PHYSICS TODAY
February 2022 • volume 75, number 2
A publication of the American Institute of Physics

HYDROLOGY FROM SPACE

Supply-chain woes

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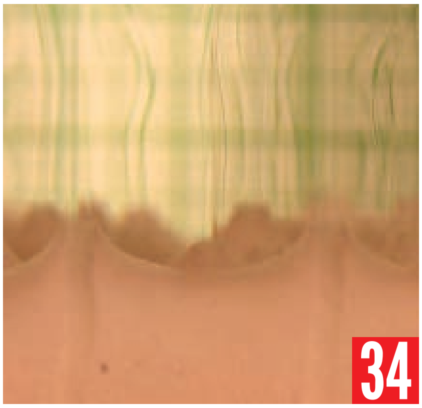

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PHYSICS TODAY

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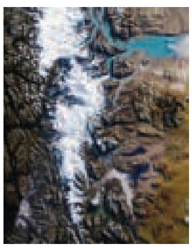
FEATURES



ON THE COVER: The Southern Patagonian Ice Field, which straddles Chile and Argentina, feeds glaciers, lakes, and rivers that ultimately flow into the Pacific and Atlantic Oceans. Scientists now can remotely monitor sea ice, snow depths, and soil moisture there and elsewhere by using GPS signals reflected from Earth's surface. To read about how GPS antennas sense the hydrological cycle, turn to Clara Chew's article on **page 42**. (*Landsat 8* image, courtesy of NASA's Earth Observatory/Jesse Allen, using data from the US Geological Survey.)

Recently on PHYSICS TODAY ONLINE

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Art analysis

Materials scientist Robert Erdmann talks to Physics Today's Toni Feder about how he combines x-ray and IR imaging with neural networks to understand artworks' physical features and how they were made. His analyses of old paintings have revealed covered-over figures, the composition of pigments, and more.

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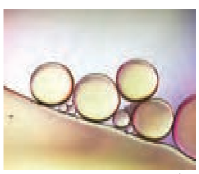

A_DIFFERENT_PERSPECTIVE/PD

Oil and water

Why don't oil and water mix? The classic explanation is that water molecules are polar and oil ones are not, yet oil droplets can have negative surface charge. Physics Today's Alex Lopatka examines a new study that may explain how water can transfer negative charge without promoting mixing.

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JULIETA LABATUT

Labatut Q&A

In *When We Cease to Understand the World*, Benjamín Labatut uses scientists such as Fritz Haber and Werner Heisenberg to explore the destructive potential of science. The writer talks to Books editor Ryan Dahn about his interest in physics and the book's special blend of fact and fiction.

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Physics Today (ISSN 0031-9228, coden PHTOAD) volume 75, number 2. Published monthly by the American Institute of Physics, 1305 Walt Whitman Rd, Suite 110, Melville, NY 11747-4300. Periodicals postage paid at Huntington Station, NY, and at additional mailing offices. POSTMASTER: Send address changes to Physics Today, American Institute of Physics, 1305 Walt Whitman Rd, Suite 110, Melville, NY 11747-4300. Views expressed in Physics Today and on its website are those of the authors and not necessarily those of AIP or any of its member societies.

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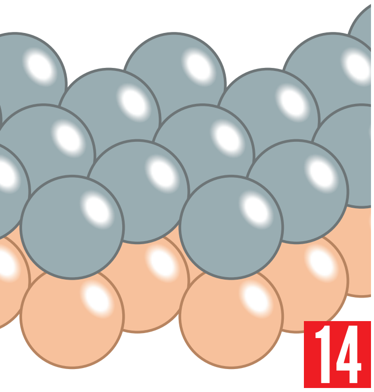

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FROM THE EDITOR

If this, why not that?

Charles Day

The plot of Frank Herbert's 1965 novel *Dune* and its prequels, sequels, and adaptations centers on controlling the supply of a potent mind- and body-altering drug called melange or, more familiarly, spice.

Spice is harvested from the desert sands that cover most of the planet Arrakis, the drug's only source. Just how the corresponding molecules are made is unclear, but the process as described in the books involves organisms, fermentation, and possibly photochemistry.

In 1959, six years before *Dune* was first published, Paul Janssen discovered fentanyl, a synthetic opioid that's 100 times as potent as morphine and 50 times as potent as heroin. Heroin itself was first synthesized in 1874. Given how valuable spice is in the world of *Dune* and given that the world features faster-than-light travel and antigravity suspensors, it's remarkable—and I would say implausible—that spice has to be harvested from sand rather than manufactured in a lab.

Science fiction often posits technologies not just that are beyond current capabilities but that violate the laws of nature. Nuclear fusion might one day power spacecraft, but it won't propel spaceships to faster-than-light speeds, as in *Star Trek*. Readers, even physicist readers, suspend their disbelief because implausibly advanced technologies make it possible for authors to explore rich, morally fraught scenarios that a strictly realistic setting could not accommodate.

But what should we make of Herbert's decision to do the opposite—that is, to posit a future technology, spice harvesting, that's *less* advanced than a current technology, drug synthesis? Of course, Herbert devised a natural and scarce source of spice to serve his plot. But I can't help thinking that he was unaware of modern pharmaceutical science.

Military technology is another area that science fiction sometimes underestimates, especially in movies and on TV. George Lucas based the climatic assault on the Death Star in *Star Wars: Episode IV—A New Hope* on a similar scene in the 1964 British movie *633 Squadron*, which is set during World War II.[1] In the advanced world of the Galactic Empire, the appearance of 1940s military technologies (joystick-controlled guns) and tactics (low-altitude bombing) is incongruous.

Remote sensing is another current technology that science fiction underestimates. Instruments aboard orbiting spacecraft are determining the topography, gravity distribution, and atmospheric composition of Earth, Mars, and other planets. But in the movie *Prometheus*, which is set in the years 2089–93, astronauts rely on their own eyes to find things of interest on the surface of their destination, the moon LV-223. And they wait until they're in the planet's lower atmosphere to assess whether it's safe for them to breathe.

All this might seem like the quibbling of a science pedant. But it's troubling that authors and directors of science fiction either are ignorant of science or can assume their audiences are ignorant of science. Among the most egregious recent examples is the following: In *Star Wars: Episode VIII—The Last Jedi*, the StarFortress *Hammer* released its payload of bombs that somehow fell toward their target, the Siege Dreadnought *Fulminatrix*, in the microgravity of outer space.

Does it matter that the creators and consumers of science fiction and, by extension, the rest of the general public might be unaware of just how far some sciences have advanced? Yes. It's better for society that the ethical, environmental, and economic implications of new technologies be discussed well before the technologies are ready for deployment. Fortunately, that seems to be the case with CRISPR-Cas9 gene-editing tools. But the combination of two other technologies—facial recognition and cloud-based computation—has received less attention. And we are still grappling with what to do with nuclear waste 70 years after the first nuclear power stations came on line.

Some science fiction writers explore the consequences of just-out-of-reach technologies. William Gibson's Blue Ant trilogy (2003–10) and Charlie Brooker's anthology TV series *Black Mirror* (2011–19) are notable recent examples. But what we really need is a high-quality, unfrivolous popular outlet for science fact.

REFERENCE

1. This YouTube video pairs footage from *633 Squadron* with the soundtrack from *Star Wars: Episode IV—A New Hope*: www.youtube.com/watch?v=4OZq-tlJTrU.

PT

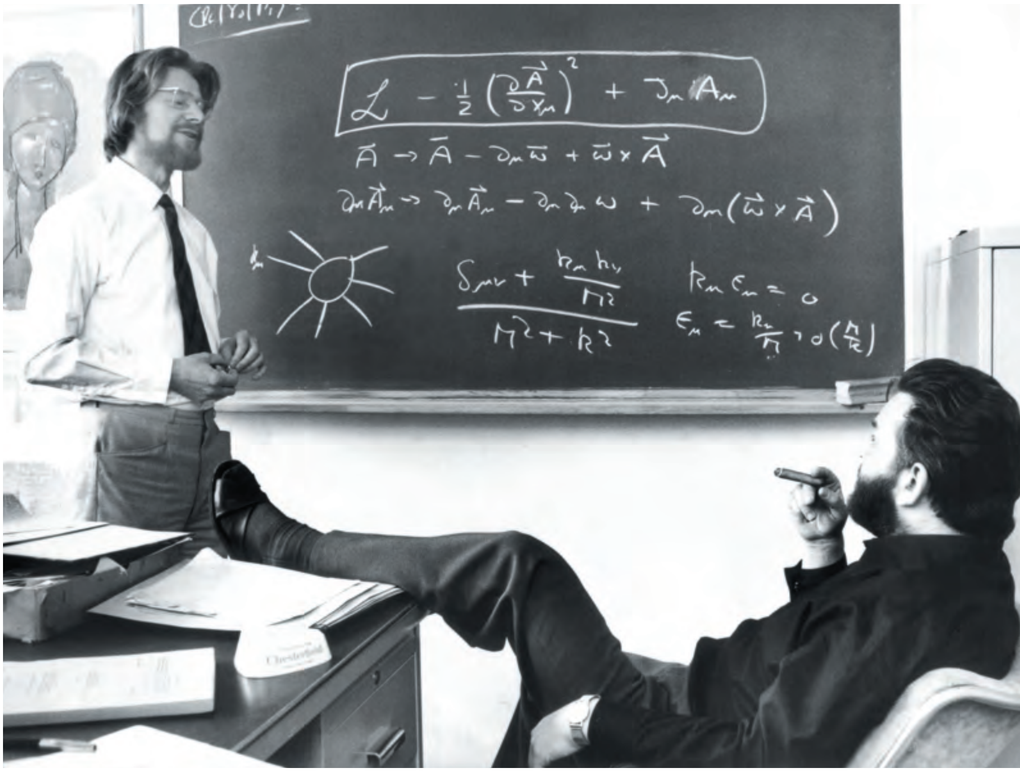
Commentary

A physicist's perspective on COVID-19

The COVID-19 pandemic has not only killed a large number of people—approximately 5.5 million worldwide at the time PHYSICS TODAY went to press in mid-January—it has also disrupted life in a fundamental, nonperturbative manner, forcing large-scale changes in human behavior from without.

The total effect of the pandemic is, of course, unknown at this point, since we are very much in the midst of it and the end is still at some unknown future. In fact, it is entirely possible, perhaps even likely, that the pathogen originally known as the 2019 novel coronavirus, SARS-CoV-2, will never leave the human host and will become endemic, just as other, not-so-novel coronaviruses that cause the common cold have done already.

COVID-19 predictions are pretty much like all large-scale nonlinear predictions, such as those for weather: It is possible to make not-so-useful, long-term qualitative predictions globally, and it is possible to make relatively accurate, very short-term quantitative predictions locally, but that is about it.



