthur Ashkin, a groundbreaker in the study of light–matter interaction and the discoverer of optical trapping, died on 21 September 2020 in Rumson, New Jersey. He shared the Nobel Prize in Physics in 2018 for "optical tweezers and their application to biological systems."

On 2 September 1922, Ashkin was born into a Ukrainian Jewish family in Brooklyn, New York. He received a physics BS from Columbia University in 1947. At Columbia's Radiation Laboratory, he constructed magnetrons for US military radar systems. He then went to Cornell University, where he interacted with many physics luminaries, including Hans Bethe and Richard Feynman.

In 1952, after getting his doctorate in nuclear physics under William Woodward, Ashkin went to work for Bell Labs. He initially studied microwaves but switched to lasers in 1961 and worked on parametric oscillators and nonlinear aspects of light propagation in optical fibers. His curiosity about radiation pressure had already been piqued. At a lecture, he heard about the peculiar motion of small particles inside a visible laser's resonant cavity. Called runners and bouncers, the particles were moving back and forth and doing crazy things. Ashkin said at the time, "We think it might be radiation pressure."

Ashkin's vision was to exploit the momentum of light and its interaction with matter. He showed in a seminal 1970 paper that two laser beams pointed at one another could hold tiny inert objects. Removing one laser propelled a particle along the other's direction of propagation. Ashkin built on those concepts and developed optical tweezers. He was interested in both trapping and moving different-sized objects, from atoms to cells. Having gained through that work a deeper insight into the role of radiation pressure and dipole forces of light, Ashkin became part of a team aiming to cool and trap an ensemble of atoms. The researchers succeeded in slowing atoms in "optical molasses" cooled to a mere 300 μK.

Confining atoms close to absolute zero was parallel to trapping larger particles in water. In 1986 Ashkin trapped micron-sized objects using a single tightly focused laser beam. Thus the field of optical tweezers was born. The elegance of the approach cannot be overstated. The insights Ashkin gained were built on exploiting the momentum of light.

Ashkin was also part of a team that applied the principle of a single-beam (dipole) trap to grab a few hundred sodium atoms, for a few seconds, directly from optical molasses. Although minuscule, those studies showed that momentum may impart meaningful and important forces and displacements to objects ranging from a single atom to cells and beyond. Ashkin then initiated the use of optical tweezers on various living systems, including the tobacco mosaic virus, bacteria, red blood cells, and algae, with no damage. In his Nobel Prize interview, he said that when he told colleagues he was "catching living things with light, people said, 'Don't exaggerate, Ashkin.' "

It's no exaggeration, though, to say that optical tweezers have revolutionized biological science, particularly single-molecule biophysics. Although the forces exerted by tweezers are small and cannot break a covalent bond, they are ideal for exploring protein–protein interactions and the forces produced by most motor proteins. Optical tweezers are versatile; they demonstrate an exquisite example of a calibratable, Hookean spring. Scientists became adept at trapping microscopic beads tethered to molecules to make precision measurements.

Importantly, Ashkin's work moved the science away from exploring ensembles of molecules to performing true single-molecule studies. However, to focus solely on the impact of optical tweezers to biology would be a disservice. They have expanded and enriched our understanding of startlingly diverse areas, including nonequilibrium thermodynamics, the very nature of the linear and angular momentum of light, and colloidal science. Today optical tweezers are successfully used in levitated optomechanics, which is poised to provide one of the highest-precision terrestrial sensors and probe the puzzling classical–quantum boundary for mesoscopic particles. At SPIE's 2015 annual meeting on optical trapping and manipulation, Ashkin sent a warm message saying that he was excited to see everyone working on "an ever-expanding field" of tweezers and "wished the community continued success."

Ashkin was also a lauded mentor and teacher. Ursula Gibson, a physics professor at the Norwegian University of Science and Technology and past president of the Optical Society, met Ashkin when she had an internship at Bell Labs. She says of him, "His generous humor, geniality, and interest in a wide range of discussions were wonderful parts of lunchtime conversations. I was not working with him directly, but learned of his experiments. It was a special treat to use optical tweezers while on sabbatical in 2004, furthering the techniques he pioneered."