AT CERN IN 1973, John Bell (left), who was working there at the time, interacts with Martinus Veltman (right), who was then a professor at Utrecht University in the Netherlands. Since early 2020, COVID-19 has hindered physicists' ability to travel and discuss physics in person. (Courtesy of CERN.)

Early in 2020, I did some large-scale COVID-19 dynamics simulations with considerable help from my student Haining Pan. My simulations were lattice based with long-range coupling and hopping to represent disease transmission. What I quickly found out is that the simulation results depend *entirely* on the input parameters, none of which are known with any accuracy, and those parameters are almost randomly time dependent.

Many papers written by physicists reported similar simulations along with many predictions. Alas, it turns out that SARS-CoV-2 is too elusive a virus for any such simulations, by physicists or by others, to have any real predictive power except in the broadest terms—for example, for confirming that vaccination and testing are good.

It was difficult in the beginning of 2020 to anticipate the great COVID-19 calamity awaiting the world. In February of that year, I was apparently among the first people to have urged the leadership of the American Physical Society to cancel its upcoming March Meeting in Denver, which APS finally did at the last moment after considerable hesitancy.

The logistics of canceling a meeting of 10 000 people right before the event are not trivial. But given the crowd density in APS March Meetings, it is reasonable to assume that the 2020 event would have led to a few thousand COVID-19 cases *just* among the physicist attendees. Overall, it may have led to many tens of thousands, perhaps even hundreds of thousands, of cases, if not more. That estimate is based on research related to the now-infamous Boston Biogen superspreader conference in late February 2020. Within a month, roughly 100 people in Massachusetts who either went to the conference or were a household contact of someone who went tested positive. Genetic-code-based investigation estimated that the event led to 300 000 COVID-19 cases worldwide by the beginning of the following November. APS made the right call in canceling the meeting.

Even before the appearance of the

Omicron variant in mid-November 2021, roughly 250 million COVID-19 cases had been reported to the World Health Organization. Random stochastic counting says that out of those 250 million cases, some 10 000 should have been physicists. But physicists are rational and generally careful people, so the actual number of infected physicists may have been much lower than that.

I write from the perspective of a highly active theoretical condensed-matter physicist who also happens to be the director of the University of Maryland's Condensed Matter Theory Center (CMTC), which consists of more than 30 young researchers. All CMTC members and all my colleagues in the University of Maryland physics department are fully vaccinated, and quite a few had received their booster shots by early November.

The physicists I know understand the science well and have taken responsible precautions throughout the pandemic. But infection and illness are just two aspects of the COVID-19 pandemic. The all-encompassing ramifications of COVID-19 extend way beyond the disease itself.

From my perspective, the most profound effects of COVID-19 on the physics community have been the absence of direct face-to-face discussions among physicists at the blackboard and of in-person conferences and workshops. I used to travel 150 000 to 500 000 kilometers per year before COVID-19, attending conferences all over the world, giving talks, and interacting with collaborators face to face. CMTC members and visitors used to go out to lunch or dinner together, often in groups of 10–15. The center used to host around 30–50 seminars per year, with the seminar speakers spending several days on campus.

All of that has vanished and may not come back for a long time. My last extended physics-related trip was to Aspen, Colorado, for a month in the summer of 2019, and the CMTC has hosted only one visitor during the past 20 months. The very thought of wearing a mask while traveling and then throughout a conference is sobering, and for me, foreboding. Traveling to do physics is supposed to be fun, not a chore. In-person interaction with other physicists at other institutions often led spontaneously to new ideas and new physics. I worry that it will be a long time before the culture of direct face-to-face interaction among physicists gets reestablished.

Of course, physics talks and conferences continue in virtual modes. Some of those meetings are excellent, and often the question sessions can go on for a long time, which is useful. My remotely delivered 2021 APS March Meeting talk on Majorana quasiparticles was followed by an almost hour-long discussion online. But such discussions can never replace the in-person interactions that dominated physics conferences and workshops. Among all COVID-19-related problems adversely affecting the physics community, I miss in-person interactions the most.

To view my writings on COVID-19 and its dynamics, see my blog at https://condensedmattertheorycenterblog.wordpress.com/blog/.

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LETTERS

Solar energy considerations

I would like to add several details to David Kramer's item "The cost of solar energy production has plunged, but it needs to fall further" in the June 2021 issue of Physics Today (page 27).

First, while the monetary costs are important for investment decisions, they are less relevant in decisions regarding sustainability and decarbonization because they depend not only on where and with what energy source panels are made but also on financing, depreciation, taxes, and government subsidies. Costs should be accrued in energy units and compared with energy outputs in the same units. This ratio is typically referred to as energy return on energy invested (EROEI), which is a useful figure of merit for an energy source. Carbon saved over carbon invested would be another useful figure of merit.

I presume that the costs of solar photovoltaics (PV), particularly for the energy-intensive production of silicon crystals and aluminum frames, have not fallen in energy units as much as they have in dollars. I also presume that the EROEI for solar PV is still rather poor, and storage further reduces EROEI. In addition, one must consider the low duty factor (around 20% in my area) for solar energy.

Second, while solar PV is locally "clean," one must look at the whole production cycle—including mining of materials, fabrication (particularly of crystalline silicon and the aluminum frames), and transportation—and the energy involved and carbon produced in those processes. All these energy and carbon costs are up-front, and they are only recovered over some fraction of the life expectancy of the facility, which is about 25 years. The disposal process must be considered as well.

Third, I have found the transparency about the costs of solar PV to be abysmal, and I have found it nearly impossible to get detailed information about projects in my region. When public support, in the form of subsidies, tax advantages, or soft costs such as government reviews, goes to such projects, the public has a right to know about them. If the economics and the sustainability of the projects were as good as we are led to believe, I expect that this information would not be hidden behind corporate and government curtains.

David Kramer is right that the costs of solar PV need to fall further, but I would modify that to read as follows: The costs of solar PV measured in energy units need to fall a lot.

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David Kramer's report "The cost of solar energy production has plunged, but it needs to fall further" (Physics Today, June 2021, page 27) gives an excellent overview of the present state of solar technology. One point, however, needs clarification. In evaluating cadmium telluride, the author correctly recognizes the toxic properties of cadmium, which is a carcinogen. He cites the claim that CdTe is virtually insoluble in water, but that dismisses the groundwater contamination risks posed if CdTe panels end up in a landfill.

In 2010–11, I worked at the now-defunct Amelio Solar in Ewing, New Jersey. Suspecting that the fluid that oozes through most landfills might be sufficiently acidic (or sometimes basic) to dissolve CdTe, my colleagues and I conducted experiments in collaboration with a team at the Catholic University of America in Washington, DC.[1]

Both groups cut 50 mm squares from a commercial CdTe module. My team cracked each square with one hammer blow to simulate the breakage that would likely occur when discarded panels were dumped. We then placed each piece in a closed jar containing 150 mL of citric-acid-based buffer solution with a pH value of either 3, 4, 5, or 6. The last square went into deionized water. The Catholic University team members scribed their samples with a diamond saw to avoid the randomness of the hammered breakage. They used rainwater as the reference and solutions with pH values of 4 for acid and 10 for base.

Over the course of six months, my team analyzed the solutions for cadmium using inductively coupled plasma optical spectrometry. The sample in pure water with a pH of 7 showed no additional damage, and even at the end, the cadmium concentration in the solution was only 7 ppm. The results were markedly different for the acidic solutions. The farther the pH diverged from 7, the faster the cadmium leached into the solution. After three months, the most acidic samples had completely delaminated, and the cadmium concentrations in the solutions in which they were immersed had reached over 100 ppm. We also observed that the higher concentrations had leveled off well before the end of the experiment, suggesting that virtually all the cadmium had leached out of those specimens.

The Catholic University team ran their tests for 70 days. They obtained essentially similar results, with about 3 ppm cadmium for rainwater, 54 ppm for pH = 4, and 140 ppm for pH = 10.

In 2017 a team at the University of Arizona published a study with experiments similar to ours in both method and results.[2]

Even if CdTe-module makers promise to reclaim the products at the end of their useful life and recycle the cadmium, can we be confident that they will actually do so 30 years in the future?

At least two additional tests have shown that CdTe modules present a serious groundwater pollution hazard if they end up broken in a landfill permeated by something other than neutral water with a pH of 7.[3,4] If we are to use such technology, we must guarantee a safe disposal and recycling program, and include its full cost and risks in any evaluation of CdTe photovoltaics.

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Medieval astrometeorology's legacy

Anne Lawrence-Mathers's article "Medieval weather prediction" (PHYSICS TODAY, April 2021, page 38) is a welcome work of history of science that introduced me to some people and works I had never before encountered. As far as I can judge, it is quite accurate, although Johannes Kepler was surely never a *pupil* of Tycho Brahe.

It is nonetheless a serious failing of the article to not call attention to the most striking feature of medieval astrometeorology: It did not work. That Eyno of Würzburg claimed to have predicted heavy snow three times is no more an indication of success than an occasional win yielded by a gambler's system.

In a follow-up online piece ("The triumphs and failures of astrometeorology," PHYSICS TODAY online, 30 April 2021), Lawrence-Mathers acknowledges that the theoretical basis of astrometeorology was incorrect but states that, on balance, its contributions to scientific developments were positive. She seems to think the complexity of astrometeorology was a beneficial aspect of it. But astrology, which shared features with astrometeorology, was just as complex. So, was astrology a plus for the development of astronomy? Well, in a way it was, but it was also an obstruction to it.

Kepler knew astrology was nonsense but hoped to improve it. His enhancements were equally nonsensical at first, but they drove him toward creating a really good astronomy. I rate astrology a net negative, but nonetheless, we can acknowledge and learn from the ways it was positive. Similarly, while we can learn from medieval astrometeorology, the predictions it produced "worked" only accidentally. I call that a net negative. There is no arithmetic for weighing the pluses and minuses of history. Any such weighing is therefore a personal judgment.

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▶ **Lawrence-Mathers replies:** Astrometeorology was fully compatible with models of the universe going back to the classical period; it was radical in that it made detailed calculations about localized weather. Its power is seen in its practitioners' quest to improve the model by keeping weather records and attempting to correlate them with predictive factors in it. In espousing that tradition, Kepler, and many others, paved the way for the expanded observations of the 18th century. It was that practice, rather than the theoretical model, that was astrometeorology's lasting contribution.

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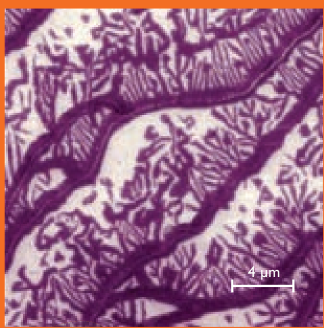

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Two-faced ions form a promising battery material

Electrolyte molecules that have both positive and negative charges stay in place while lithium ions move among them.