Retiring from Bell Labs in 1992 did not abate Ashkin's passion for new discoveries. When he heard about his Nobel Prize, he was working on a project in his basement to improve solar energy collection. Physicists consider light to hold a privileged place in the universe; Ashkin saw the potential of light's interaction with matter and exploited it in a unique way. His insight and genius have left an exceptional imprint and legacy, and he has inspired and enthused generations of scientists. Optical tweezers continue to fascinate and pervade many areas of science.

Kishan Dholakia
University of St Andrews
St Andrews, Scotland
Halina Rubinsztein-Dunlop
University of Queensland
Brisbane, Australia

John David Barrow

John David Barrow was a distinguished cosmologist, an original and creative thinker, and a brilliant communicator. His work addressed fundamental questions about why our universe is the way it is and whether it could have been otherwise. Always smartly turned out and brimming with energy, he was an eloquent speaker and a prolific scientist who published several hundred papers and wrote or cowrote 20 books.

Born in the north London suburb of Wembley on 29 November 1952, John went to Ealing Grammar School for Boys, where he was an accomplished sportsman as well as a scholar. He had a trial for Chelsea as a youth footballer, and in a junior middle-distance race he beat Steve Ovett, who went on to become an Olympic champion.

John earned a degree in mathematics and physics from the University of Durham in 1974. For his doctorate, he went to the University of Oxford and worked under the supervision of the legendary Dennis Sciama. In 1977 John completed his DPhil thesis on nonuniform cosmological models, one of many investigations he made into anisotropic and inhomogeneous spacetimes that lie beyond the more restricted class of cosmologies usually considered to describe our universe. He pioneered the use of dynamical systems techniques to describe and classify the rich and sometimes chaotic behavior of generalized cosmological models.

John won a junior research lectureship at Christ Church, Oxford University, and earned postdoctoral scholarships to study at the University of California, Berkeley. There he collaborated with Joseph Silk; in 1983 they wrote what would become John's first popular science book, *The Left Hand of Creation: The Origin and Evolution of the Expanding Universe*. At the University of Sussex, he joined the Astronomy Centre in 1981 as a lecturer; he became a professor in 1989 and its director in 1995. I was a student of John's, and my abiding memory of that time is sitting at a table in the coffee room listening to him, then the young professor, swapping tales about astronomy and astronomers with William McCrea, Roger Tayler, and Leon Mestel, the great old men of the department. John loved to tell a story. He had a remarkable memory and was able to recall and recount facts and humorous anecdotes for any occasion.

In 1999 John moved to Cambridge University to become a professor of mathematical sciences and director of the Millennium Mathematics Project, an outreach program for students and the general public. His interest in the mathematics of sport led to the project's partnership with the London 2012 Olympic and Paralympic Games education program.

John was fascinated by initial conditions in the very early universe. He studied the dynamics of cosmic inflation, an accelerated expansion at ultrahigh energies that could smooth out early inhomogeneities and anisotropies. His work classified and extended studies of inflationary dynamics. He championed the study of inflation in generalizations of Einstein's theory of gravity, which lead to a time-dependent effective gravitational "constant." John was intrigued by whether apparently fundamental constants could change in time. He argued that "although we can measure the constants of nature to a great degree of accuracy in experiments, we have no idea why they take the values they do." In *The Anthropic Cosmological Principle*, written with Frank Tipler in 1986, he explored the many aspects of our universe that are intimately connected to the very existence of intelligent life.

John's popular writing reached a huge audience, and he was a frequent guest on radio programs. He valued his privacy, however, and declined invitations to appear on TV. He also was an inspirational lecturer. At Gresham College in London, John was appointed professor in both astronomy and geometry; he is the only person since the 17th century to be appointed in two subjects. John spoke to prime ministers and popes, and he liked to say that he had dared to lecture Margaret Thatcher on inflation—cosmic inflation, of course.

John David Barrow

MAX ALEXANDER

Such was his versatility that he even wrote an award-winning play, *Infinities*, which premiered in Milan in 2002.

Among John's numerous prizes were the 2016 Gold Medal of the Royal Astronomical Society and the 2015 Paul Dirac Medal and Prize of the Institute of Physics. In 2006 he was awarded the Templeton Prize for his "writings on the relationship between life and the universe."