Lithium-ion batteries have seen stunning improvements in their size, weight, cost, and performance. (See PHYSICS TODAY, December 2019, page 20.) But they haven't yet reached their full potential. One of the biggest remaining hurdles has to do with the electrolyte, the material that ferries lithium ions from anode to cathode inside the battery to drive the equal and opposite flow of charge in the external circuit.

Most commercial lithium-ion batteries use organic liquid electrolytes. The liquids are excellent conductors of lithium ions, but they're volatile, flammable, and defenseless against the whisker-like lithium-metal dendrites that can grow between the electrodes and eventually short-circuit the battery. Because safety comes first, battery designers must sacrifice some performance in favor of not having their batteries explode or catch fire.

A solid-state electrolyte could solve those problems. For the past two decades, Jenny Pringle, Maria Forsyth, and colleagues at Deakin University in Melbourne, Australia, have been exploring a class of materials, called organic ionic plastic crystals (OIPCs), that could fit the bill. Now, along with research fellow Faezeh Makhlooghiazad, they've built on that work to create a new type of electrolyte material: an OIPC made of molecules that contain both positively and negatively charged components.[1]

The two-faced ions, called zwitterions (from the German word *Zwitter*, meaning "hermaphrodite"), have the advantage of being unaffected by the electric field produced by the battery's positive and negative electrodes, as shown in figure 1. As a result, they don't compete with the lithium ions flowing through the battery. Although the specific zwitterionic materials studied so far aren't quite suitable for commercial batteries, the diversity of organic molecules means that many more possibilities are available to investigate.

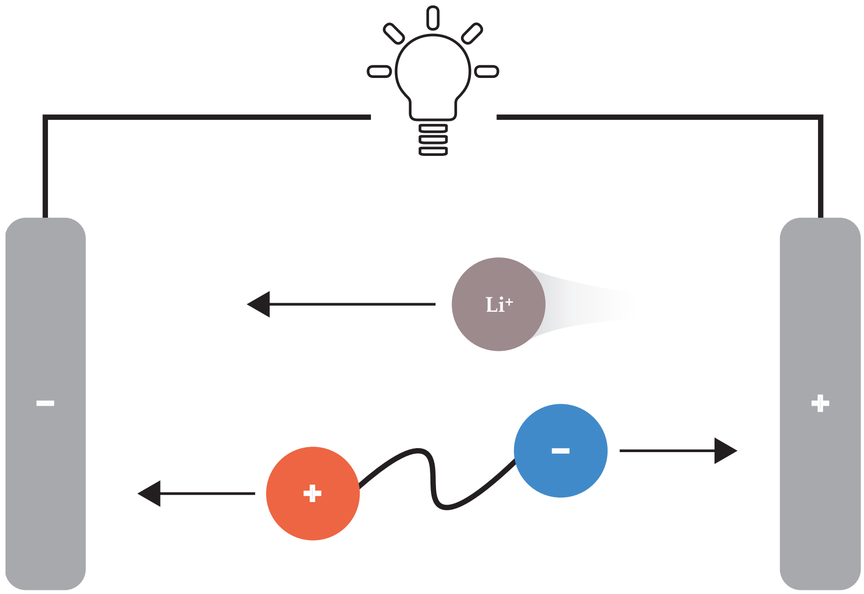

FIGURE 1. INSIDE A BATTERY, working ions, such as lithium, flow between the electrodes to counter the flow of electrons in the external circuit. If the battery electrolyte contains other charged species, they, too, can move under the battery's electric field, compete with the flow of working ions, and compromise performance. But when the electrolyte's positive and negative charges are tethered together in a single molecule, called a zwitterion, the electric forces cancel and the electrolyte molecules stay in place. (Courtesy of Jenny Pringle, adapted by Freddie Pagani.)

Plastic crystals

What kind of solid conducts ions? A perfectly ordered crystal won't do. When every site in a crystal lattice is filled, ions passing through have nowhere to move to. An ionically conductive solid therefore needs to have a disordered structure that's full of lattice dislocations and other defects along which ions can move.

In the 1970s, many researchers worked on designing defect-riddled ceramics with high ionic conductivity. (See the article by John Bates, Jia-Chao Wang, and Nancy Dudney, PHYSICS TODAY, July 1982, page 46.) The idea at the time was to create batteries with liquid electrodes—molten metal and molten salt, say—that needed a solid electrolyte to keep them physically separated.

But rigid ceramic electrolytes work far less well with the solid electrodes of today's lithium-ion batteries. As a battery is charged and discharged, its electrodes slightly expand and contract, so they'd quickly break their electrical contact with a rigid electrolyte. The ideal electrolyte should be solid but also soft enough to deform and accommodate the growing and shrinking of the electrodes.

Toward that end, Pringle, Forsyth, and colleagues embarked on their study of OIPCs.[2] Like other ionic solids, such as sodium chloride, OIPCs are made of regular arrangements of positive and negative ions. Because an OIPC's ions are polyatomic organic molecules, researchers have a lot of leeway to design their shapes and tune their properties.

An OIPC's characteristic plasticity is thought to stem from rotational disorder in the lattice. The molecular ions are rotationally asymmetric, and they needn't all be oriented the same way in their lattice sites. Rotational disorder then gives rise to positional disorder—lattice planes more easily sliding against each other, for example—which endows the material with both a network of defects for conducting ions and the malleable, waxy texture needed to maintain contact with the electrodes.

Despite 20 years of research, much about OIPCs is still unknown. The mechanism that connects the rotational and positional disorder is not well understood, and a formula to predict which combinations of ions form OIPCs and which don't is still lacking. "The challenge is in studying the disordered state," explains Pringle. Tools such as x-ray diffraction are well suited to studying crystalline structures, but when the deviation from crystallinity is the very property of interest, they're less useful. Even methods for studying noncrystalline materials, such as solid-state NMR and molecular dynamics simulations, do their best work when a crystal structure exists as a starting point.

Nevertheless, the Deakin researchers have gained some insights into how to identify an OIPC when they've made one. In particular, they've found that the OIPC phase is often associated with a solid–solid phase transition that marks the onset of rotational disorder: Below the transition temperature, the ions are more rotationally ordered; above it, they're more disordered. And phase transitions are easy to recognize with differential scanning calorimetry.

Ideally, the most disordered phase should span the range of battery operating temperatures, from room temperature up to around 100 °C. The ions, therefore, must be prone enough to disorder that they enter the OIPC phase, but not so much that the material melts.

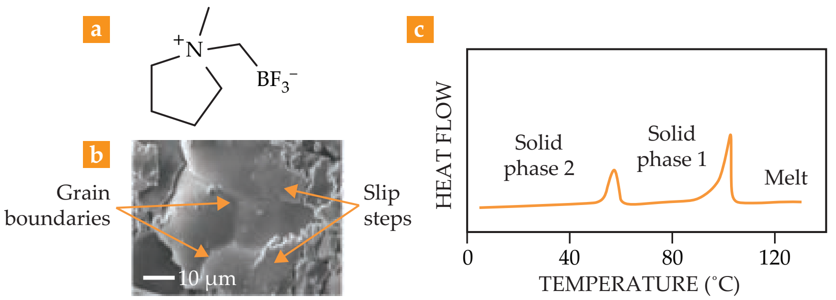

FIGURE 2. MOST ZWITTERIONS form crystalline phases that are unsuitable for solid-state battery electrolytes. But one newly synthesized zwitterion **(a)** exhibits a promising degree of disorder and plasticity. **(b)** An electron micrograph of the material shows small grains rife with defects. **(c)** A differential scanning calorimetry trace reveals a solid–solid phase transition, a known sign of an organic ionic plastic crystal. (Adapted from ref. 1.)

Designing zwitterions

Some classes of OIPCs show promise as electrolytes, but they all share a common weakness. Because they're made of separate positively and negatively charged ions, the constituent ions themselves can migrate through the lattice under the battery's electric field. The migrating ions may compete with the Li^+ conductivity and compromise the electrolyte's performance.

Zwitterions could solve that problem. With positive and negative charges on the same molecule, as sketched in figure 1, they experience no net force under the battery's electric field. They've been explored before in the context of battery electrolytes, but until now only as additives to other electrolyte materials.[3] No one had ever made an electrolyte wholly or even mostly out of zwitterions.

Most known zwitterions, after all, form rigid crystals that don't conduct ions. But the known ones constitute only a tiny fraction of all possible zwitterions. Organic chemists are adept at designing and synthesizing new molecules, but they have a limited kit of tools for adding a negative charge to a molecule that's already positively charged, or vice versa. Almost all zwitterions studied so far for electrochemical applications have their negative charge on an SO_3^- group.

To broaden their horizons, the Deakin researchers turned to colleagues in industry skilled in the chemistry of boron and fluorine. Together, they developed three new zwitterions, including the one in figure 2a that they further explored, with the negative charge on a BF_3^- group. The positive charge, in each case, is spread around a ring of carbon and nitrogen atoms, an arrangement known to lend itself to rotational disorder and OIPC behavior.

The room-temperature micrograph of the zwitterionic material seen in figure 2b already shows promising signs of disorder, with small, irregular grains full of defects. And the calorimetry trace in figure 2c shows the telltale sign of a plastic crystal: a clear transition between two solid phases, tens of degrees below the melting transition.

Even so, the pure zwitterionic material is a poor electrolyte. Its ionic conductivity is less than 10^{-9} S/cm, far below the target of 10^{-4} S/cm for a solid-state electrolyte. But mixing in a small amount of lithium salt—a known trick for optimizing electrolytes—boosts the conductivity all the way to 3×10^{-6} S/cm. That's still not ideal for a real battery, but it's good enough to be tested in a model battery, which could be cycled hundreds of times without the electrolyte breaking down or losing contact with the electrodes.

Aside from the conductivity, the researchers also need to work on the temperature range of the disordered zwitterionic phase. The solid–solid phase transition lies above 50 °C, so the material isn't a plastic crystal at room temperature. But the researchers stress that they're just getting started: This is only the first of a new class of fundamentally different electrolyte materials. Now that they know how to make BF_3^--based zwitterions, they can adapt the synthesis protocol to create new zwitterionic materials and catalog their properties.

"And this isn't just about lithium," notes Pringle. Although Earth's crust has enough accessible lithium to meet humanity's energy-storage needs for the time being, stocks could run out in generations to come, and a different element may be required. Sodium, easily extractable from seawater, is a natural choice. Many OIPCs already conduct sodium ions, and there's every reason to think that a suitably chosen zwitterionic material could do the same.

Johanna Miller

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Stacked materials build up massive electrons

A heterostructure exhibits unusual electronic behavior previously seen only in materials with rare-earth or actinide elements.

As early as the 1930s, researchers began puzzling over an aspect of the electrical response in some nominally pure metals: At temperatures of a few kelvin, resistivity doesn't decrease with decreasing temperature, as they had come to expect; rather, it increases. Jun Kondo finally explained that behavior in 1964. The Kondo model describes an interaction between magnetic impurities in those metals and the conduction electrons. When the metal is sufficiently cooled, the scattering of conduction electrons increases because spin-exchange scattering with the impurities becomes possible.

About a decade after Kondo's initial work, Kenneth Wilson predicted that below a certain temperature, the coupling between the magnetic spins and conduction electrons is so strong that it quenches the localized spins, and the spins and electrons form a combined ground state known as the Kondo singlet. In the 1970s that so-called Kondo effect became widely studied in rare-earth compounds, with the role of magnetic impurities played instead by electron spins in the 4*f* and 5*f* orbitals of heavy ions in the materials.

A crystalline material's repeating spins create a lattice of Kondo singlets. In 1975 one such Kondo lattice in $CeAl_3$ was found to induce electronic behavior indicative of charge carriers more massive than those in most condensed-matter systems. Dozens of materials with rare-earth and actinide ions have since shown electrical responses indicating quasiparticles of an effective mass anywhere from 50 to 1000 electron masses. Those heavy fermions often give materials atypical electronic phases, such as multiple superconducting states (see PHYSICS TODAY, November 2021, page 19).

Now Peter Liljeroth and his colleagues at Aalto University in Finland have observed the formation of heavy fermions in a two-layer stack of tantalum disulfide, the first heavy-fermion material without rare-earth or actinide elements.[1]

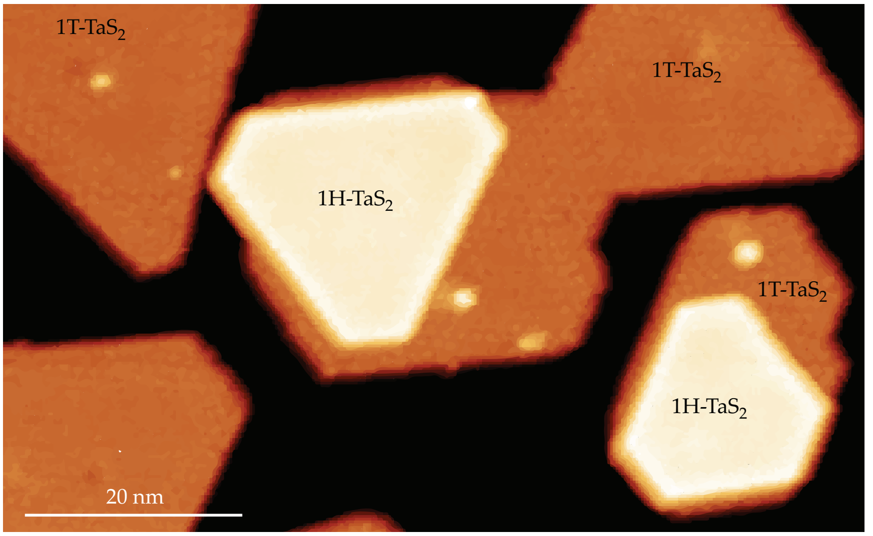

FIGURE 1. TANTALUM DISULFIDE grown by molecular-beam epitaxy forms two crystal structures, 1T and 1H. The random growth process creates three-atom-thick monolayer islands, shown in orange in this scanning tunneling microscopy image, and bilayer regions with the two layers taking the same or different crystal structures. The bright yellow regions are 1H-TaS_2 on 1T-TaS_2. Such heterostructures act as though their electronic behavior arises from charges of a mass that is one or two orders of magnitude larger than an electron mass. (Courtesy of Viliam Vaňo.)

Their system is easy to make, handle, and tweak and potentially offers an accessible method to explore a wider range of heavy-fermion physics.

Happy accident

The Liljeroth group members stumbled on their heavy-fermion material by chance. They were originally growing TaS_2 to investigate whether it hosts a quantum spin liquid, a state whose unusual characteristic quasiparticles, known as spinons, have spin-½ but no charge. (For more on spin liquids, see the article by Takashi Imai and Young Lee, PHYSICS TODAY, August 2016, page 30.) Spinons are tricky to examine because they're chargeless, but the spatial pattern they adopt can conceivably be picked out with a scanning tunneling microscope or other probe.

Five years ago researchers found indications of a quantum spin liquid in bulk TaS_2, which has a layered structure of covalently bonded three-atom-thick layers weakly held together by van der Waals forces.[2] Because the influence of interlayer interactions complicated that observation, interest emerged in testing whether a single layer hosts a quantum spin liquid.

Liljeroth's chosen growth process, molecular-beam epitaxy, produces monolayer islands of TaS_2 with two possible crystal structures, denoted 1H and 1T. It also produces bilayer islands of the same layer structures and of differing structures: 1H stacked on 1T and vice versa, as shown in figure 1. Monolayer 1T-TaS_2 was what the researchers were after, but on a whim, Liljeroth's graduate student Viliam Vaňo also characterized the two heterostructure stacks with scanning tunneling microscopy and scanning tunneling spectroscopy (STS).

Vaňo saw the expected and established spectra for 1T and 1H monolayers. In heterostructures with a 1T layer on a 1H layer, an unexpected spectral spike, shown at the center of the top graph in figure 2, appeared periodically in scans over the sample. Those peaks were also recently observed in an independent study by Michael Crommie of the University of California, Berkeley, and his colleagues on a similar 1T-on-1H heterostructure of tantalum diselenide.[3] Their results, published a few months ago, include other measurements that indicate possible quantum spin liquid behavior in monolayer 1T-$TaSe_2$.

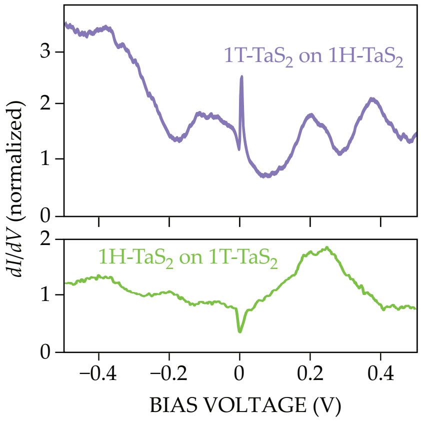

FIGURE 2. SCANNING TUNNELING SPECTRA of tantalum disulfide heterostructures reveal the heavy-fermion behavior of heterostructures of 1T-TaS$_2$ on 1H-TaS$_2$ and of 1H-TaS$_2$ on 1T-TaS$_2$. The change in tunneling current *I* relative to the applied bias voltage *V* indicates the number of electronic states at different energies for a given location on the sample. The measurements show a sharp peak at 0 V for one stacking order (purple) and a dip for the other (green). Those features taken together suggest that the material is showing electronic behavior that typically leads to unusual correlated states and that had previously been seen only in materials with rare-earth or actinide ions. (Adapted from ref. 1.)

For the 1H-TaS$_2$ on 1T-TaS$_2$ heterostructure, a dip appeared periodically in the tunneling spectrum, as shown at the center of the bottom graph in figure 2. Liljeroth's theory collaborator Jose Lado, also at Aalto University, proposed that the simplest explanation for the STS features—the spike in 1T on 1H and the dip in 1H on 1T—might be the formation of heavy fermions.

Measured response

STS measures the density of electronic states as a function of energy at single locations on a sample. At first, Liljeroth and his colleagues thought the spike in the 1T-on-1H measurements could be related to a previously observed cluster of states in bulk TaS$_2$ from a narrow electronic band near the Fermi level—the highest occupied energy level at zero temperature, or at a bias voltage of 0 V in STS measurements. But when they investigated how the peak responded to changes in temperature, its width didn't follow the thermal broadening that would be expected based on that explanation.

Instead, the spike's broadening with increased temperature suggested it was a manifestation of the Kondo effect. The associated Kondo lattice creates an intense peak in the local density of states near the Fermi level that grows as the material is cooled. Fitting the temperature dependence of Vaňo's measurements yielded 18 K as the Kondo temperature, above which the Kondo effect is negligible. What's more, an out-of-plane magnetic field broadened and eventually split the peak, an indication of the expected Zeeman splitting for a Kondo resonance.

The dip in the spectrum of 1H-on-1T heterostructures could conceivably arise for several reasons. One possible explanation is repulsive Coulomb interactions between quasiparticles. When quasiparticles are trapped in an island, their efforts to maximally avoid one another within those confines could lead to an energy gap in the material's electronic states and thus a dip in the STS measurement. Those Coulomb interactions would be stronger for laterally smaller heterostructures, but the researchers didn't see any size dependence for their spectral dip.

Other phenomena can create a gap in a material's electronic states. But as Liljeroth and his colleagues investigated them one by one, they found that the temperature and magnetic field dependence of the spectra didn't track with what's expected in those cases. The trends of the spectral dip did, however, agree with previous studies of heavy-fermion materials.

The STS spike and dip appeared in all the 1T-on-1H and 1H-on-1T heterostructures, respectively. What's more, because of the low disorder in the epitaxially grown TaS$_2$ layers, the features were more uniform across the sample than is typically the case in conventional heavy-fermion materials.

Stacking up

The two TaS$_2$ layers provide the necessary ingredients to form artificial heavy fermions. In conventional heavy-fermion systems, a single material, such as uranium ditelluride, provides the requisite conduction electrons and magnetic moments, from the electron spins in the 4*f* and 5*f* orbitals of its rare-earth or actinide ions. In Liljeroth's heterostructure, each layer provides one component. The 1T layer harbors a charge-density wave, which results in the atoms clustering into a repeating Star-of-David-shaped pattern. Each star hosts a magnetic moment from one unbonded orbital at its center, which serves the role filled by *f* electrons in conventional heavy-fermion materials. And metallic 1H adds conduction electrons, which hybridize with the magnetic moments to form a Kondo lattice.

Compared with conventional heavy-fermion materials, the heterostructure offers more avenues for tunability. For example, the relative angle of the layer lattices, the specific materials of those layers, and the magnitude of an applied electric gate voltage could all be adjusted. In the future, Liljeroth and his colleagues plan to chart the heterostructure's phase diagram, which should include a bevy of exotic phases observed so far only in rare-earth and actinide compounds.

Heavy-fermion materials are expected to show quantum criticality (see the article by Subir Sachdev and Bernhard Keimer, PHYSICS TODAY, February 2011, page 29). In a phase diagram, the quantum critical point is a precarious spot of instability near zero temperature between stable states that have transitions driven by quantum fluctuations. The materials often manifest unconventional superconductivity, which doesn't follow the Bardeen-Cooper-Schrieffer theory. Heavy-fermion superconductivity is of interest because it's highly unconventional and in some instances even topological, which means the behavior arises from the connectedness of the band structure rather than from its symmetry.