Like his mentor, Sciama, John attracted and nurtured many bright, curious young minds as a PhD adviser. He supervised 30 doctoral students, many of whom have gone on to become faculty in the UK and around the world.

John kept working right up to the end, completing several scientific papers and a book in the final months of his life. He died of cancer on 26 September 2020, at age 67, in Cambridge, UK.

David Wands
University of Portsmouth
Portsmouth, UK

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George Robert Carruthers

George Robert Carruthers was an inventor, instrument designer, space scientist, and astrophysicist. He excelled in all, but he was fundamentally an innovator who could combine emerging hardware and techniques in clever ways to record phenomena in electromagnetic wavelengths accessible only above Earth's atmosphere.

George was born in Cincinnati, Ohio, on 1 October 1939 and lived on a small farm near Wright-Patterson Air Force Base (AFB), where his father was an engineer. His father died when George was 12, and the family moved to Chicago to be with his mother's family.

George earned a BS in physics, MS in nuclear engineering, and PhD in aeronautical and astronautical engineering at the University of Illinois at Urbana-Champaign. While completing his dissertation on atomic nitrogen recombination in 1964, George was invited to give a colloquium at the US Naval Research Laboratory (NRL) in Washington, DC. He became the NRL's first E. O. Hulburt Postdoctoral Fellow that December. He accepted a full-time staff position in 1967 and spent his entire professional career there. He was often seen riding his bicycle to and from work until his retirement in 2002. George died of heart failure on 26 December 2020 in Washington, DC.

I first caught sight of George at the dedication of the Lindheimer Astronomical Research Center at Northwestern University in May 1967. I was a first-year graduate student. Fred Whipple gave the keynote talk about his icy conglomerate ("dirty snowball") explanation for comets. In a few years, George's instruments would capture UV images of comets Kohoutek and Halley and discover the atomic-hydrogen haloes that emerge when those objects pass near the Sun. George's shy demeanor was evident at the dedication.

When George began his NRL postdoc, several scientists there were using sounding rockets to explore Earth's upper atmosphere and ionosphere in the UV and also the Sun in UV and x rays. George found his niche in the "rocket UV" involving nonsolar objects—stars, gaseous nebulae, nearby galaxies, comets, and Earth's ionosphere and geocorona.

George exemplified the work ethic and values of the laboratory's initiator, Thomas Edison. Some of the research environment pioneered by Edison still existed when George arrived at the NRL. He gloried in the freedom that allowed him to invent, design, and construct his instruments. Anything that he envisioned, and for which he could muster support, could be built on-site. There were facilities to machine and coat metal parts, fabricate delicate optical and electronic components, and assemble and test instruments in simulated space environments. Access to the Wallops and White Sands facilities provided launch opportunities on sounding rockets. As the space program grew, George's longer-duration payloads were launched into Earth orbit from Cape Canaveral and Vandenberg AFB.

George flew his instruments on sounding rockets, satellites, manned space laboratories, and reusable space planes. Some of the payloads were autonomous or remotely controlled devices, whereas others required human hands to point, operate, and retrieve film canisters.

All of the cameras that George built can trace their origin to his patent in 1969 for an "image converter for detecting electromagnetic radiation especially in short wave lengths." The UV cameras typically used highly efficient opaque alkali halide photocathodes deposited on the secondary element of a Schmidt optical system. Photons would pass through a UV-transmitting corrector element and reflect off the aluminized spherical primary mirror to form an image on the curved photocathode. Photoelectrons were accelerated electrostatically and focused magnetically to pass through a hole in the primary and impinge on silver halide emulsion film, microchannel plates, or CCDs.

Sometimes devices eliminated the corrector element or had the camera viewing a diffraction grating. That was the case with George's first major discovery: On a rocket flight in March 1970, he detected molecular hydrogen in space—the most common molecule in the universe. The photograph shows George at age 30 with the instrument he used.