The Liljeroth group's results are part of a recent trend of using stacked two-dimensional metals, semimetals, semiconductors, and insulators to create new electronic and optical behaviors. (See the article by Pulickel Ajayan, Philip Kim, and Kaustav Banerjee, PHYSICS TODAY, September 2016, page 38, and PHYSICS TODAY, January 2020, page 18.) Materials in those structures include graphene, hexagonal boron nitride, and transition-metal dichalcogenides, such as molybdenum disulfide and TaS$_2$. Different layers can be assembled in various orders and combinations and at different angles to create any number of electronic and optical properties, including superconductivity, topological currents, and efficient photovoltaic responses.

Heather M. Hill

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Spectroscopy shines light on an electrode–water interface

With increasingly negative electric potentials, sodium spectator ions help split water to form molecular hydrogen.

The energy available in 1 kg of molecular hydrogen gas is the same as in almost 3 kg of gasoline. Hydrogen's superior energy density has attracted the attention of scientists and engineers working to develop more efficient and sustainable energy systems to replace fossil fuels (see the article by Joan Ogden, PHYSICS TODAY, April 2002, page 69).

One way to boost H_2 production is electrocatalysis, which drives chemical reactions with an electric potential at a liquid–solid interface. In the hydrogen-evolution reaction, two protons and two electrons combine at a cathode to yield H_2. The reaction rate strongly depends on interfacial water—that is, the water in the immediate vicinity of a solid electrode's surface. It behaves differently from the bulk and forms a layered, ordered structure.

Chemists have used various spectroscopic methods over the years to try to better understand how the specific structure interacts with cations in the electrolyte to regulate the hydrogen-evolution reaction. But many of those methods are limited to working at a modest range of electric potentials near the value for which an electrode lacks any free charge at its surface. Those conditions are quite different from the electric overpotentials that interfacial water experiences on single-crystal surfaces in cells designed for producing H_2.

Now Feng Pan of Peking University in Shenzhen, Jian-Feng Li of Xiamen University, both in China, and their colleagues have measured interfacial water at conditions more suitable for producing H_2. When sodium ions are added to the solution, their interference with hydrogen bonding helps form the water's structure.[1] Those findings may affect the electrolyte chosen to promote water dissociation, lead to enhancements in the rate and efficiency of the hydrogen-evolution reaction, and further improve hydrogen-fuel production.

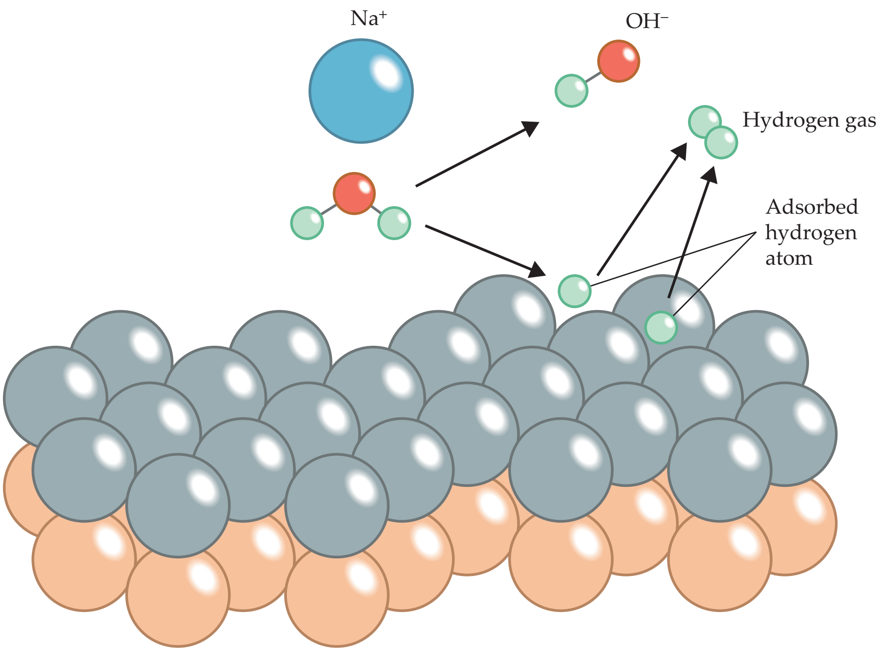

FIGURE 1. A SODIUM ION (blue) helps split a nearby water molecule, a process that accelerates the formation of molecular hydrogen at a water–electrode interface. At strongly negative electric potentials and high sodium concentrations near a palladium–gold electrode surface (silver and orange circles, respectively), sodium cations help pull water molecules toward the interface. Once there, adsorbed hydrogen strongly bonds to the palladium. That bond promotes water dissociation and, through a series of steps, the production of H_2 gas. (Adapted from M. M. Waegele, *Nature* **600**, 43, 2021.)

SHINERS

Surface-enhanced Raman spectroscopy (SERS) has been the standard method to characterize interfacial water. When light shines on a metal with water or other molecules adsorbed to the surface, conduction electrons at the interface are stimulated by the incident light and generate a surface plasmon resonance. Electromagnetic theory predicts that the plasmon resonance enhances Raman scattering at a surface. Chemical theorists, on the other hand, have argued that the enhancement arises from a transfer of charge at the surface. (See the article by Katrin Kneipp, PHYSICS TODAY, November 2007, page 40.)

Regardless of the exact mechanism, the practical result is that the light interaction excites a molecule into a higher-energy vibrational state. That signal can be exploited to identify the constituent atoms, bond lengths, and molecular structures.

With SERS, even single molecules are detectable. But the typical atomically flat single crystals that are used as reaction surfaces for studying the hydrogen-evolution reaction cannot host the necessary surface plasmon resonance that SERS requires. And other spectroscopy techniques are only effective at measuring interfacial water at relatively low electric potentials.

To collect their data, Pan, Li, and their colleagues turned to a Raman-spectroscopy technique that Li helped design in 2010. That method, shell-isolated nanoparticle-enhanced Raman spectroscopy (SHINERS), uses a layer of gold nanoparticles to amplify the Raman scattering signal.[2] To prevent any unwanted chemical interactions between the interfacial water and the gold surfaces, the researchers coated each nanoparticle with a 2 nm shell of inert silica. Li says, "The SHINERS technique overcomes the

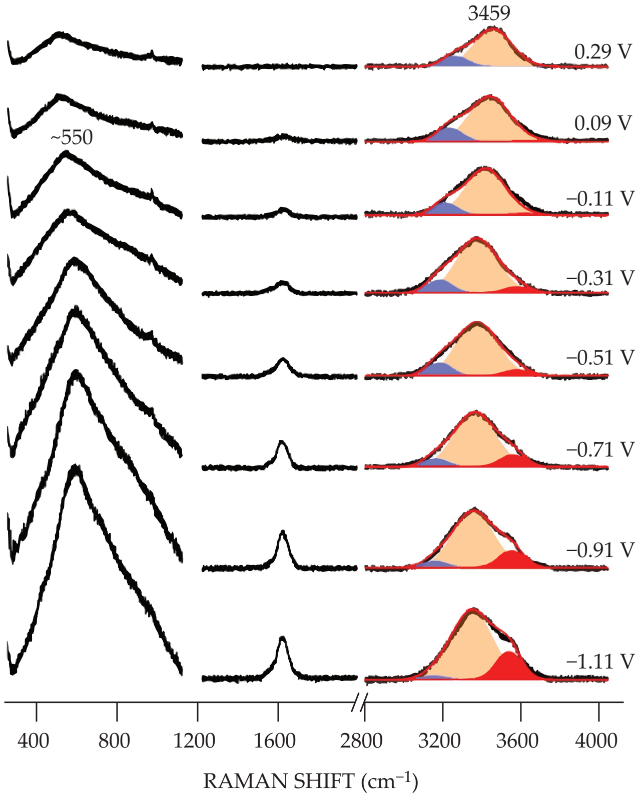

FIGURE 2. RAMAN SHIFTS help reveal the underlying structure of water in an aqueous electrocatalytic system. The spectral peak centered at approximately 550 cm^{-1} grows increasingly prominent at progressively more negative electric potentials. The peak corresponds to a vibrational motion of water whose molecules have formed a series of densely packed layers near an electrode surface. The Raman shift at approximately 3400 cm^{-1} indicates three modes of water's oxygen–hydrogen bond (red, orange, and blue peaks). At highly negative electric potentials, the O–H bonds with weakened hydrogen bonding and strongly hydrated sodium ions (red peaks) prevail over the O–H bonds with fully filled hydrogen bonds (blue peaks). (Adapted from ref. 1.)

long-standing limitations of SERS and can precisely characterize various materials, especially those on single-crystal surfaces."

The researchers focused on measuring interfacial water's structure by preparing a 50-μm-thick electrolyte solution, which shares little to no behavior with bulk water, and trapping it between two electrode surfaces. The formation of H_2 bubbles interfered with previous spectroscopy measurements, but the vertically oriented reaction cell the researchers designed mitigated that problem.

Figure 1 shows an atomic-level schematic of the experimental system. In it, the interfacial water reacts with a crystalline-electrode surface made of palladium, which sits atop a layer of gold nanoparticles. Compared with other surfaces, palladium is a better electrocatalyst for the hydrogen-evolution reaction and epitaxially grows as uniform films on gold.

At the water–electrode interface, the researchers applied an electric potential ranging from 0.29 V to −1.11 V. Figure 2 shows the Raman-spectroscopy results. Starting at negative electric potentials, the Raman spectra of the interfacial water includes a broad band of spectral lines centered at approximately 550 cm^{-1}. That band indicates a reciprocating vibrational motion of interfacial water. A second band with a Raman shift centered around 3550 cm^{-1} is indicative of hydrated sodium cations concentrated in the interfacial water.

The intensity of the 550 cm^{-1} band steadily increased as the electric potential became more negative. The new results agree with previous work that found the 550 cm^{-1} band is related to an ordered water structure.[3] At a distance of up to three molecular diameters from the electrode, water forms layers of molecules far denser, and consequently with different properties, than bulk water.

A structure revealed

To learn more about how sodium contributes to the ordered structure of interfacial water, Pan and some of his colleagues modeled the experimental system using density functional theory. Their *ab initio* molecular dynamics simulations found that sodium weakens the network of hydrogen bonds that help hold water molecules together.

The enfeebled hydrogen bonding is also evident in the spectral observations of the oxygen–hydrogen bond, shown in figure 2. That bond has three types of stretching vibrations, and each roughly corresponds to how many sites on a water molecule are available for hydrogen bonds. At more negative electric potentials, the intensity of the O–H vibration decreases at sites for four hydrogen bonds while that of the O–H vibration associated with two coordinated hydrogen bonds increases.

The liberated individual water molecules gather in a ring around a sodium ion to form a hydration shell. The positively charged hydrated sodium is naturally attracted to the negatively charged surface of the palladium–gold electrode. In fact, the simulations show that hydrated sodium brings water with weakened hydrogen bonds nearer to the electrode surface than it would otherwise reach without the sodium.

Once sufficiently close to the electrode, some hydrogen preferentially adsorbs to the surface, and Pd–H bonds form. After a series of additional chemical steps, H_2 gas is produced.

According to the simulations, Pd–H bonds are shorter at progressively more negative potentials and at higher concentrations of hydrated sodium. A shorter bond is a stronger one and, therefore, promotes more water dissociation. The proximity of water molecules to the metal surface, the researchers say, also improves the electron-transfer efficiency between the electrode and the interfacial water. Under those conditions, the hydrogen-evolution reaction can proceed more easily and efficiently.

The researchers note that the relevance of sodium cations in improving the production rate of H_2 may be applicable for cations in other aqueous electrocatalytic reactions. Converting carbon dioxide to hydrocarbons or nitrogen to ammonia, for example, requires water dissociation. Tuning cations to more carefully control the structure of interfacial water may help improve the rate and efficiency of those reactions too.

Alex Lopatka

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Supply-chain issues compound research slowdowns

Researchers make do with alternative sources, methods, materials, and activities.

"Everyone is screaming about acetone," says Charlie Veith, chair of vendor relations for NSF's National Nanotechnology Coordinated Infrastructure. Acetone, which researchers use for lithography, among other things, is one of countless items that have become hard to obtain since the pandemic began. When two East Coast university nanotechnology labs were on the verge of closing last fall for lack of acetone, says Veith, he stepped in to help. He has rustled up chemicals, personal protective equipment, fused silica wafers, and more for laboratory use.

The supply chain includes sourcing, processing, controlling quality, cleaning, packaging, and shipping. "When everything along that chain is JIT [just in time], any problem screws the whole chain up," Veith says.

Supply shortages during the COVID-19 pandemic hit researchers just as they do members of the public. "I don't know if people are hoarding electronic components like they hoard toilet paper," says a spokesperson for a European company that makes laboratory instruments. Orders picked up in the second half of 2021, and her company has struggled with obtaining electronics and raw materials. "Everyone has the same problem, but companies don't want to admit it," she says, explaining her request for anonymity. "We are busting our guts trying to be on time, but we are limping along because we can't get components for our products."

Delayed deliveries, extended lead times, and ever-changing quotes for consumable and durable equipment are the main ways researchers feel the effects of global supply-chain issues: Their research is hampered and they are forced to adjust priorities. "People work hard to find work-arounds," says Douglas Natelson, chair of physics and astronomy at Rice University. "But the supply difficulties enhance everyone's stress levels. I worry most about the people who are just starting out."

NASIR BASIT

AN OVERSIZED COVERALL is Ying Jia's only choice at Northwestern University's Micro/Nano Fabrication Facility, where she works. Since the pandemic began, facility managers have had to scramble to find clean-room supplies.

Kludge, share, innovate, pay

Nitrile gloves for clean environments, face masks, coveralls, hairnets, booties, and the like have been scarce off and on during the pandemic, at least partly because of demand for such items for medical use. Shortages of such supplies haven't led to shutdowns at Northwestern University's Micro/Nano Fabrication Facility, says Nasir Basit, director of operations. "But we have had panics." He now spends a lot of time checking with different vendors. "We will buy basically whatever we find," he says. And Stanford University's Mineral and Microchemical Analysis Facility has taken to reserving the best gloves for areas "where contamination could have a serious impact on research" and reusing them for "dirtier tasks," says geochemist Dale Burns, the lab manager.

Guido Pagano started on the tenure track in physics at Rice in early 2020. He investigates quantum information processing by manipulating trapped ions and atoms with lasers. He lost more than two months in setting up his lab when the campus was closed during lockdown. But what came next was worse, he says.

LIGO LABORATORY, CALIFORNIA INSTITUTE OF TECHNOLOGY

PANDEMIC-RELATED DELAYS in obtaining steel held up work by four months on an upgrade at the Laser Interferometer Gravitational-Wave Observatory's site in Hanford, Washington. The new 300-meter-long building will house a narrowband optical cavity to improve LIGO's sensitivity.

"The economy restarted, and the supply-chain problems started killing me."

Pagano ordered a high-power UV pulsed laser in October 2021. The wait for the $100 000-plus laser was given as 10 or 11 months rather than the usual 3 or 4 months. "I need this particular laser for realizing quantum gates. Without it, I can't do any coherent operations on qubits," he says. He's trying to borrow a laser from other research groups.

And in March 2021, Pagano ordered a custom aluminum board on which to mount optics. He wants screw holes that are closer than the standard one-inch separation. Normally, he says, such an item would take about six weeks. A board was produced but lost by the shipper in September, and he was still waiting in December. The company attributed the delays to aluminum being unavailable and to staff shortages. In the meantime, Pagano has kludged a temporary solution.

"In some cases, we have to spend extra money to buy more sophisticated products than we need," says Jaime Cardenas, who is on the tenure track at the University of Rochester. His research focuses on integrated photonic devices for applications in communications, sensing, and quantum information. Among the materials he buys is graphene fixed to copper tape. "It's standard and inexpensive," he says. "But the last time we tried to order it, the vendor was having trouble obtaining copper." So he bought what he could get: graphene on a dissolvable polymer tape that cost 30% more. Concerned that supplies would continue to be tight, he bought extra.

And when his usual vendor couldn't supply fused silica wafers, Cardenas found a new source—and paid 50% more. Another example of fallout from global supply-chain issues occurred when he and colleagues ordered a dicing saw from Japan. With shipping containers backed up offshore, he says, "shipping by sea wouldn't make the deadline before the funding 'vanished.' We had to fly a big piece of equipment by air. It tripled the shipping cost."

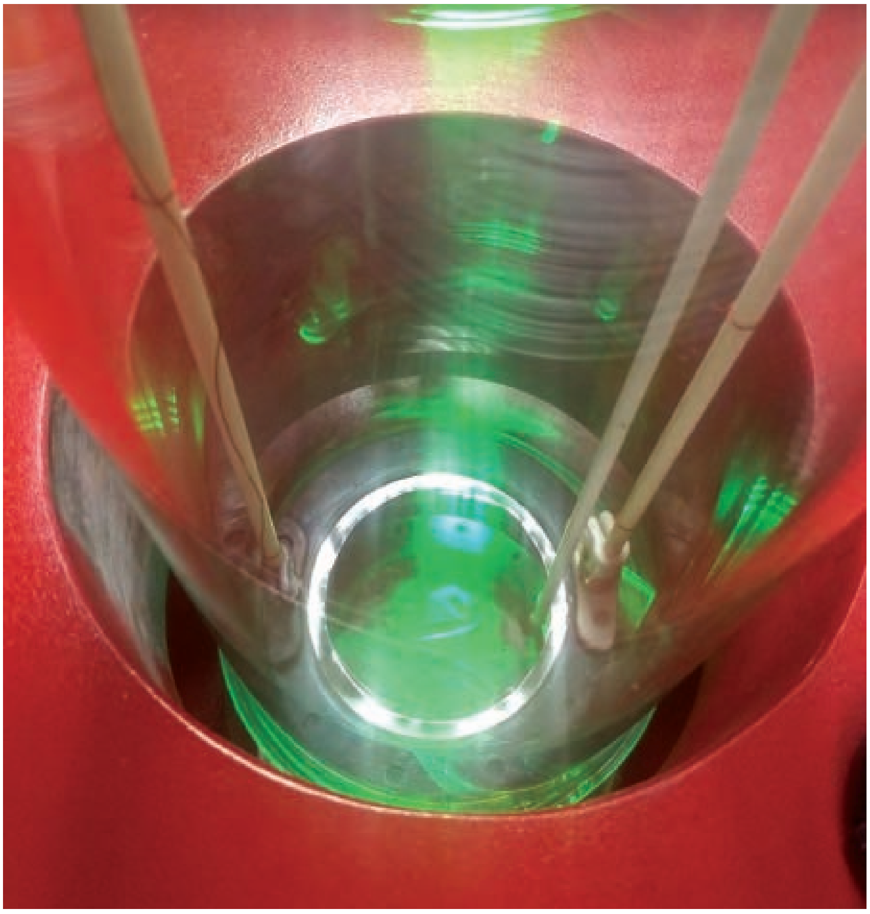
Matthew Yankowitz joined the University of Washington as an assistant professor of physics in August 2019. He studies layered two-dimensional quantum materials with emergent magnetic, superconducting, and topological properties. A dilution refrigerator for a shared facility arrived before the pandemic—and then gathered dust for months until technicians from the Finnish supplier could enter the US and assemble it. A cryostat he ordered from Tennessee and a scanning tunneling microscope from Germany arrived months late.

Obtaining consumables can also be problematic, says Yankowitz. "You don't know what will be available until you order, and lead times can be shockingly long." An example is the package mount that creates an electrical connection between a sample and the wires on a probe. In the past they were "ready to ship immediately," he says. Now the quoted time for delivery is five months. "I doubt anyone can realistically project that far out."

"If we got desperate, we would remove devices we had measured previously and reuse the package mounts," Yankowitz says. "We'd have to make difficult decisions about which working devices we should dismount."

Small peanuts and long drives

Carlos Romero-Talamás of the University of Maryland, Baltimore County, is overseeing the construction of two plasma devices. For a centrifugal magnetic mirror, a fusion reactor candidate, the delivery times for a 6-meter-long aluminum chamber and a vacuum pump are delaying the work schedule by at least three months. The other device, a 7-tesla



CARLOS A. ROMERO-TALAMÁS

FINDING A VENDOR to customize parts for their planned high-magnetic-field (7 tesla) studies has been difficult for Carlos Romero-Talamás and his group at the University of Maryland, Baltimore County, so for now they have intensified their investigations of dusty plasmas at low magnetic fields (0.08–0.12 tesla).

pulsed Bitter magnet for investigating dusty plasmas, needs metal plates with holes for cooling. Romero-Talamás has the metal, but he hasn't been able to find a company to make a die to punch the holes. "I've contacted at least a dozen vendors," he says. "The ones that reply don't want the business. It will be less than $100 000, and that seems to be small peanuts for them."

With the dusty plasma project stalled, Romero-Talamás says that for now his group is focusing on experiments at around 0.1 tesla and "making the most of the tools we have at hand." Still, he says, "I'm worried about students not finishing on time."

At the University of Pennsylvania, Daeyeon Lee's group in the chemical and biomolecular engineering department uses microfluidic devices to synthesize materials for biomedical applications. One of their projects involves encapsulating mRNA into lipid nanoparticles for vaccines. Starting last summer, they couldn't get the polydimethylsiloxane they need to make the devices. "PDMS is a common, cheap elastomer," says Lee. "You normally never think about running out of it. This [shortage] stops many people's research."

His students identified and bought similar elastomers, tested them, and created new protocols to make stopgap microfluidic devices, says Lee. The devices do the job, he says, but the material is not as well characterized as PDMS. "Is the behavior impacted by the new material? When we try to publish, there will be questions."