I first spoke with George in the Mission Control visitor gallery at NASA's Manned Spacecraft Center in April 1972. I was in my second year of a postdoc. George, not quite five years older than I, was having a

George Robert Carruthers

US NAVAL RESEARCH LABORATORY

gold-plated camera operated on the lunar surface by *Apollo 16* astronauts. My *entrée* was that I was using a Kron electronographic camera on the telescopes at McDonald Observatory. But George's mind was understandably occupied by worries whether his camera would not be properly operated or function as planned. So our conversation was polite but brief. The camera received considerable notoriety as the "first astronomical observatory on the moon" and is most remembered by the dramatic image of Earth's geocorona, tropical airglow belts, and polar aurora—the first time the whole Earth had been viewed in the far-UV.

My next contact with George occurred when I gave a colloquium at the NRL. I subsequently spent 15 years working in the office next to George and across the hallway from his laboratory.

In the early 1990s, George was determined to give back. He became quite involved with various educational outreach programs and mentored African American high school and college students at the NRL, Howard University, and around Washington, DC.

George received many honors and awards. The most significant was the National Medal of Technology and Innovation, presented by President Barack Obama in 2012. But I suspect the one George enjoyed most was being inducted into the National Inventors Hall of Fame—as was Edison.

Harry Heckathorn
Church Creek, Maryland PT

Axel Lorke is a professor of physics at the University of Duisburg-Essen in Germany.

Boiling eggs, radiation damage, and the Arrhenius plot

Axel Lorke

In 1899 a Swedish chemist created a method to analyze the effect of temperature on the rates of chemical reactions.

Svante August Arrhenius (1859–1927) was one of the most accomplished scientists of his time. A founder of physical chemistry, he contributed to such diverse fields as meteorology, geophysics, physiology, and cosmology. In 1896, he was the first to predict global warming as a consequence of human carbon dioxide emissions. His early dissertation work on the theory of ionic dissociation, however, was met with skepticism. Many scientists of his time just could not imagine that the intimate bond between, say, sodium and chlorine in table salt could simply fall apart in water, and that all those chlorine atoms would not reveal themselves through their characteristic smell.

A travel grant from the Swedish Academy of Sciences gave Arrhenius the opportunity to discuss his ideas with such great minds as Walther Nernst and Ludwig Boltzmann, shown in figure 1, Jacobus van't Hoff, and Wilhelm Ostwald. His groundbreaking work on the electrolytic theory of dissociation was soon widely recognized, and in 1903 he was awarded one of the first Nobel Prizes in chemistry.

Today, Arrhenius is best known as the name of a data-evaluation method that is almost universally used in chemistry, physics, and materials science. The Arrhenius plot reflects the thermal Boltzmann equation, which gives the probability for a state to be occupied as $e^{-\Delta E/k_B T}$. In the equation, ΔE is the state's excitation energy, k_B is the Boltzmann constant, and T is the temperature.

FIGURE 1. SVANTE ARRHENIUS and Ludwig Boltzmann's group in Graz, Austria, 1887. Boltzmann sits in the center, Arrhenius stands behind him on the right, and Walther Nernst stands at the far left. (University of Graz, Wikimedia Commons, CC-PD Mark 1.0.)

The shape of a reaction

For a wide range of thermally induced processes, plotting the logarithm of the data against the inverse temperature gives a linear dependence. The slope of the regression line in the plot then gives the characteristic excitation energy needed for the process. Today the Arrhenius equation is considered an empirical relationship, and more rigorous treatments have replaced it for many specific problems. But what it may lack in rigor, it makes up in practicality and generality.

In chemistry, for example, the Arrhenius plot is commonly used to determine the activation energy of a reaction from the temperature dependence of its reaction rate. Figure 2 shows a textbook example from solid-state physics, in which two characteristic energies can be derived from a single Arrhenius plot. The carrier density in the conduction band of a doped semiconductor is plotted against the inverse temperature. At high temperatures (top scale), notice the steep slope, which corresponds to electrons being lifted from the valence band across the bandgap ($\Delta E_g \approx 1$ eV) into the conduction band. At low temperatures, that process is frozen out and no longer relevant. Rather, a different Arrhenius-type behavior occurs, in which the characteristic energy is now the (much smaller) donor ionization energy ($\Delta E_d \approx 50$ meV).

Contrary to common belief, an Arrhenius plot does not require $\Delta E \approx k_B T$. That's evident in figure 2: To induce enough carriers to make silicon conducting, you do not have to heat it up to temperatures around 10 000 K ($k_B T \approx 1$ eV). Just a few hundred kelvin will suffice. Another appealing feature of the Arrhenius plot is the deep insight it can provide into a system, even when the measured property is easily accessible. For example, from the tabulated, roughly exponential decrease in air pressure with height above sea level, one can deduce the average mass of molecules in the lower atmosphere with surprising accuracy. In that case, the potential energy ΔE (which equals molecular mass × gravitational acceleration × height), rather than the inverse temperature, should be used as the abscissa.

An egg's gelation rate

Those advantageous properties of the Arrhenius plot recently came to mind in a discussion with a colleague about the harm-

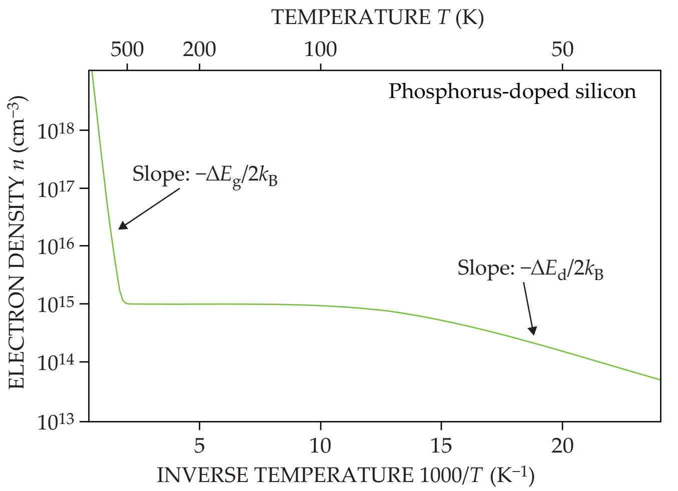

FIGURE 2. ARRHENIUS PLOT of the electron density n in phosphorus-doped silicon. Two distinct regions can be seen with a linear relation between the inverse temperature $1/T$ and the natural logarithm of the density. At temperatures above a few hundred kelvin (top scale), the slope corresponds to the excitation of carriers across the bandgap ΔE_g. In the low-temperature regime, a much smaller slope yields the ionization energy of the dopant. The factor of two in the denominator arises because electrons obey Fermi–Dirac statistics rather than classical Boltzmann distribution. (Data from Cornell University's Solid State Simulation Project at http://pages.physics.cornell.edu/sss.)

fulness of human exposure to UV radiation. Where, approximately, would one set the boundary between safe and harmful? On a molecular level, the threshold would be the energy sufficient to deteriorate vital biological matter, such as proteins. And surely, medical scientists have performed careful *in vivo* and *in vitro* studies to identify that threshold.

For a quick estimate, though, would the Arrhenius approach be helpful? Inspiration came from an outreach activity of our department's Collaborative Research Center. For the Easter holiday, we in the department featured the physics of boiling eggs and came across some surprisingly rigorous studies.

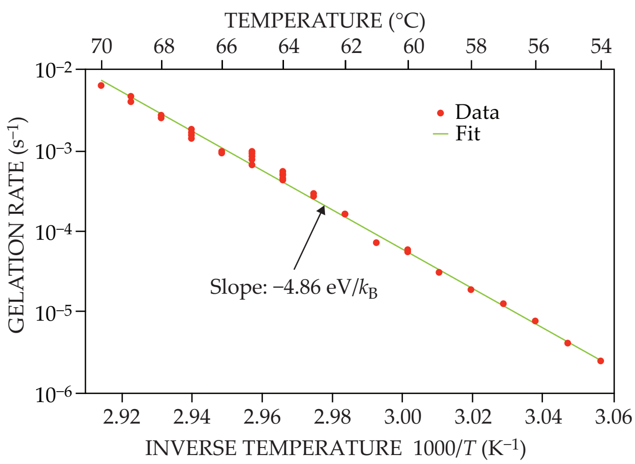

FIGURE 3. GELATION RATE (log scale) of egg yolk as a function of inverse temperature. For each data point, the yolk was heated to a particular temperature until it gelled. By definition, that happens when the elastic and viscous moduli become equal. (Data from C. Vega and R. Mercadé-Prieto, *Food Biophysics* **6**, 152, 2011.)