Lee's group encountered another supply-chain issue when a bonder in the local clean room broke down. Bonding is the last step in fabricating silicon-and-glass microfluidic devices. "The vendor came and diagnosed the problem," says Lee, "but couldn't get the parts to fix the instrument." For now, a postdoc and a student pack up partly fabricated devices and drive about 320 kilometers to complete the process at a facility at the Pennsylvania State University. That work-around risks contaminating the devices, costs more, and takes longer. "What should take an hour takes a week," Lee says.

"A strategic game"

Some companies say the pandemic hasn't affected their business or ability to deliver products on time. "We have things under control, we have planned ahead, and our customers don't feel drawbacks," says Stephan Koch, vice president of sales with the test and measurement manufacturer Zurich Instruments. And at least for some software companies, the pandemic has been a boon: "We have seen corporations spending more time with design software," says Chris Maloney, managing director of US operations and director of business development for VPIphotonics, a design automation company. "They test their design before purchasing something. It's become more important because it's hard to get components."

Still, many tech companies are seeing a surge in orders. And even if the companies don't want to admit difficulties, it's clear from what their customers say that delays and scarcities are common.

Diane Blake is director of strategic sourcing at Lake Shore Cryotronics, an Ohio-based company that makes temperature and magnetic field monitoring instruments and materials characterization products. "For us," she says, "the supply problems started last year with the freeze in Texas," where the company's main source of epoxy for sensors is located. Add to that delays in the delivery of analog-to-digital converters after a fire at a Japanese company in March 2021 and microchips being held up because of water shortages in Taiwan and COVID-related workforce reductions in Malaysia. "We have so many single-source critical components," says Blake.

The company's longtime supplier of alumina probe blades shut down when the owner contracted COVID-19, Blake says. "These parts go into systems that could cost $200 000. This was urgent." Additionally, the company previously machined parts from aluminum tubes, but recently it has only been able to get solid rods, which makes fabrication more time consuming and expensive. And for electronics components for her company's products, lead times used to be 8–10 weeks. Now, she says, it's increased to 52 weeks. "Arrival times have been pushed into early 2023."

"We are looking at alternative parts," Blake says. "And we will have to review what instruments to concentrate on for 2022. It's a strategic game we are playing."

Toni Feder

DOE medical isotope campaign nears completion

The US Department of Energy says it has provided enough support to get a domestic industry off the ground without weapons-usable material.

AN ELECTRON-BEAM ACCELERATOR that NorthStar Medical Radioisotopes will use to manufacture molybdenum-99 by knocking off a neutron from ^{100}Mo. The company expects to begin producing ^{99}Mo using that method early in 2023; it has been making the isotope by a different method since 2018.

A nearly three-decade-long quest to end US exports of weapons-grade uranium has surmounted one of the last remaining hurdles. On 20 December two federal agencies announced that highly enriched uranium (HEU) no longer needs to be shipped to facilities abroad for sufficient molybdenum-99 to be produced to meet US medical demand. (Weapons-grade uranium is enriched to more than 93% in ^{235}U; HEU contains 20% or more ^{235}U.)

Weeks earlier, the Department of Energy's National Nuclear Security Administration (NNSA) announced the last in a series of grants made during a nine-year-long campaign to build a domestic ^{99}Mo industry from scratch. Despite consuming roughly half of the world's ^{99}Mo, from 1989 to 2018 the US lacked its own production source. Molybdenum-99 is the parent of the medical isotope technetium-99m, which is used in about 40 000 US diagnostic procedures daily.

A $13 million award to Niowave, of Lansing, Michigan, followed grants made earlier last year of $35 million to SHINE Technologies in Janesville, Wisconsin, and $37 million to NorthStar Medical Radioisotopes in Beloit, Wisconsin. Joanie Dix, the deputy director of the NNSA's Office of Conversion, says the agency has informed lawmakers that it won't need further appropriations to subsidize domestic ^{99}Mo production. Congress had ordered the funding program in the American Medical Isotopes Production Act of 2012.

Cross purposes

For decades, DOE has been torn between its conflicting missions of halting international commerce in weapons-grade HEU and ensuring an adequate US ^{99}Mo supply. Over that period, the agency has cajoled and helped operators of foreign research reactors to convert their US-origin HEU fuel to low-enriched uranium (LEU), which is enriched to less than 20% in ^{235}U and isn't considered a proliferation concern (see PHYSICS TODAY, April 2016, page 28).

Yet at the same time, the NNSA routinely supplied HEU for fabrication into ^{99}Mo targets by a Canadian research reactor that had met half of US demand until its 2018 shutdown. Until last year, the agency shipped HEU for the manufacture of targets by two European ^{99}Mo producers, Curium, headquartered in London and Paris, and Belgium's Institute for Radioelements. Both companies bombard the targets with neutrons in reactors located in Belgium, the Netherlands, France, the Czech Republic, and Poland.

The last license for a shipment of weapons-grade uranium for use in targets was issued to the Institute for Radioelements by the US Nuclear Regulatory Commission in April 2020, with an expiration date of December 2021. That license authorized the export of 4.5 kg to the French company Framatome, which fabricates the targets. For security reasons, actual shipment dates are not made public.

The 20 December ^{99}Mo announcement

by Energy secretary Jennifer Granholm and Health and Human Services secretary Xavier Becerra won't end all HEU shipments. The NNSA will continue to supply weapons-grade HEU to fuel two European research reactors: Belgian Reactor 2 and the Institut Laue–Langevin research reactor in Grenoble, France. SCK CEN, which operates Belgian Reactor 2, has pledged to convert the reactor to LEU fuel by 2026. The reactor consumes 20–30 kg of HEU annually, says Alan Kuperman, coordinator of the Nuclear Proliferation Prevention Project at the University of Texas at Austin.

But the Institut Laue–Langevin isn't scheduled to switch to LEU until 2031. The Nuclear Regulatory Commission is now considering the institute's request for 130 kg of HEU, which the French facility has told the NNSA will meet its needs through 2026. Kuperman, however, says the requested amount should be sufficient through 2028. The NNSA is likely to provide at least one more fuel shipment each to the Belgian and French reactors, he adds.

The drive to phase out HEU shipments abroad dates to a directive in the Energy Policy Act of 1992. But a provision allowed exports needed for ^{99}Mo targets to continue until a supply of the isotope sufficient for US needs could be made with LEU targets alone.

"The secretaries' bold action puts one dangerous nuclear genie back in the bottle and brings to fruition more than three decades of efforts," Kuperman says. Those efforts included the Reduced Enrichment for Research and Test Reactors Program at Argonne National Laboratory, which designed LEU fuels compatible for reactor cores originally fueled by HEU. R&D continues at Argonne and at other DOE labs to develop fuels for remaining HEU-fueled high-performance research reactors, four of which are in the US.

The domestic program

Since 2012, the NNSA has awarded a total of $256 million to seven aspiring US producers of ^{99}Mo. The recipients must provide matching funding. The agency also provided $152 million to the national laboratories to provide nonproprietary technical support to any prospective domestic producer, including nonawardee companies (see "Competition heats up to produce medical radioisotope," PHYSICS TODAY online, 15 November 2019).

Three of the NNSA's earlier ^{99}Mo awardees—GE Hitachi Nuclear Energy, General Atomics, and Northwest Medical Isotopes—abandoned their plans and returned portions of their awards. BWX Technologies, which received $9 million from the NNSA, continues its ^{99}Mo development program, says a spokesperson.

The three 2021 grant recipients signed cooperative agreements with the NNSA requiring them to achieve specific production capacities by the end of 2023. SHINE and Niowave are each to have the capability of producing 1500 six-day curies per week. (A six-day curie is a measure of the remaining radioactivity of ^{99}Mo six days after it leaves the processing facility. The isotope's half-life is 66 hours.) NorthStar is expected to be capable of producing 3000 six-day curies weekly: 1500 by each of its two manufacturing methods.

The NNSA's Dix says the three awardees should provide the US with the capacity to become self-sufficient in ^{99}Mo, assuming stable demand for the isotope. That demand is currently around 4000 six-day curies per week, according to the NNSA. How much each company will actually sell will be determined by the international marketplace. In addition to the Institute for Radioelements and Curium, major global suppliers are located in South Africa and Australia.

The NNSA funding is disbursed in tranches once the companies meet milestones spelled out in their cooperative agreements.

Today, NorthStar remains the only domestic producer of ^{99}Mo. Since 2018, it has manufactured ^{99}Mo by neutron capture, irradiating targets containing the plentiful ^{98}Mo isotope with neutrons from the University of Missouri Research Reactor. According to James Harvey, NorthStar's senior vice president and chief science officer, the company already has the capacity to meet 20% of US demand for the isotope.

Ironically, the University of Missouri facility is one of two remaining US university research reactors to be fueled with HEU. The university has promised to convert it when a compatible LEU fuel is developed.

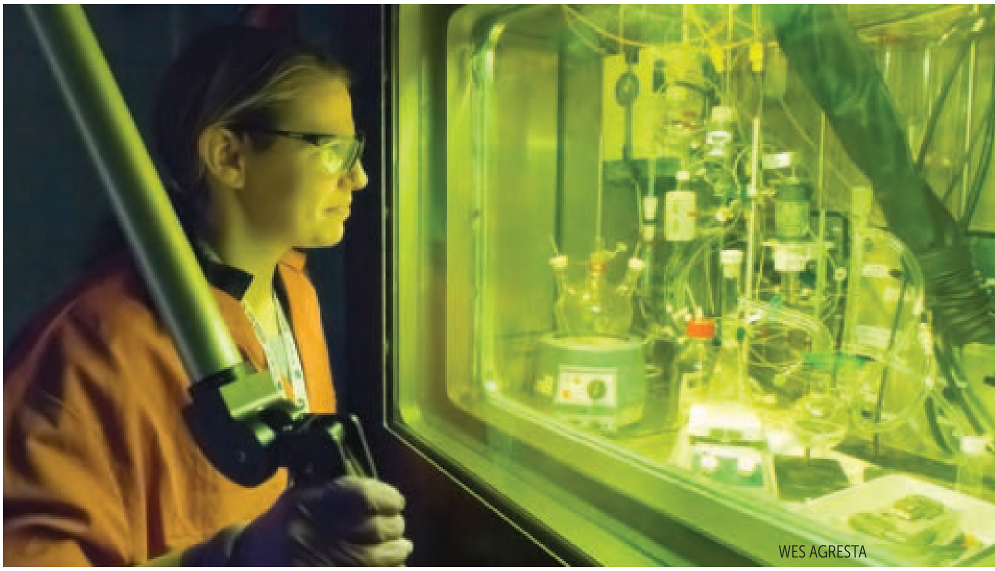
NorthStar, Niowave, and SHINE all propose to use accelerators to produce ^{99}Mo, each through a different process. Beginning next year, NorthStar plans to use electron-beam accelerators to spall, or knock off, a neutron from ^{100}Mo. The Belgian producer IBA has already delivered two 40 MeV accelerators to Wisconsin, and the addition of another two that are on order will meet the NNSA's required production capability, Harvey says. Besides doubling capacity, NorthStar's dual production methods will provide the ability to ship isotopes seven days a week, he says.