Data from one study are shown in figure 3. The Arrhenius plot gives the gelation rate of egg yolks as a function of water temperature. To obtain those results, the authors, César Vega and Ruben Mercadé-Prieto, had to patiently "cook" eggs for up to 100 hours. Moreover, they also needed to establish a method to use small-deformation rheology to precisely determine the egg yolk's gelation point, at which its proteins aggregate and give the yolk viscosity.

The original data give the gelation time versus temperature. But recasting the data as a function of inverse temperature provides the rate in a best-fit Arrhenius plot—the solid line shown in the figure. That plot's slope yields 4.86 eV, which estimates the typical energy needed to degrade the biological matter present in a chicken egg.

The degradation of proteins that leads to gelation can be triggered by more than just thermal energy. Electromagnetic radiation can induce coagulation as well, and the results of the Arrhenius plot can serve as a guide to estimate the necessary photon energy. A similar situation is found in semiconductors: The characteristic energies ΔE_g and ΔE_d can be derived either from Arrhenius plots, such as figure 2, or from spectroscopic data at the onset of light absorption.

A 4.86 eV photon corresponds to a wavelength of 255 nm, which places the threshold for radiation damage in the UV-C region of the electromagnetic spectrum. That placement agrees with the absorption maxima of vital biological compounds, such as proteins (280 nm) and nucleic acids (260 nm). Indeed, UV-C radiation is lethal for microorganisms and is used in germicidal lamps for medical applications and for sterilizing seeds, nuts, herbs, spices, and teas. Were you to zap an egg yolk with a 255 nm laser pulse, it may not cook instantly, but it would coagulate. And with a strong laser that might happen quite quickly.

Light from the UV-A and UV-B regions (315–400 nm and 280–315 nm, respectively) is not entirely harmless. But it is much less damaging than shorter-wavelength radiation, and some exposure to UV-B is, in fact, beneficial for the production of vitamin D in biological tissue. Fortunately, UV-C radiation is efficiently blocked by Earth's atmosphere, so that living organisms are well shielded from its detrimental effects. Apparently, life on Earth has adjusted to these environmental conditions by clever design of its vital compounds—a sample of which can be found in your breakfast egg.

Additional resources

▶ B. Van Zeghbroeck, *Principles of Semiconductor Devices*, https://ecee.colorado.edu/~bart/book.

▶ H. Neurath et al., "The chemistry of protein denaturation," *Chem. Rev.* **34**, 157 (1944).

▶ C. Vega, R. Mercadé-Prieto, "Culinary biophysics: On the nature of the 6X°C egg," *Food Biophysics* **6**, 152 (2011).

▶ R. Munroe, "Can you boil an egg too long?" *New York Times*, 9 June, 2020.

▶ For scientific aspects of boiling an egg, see http://newton.ex.ac.uk/teaching/CDHW/egg; for a culinary approach to cooking the perfect egg yolk, see https://blog.khymos.org/2011/04/18/perfect-egg-yolks.

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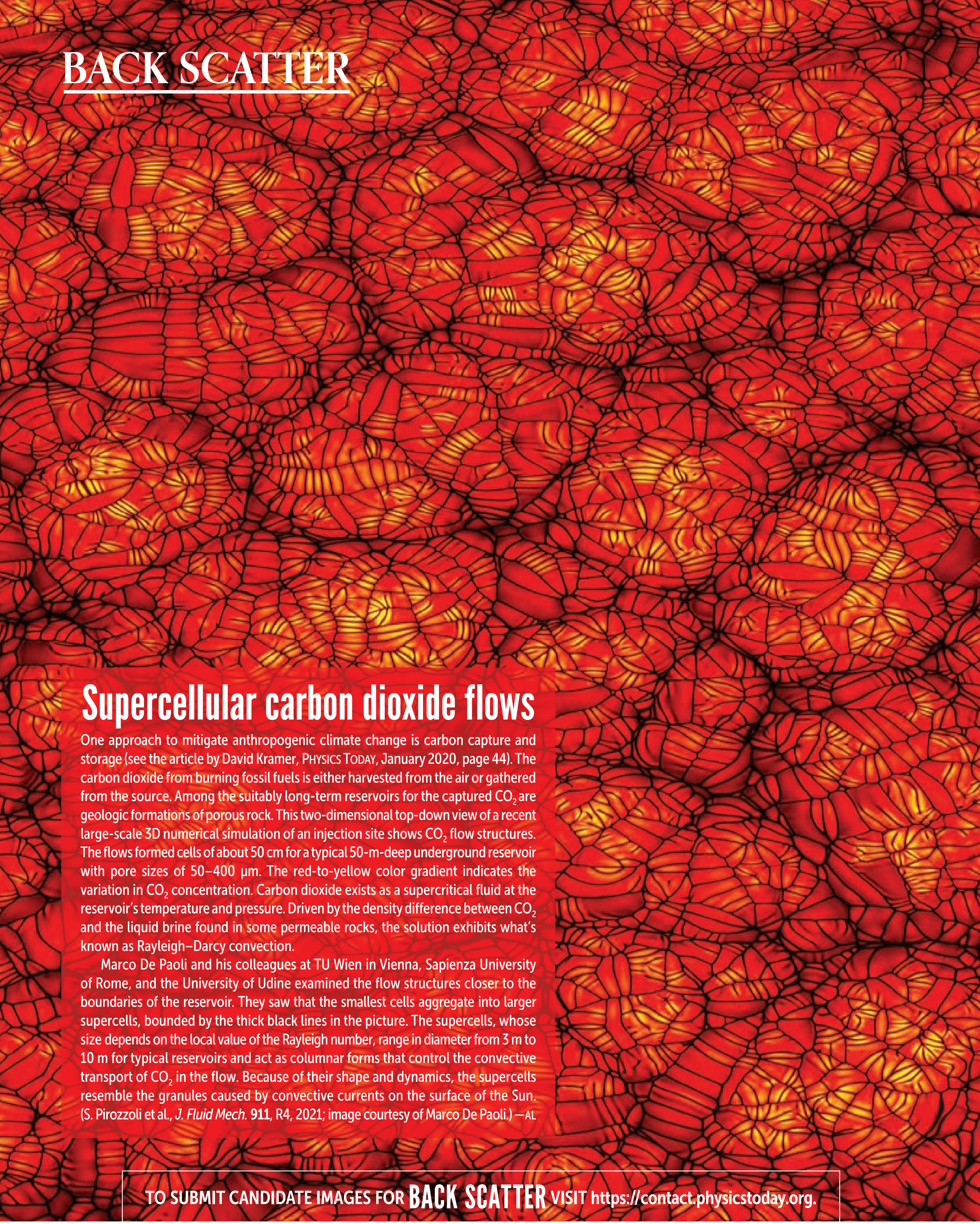

Supercellular carbon dioxide flows

One approach to mitigate anthropogenic climate change is carbon capture and storage (see the article by David Kramer, PHYSICS TODAY, January 2020, page 44). The carbon dioxide from burning fossil fuels is either harvested from the air or gathered from the source. Among the suitably long-term reservoirs for the captured CO_2 are geologic formations of porous rock. This two-dimensional top-down view of a recent large-scale 3D numerical simulation of an injection site shows CO_2 flow structures. The flows formed cells of about 50 cm for a typical 50-m-deep underground reservoir with pore sizes of 50–400 μm. The red-to-yellow color gradient indicates the variation in CO_2 concentration. Carbon dioxide exists as a supercritical fluid at the reservoir's temperature and pressure. Driven by the density difference between CO_2 and the liquid brine found in some permeable rocks, the solution exhibits what's known as Rayleigh–Darcy convection.

Marco De Paoli and his colleagues at TU Wien in Vienna, Sapienza University of Rome, and the University of Udine examined the flow structures closer to the boundaries of the reservoir. They saw that the smallest cells aggregate into larger supercells, bounded by the thick black lines in the picture. The supercells, whose size depends on the local value of the Rayleigh number, range in diameter from 3 m to 10 m for typical reservoirs and act as columnar forms that control the convective transport of CO_2 in the flow. Because of their shape and dynamics, the supercells resemble the granules caused by convective currents on the surface of the Sun. (S. Pirozzoli et al., *J. Fluid Mech.* **911**, R4, 2021; image courtesy of Marco De Paoli.) —AL