For the past year, the company has been using feedstock enriched in the ^{98}Mo isotope, which has allowed it to increase the size of its package, known as a ^{99m}Tc generator, to 20 curies, the maximum allowed by the Department of Transportation. Several companies, including Urenco, can supply enriched Mo, but there is no US source, Harvey says. NorthStar is awaiting approval from the Food and Drug Administration to use recycled Mo in its processes.

The president of Niowave, Mike Zamiara, says the company will use niobium-based superconducting accelerators of its own design to produce ^{99}Mo from LEU in a noncritical reactor. The company was founded by a former employee of the National Superconducting Cyclotron Laboratory, now known as the Facility for Rare Isotope Beams, at Michigan State University. In Niowave's process, electrons are fired at a liquid metal target, producing high-energy bremsstrahlung photons that strip neutrons from the liquid metal to fission LEU targets.

Zamiara says the $28 million total the company received from the NNSA will help it scale up operations. Niowave already produces the medical isotopes yttrium-90 and actinium-225, but with ^{99}Mo, he says, "you're dealing with kilocurie quantities and more. That's a lot of uranium and a lot of radiochemistry processing" compared with the millicurie to curie volumes that are typical for ^{90}Y and ^{225}Ac.

SHINE's process entails bombarding a uranium target with neutrons. Rather than using fission, the company produces neutrons by firing accelerated deuterons at a tritium target. The resulting fusion reaction yields high-energy neutrons that are slowed to thermal energies before entering an aqueous target containing LEU. SHINE's CEO, Greg Piefer, says the NNSA support has enabled the company to accelerate construction of the four accelerators that will provide the required capacity. He expects to receive regulatory approval for operations to begin by mid 2023.



AMANDA YOUKER, a chemist at Argonne National Laboratory, operates a remote manipulator arm in a radiation-shielded cell. The cell was used for the purification of molybdenum-99 in a demo of the production process that will be used by SHINE Technologies.

SHINE has contracted with Ontario Power Generation for tritium, which the Canadian utility extracts during the recycling of heavy water from its reactors. Piefer says SHINE's ^{99}Mo operations will likely require less than 1% of the power producer's annual output.

The American Medical Isotopes Production Act of 2012 included a provision for DOE to supply LEU from its stockpile to any US ^{99}Mo producer that needs it, and to take back any radioactive waste that the companies are unable to dispose of commercially. Companies will be charged for the associated costs. The NNSA announced the first such agreement with SHINE on 6 January. Niowave's process also requires LEU; NorthStar's does not.

Essential or not?

Though the NNSA support accelerated NorthStar's and SHINE's ^{99}Mo production plans, it wasn't necessarily essential, their executives say. Harvey notes that NorthStar has been developing its processes since its formation in 2007. Niowave, however, probably wouldn't have entered the business without government support, Zamiara admits. "I don't think we would have gone this far, just because of the sheer magnitude of the ^{99}Mo market."

"If you look at the dollars that NorthStar and SHINE have gotten [totaling $102 million and $75 million, respectively], our program is dwarfed because we did come at this late," Zamiara says. "We were scaling up our accelerator for multiple uses when we decided to apply for the second round of agreements. We felt we had a path and we could catch up with the others."

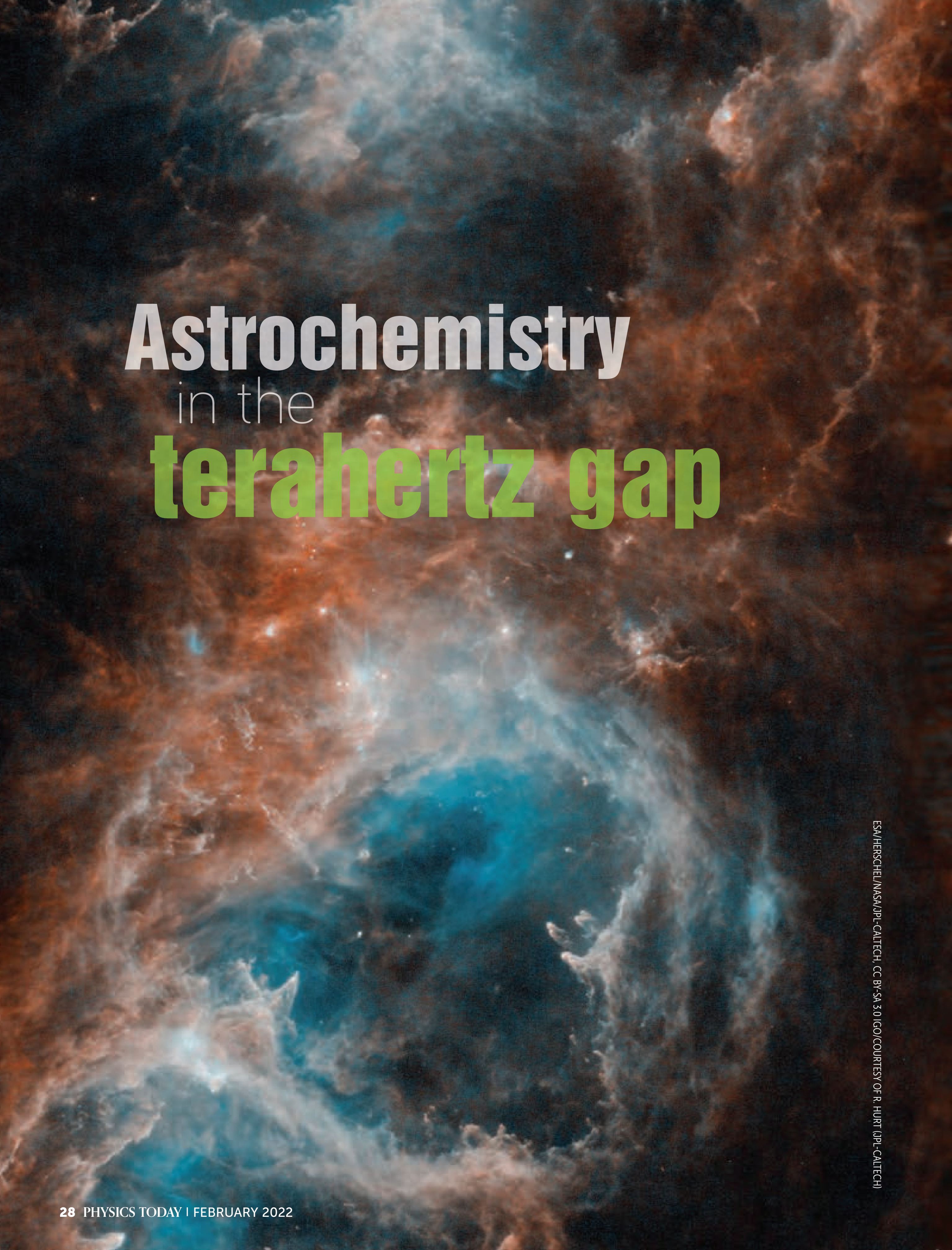
Piefer, in turn, notes that the NNSA funding pales in comparison to the billions of dollars in subsidies he says have been provided to producers in Europe, Australia, and South Africa. Moreover, he adds, the Jules Horowitz Reactor, under construction in France, is funded by multiple European governments, and plans call for it to enter the ^{99}Mo business when it's completed later this decade.

Harvey dismisses objections that might be raised to the government subsidies. "This is a perfect example of a program that the federal government embarked on to solve a serious problem affecting health care, when the US was solely dependent on foreign sources."

The NNSA's Dix concurs. "Our program was meant to kick-start a commercial enterprise and then back out. This is certainly not one of those government programs that has no end." She adds that some attrition was to be expected. "I don't think there was an expectation that all the companies we started with would be those that reached the finish line."

David Kramer PT

Astrochemistry in the terahertz gap



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Susanna Widicus Weaver is a professor of chemistry and astronomy at the University of Wisconsin–Madison.

Susanna L. Widicus Weaver

New capabilities are enabling laboratory spectroscopists to acquire more molecular spectra that advance our chemical understanding of the universe.

Studies of the atomic and molecular universes rely heavily on various spectra recorded in the long-wavelength range of the electromagnetic spectrum. At those wavelengths, astronomers identify the fingerprints of organic molecules, determine the conditions inside stellar nurseries, and detect redshifted transitions of atoms in distant galaxies. The false-color image on the opposite page, for example, shows the W3-W4-W5 complex of molecular clouds and star-forming regions in the Milky Way.

Much of the previous work has been conducted in the microwave regime, which covers 300 MHz to 300 GHz in frequency, or 1 m to 1 mm in wavelength. But recent insights into the molecular universe have come from far-IR (FIR) observations in the range of 300 GHz to 20 THz in frequency, or 1 mm to 15 μm in wavelength. The era of FIR astronomy brought about by the *Herschel Space Observatory*, the Atacama Large Millimeter/Submillimeter Array (ALMA), and the Stratospheric Observatory for Infrared Astronomy (SOFIA) has led to a recent heyday of molecular astronomy.

In the past, advancements in this field have been held back by the "gap" in the terahertz regime arising from the relative lack of molecular spectroscopic information in this range as compared with other regions of the electromagnetic spectrum.[1] The gap, illustrated in figure 1, had arisen because of historical limitations in the technology available for laboratory and observational studies. Because of advances in telecommunications, security, and astronomical instrumentation design in the past 20 years, however, astronomers are now making rapid improvements.[2] New tunable terahertz light sources, higher-power terahertz amplifiers, more sensitive detectors, and rapid and broadband data-acquisition capabilities have revolutionized the field. Researchers are starting to fill the terahertz gap.

Terahertz spectroscopy

Atomic and molecular spectra in the FIR range are the tools that astronomers and planetary scientists most commonly use to study chemistry in space. Important features found in the regime include the electron spin flip of the hydrogen atom at a wavelength of 21 cm; the ammonia structural inversion transitions at a frequency of 23 GHz; the pure rotational lines of carbon monoxide, which are the signposts of telescope receiver bands; and the rotational and rovibrational lines of organic molecules that have been seen in comets and the interstellar medium and may be the precursors to life throughout the universe.

But what is a spectral line? Atoms and molecules absorb only at certain wavelengths that correspond to specific energy transitions. For molecules, that can be energy changes associated with rotation, vibration, or electronic energy. Molecular transitions are quantized, which simply means that the transitions occur only at particular amounts, or quanta, of energy. The transitions are sharp, meaning that they happen over a narrow range of frequencies. If you shine a particular wavelength of light through a sample and watch the response with a detector, you can determine how the molecules interact with the light. Repeating that process over a range of wavelengths allows you to construct a spectrum.

If a molecule responds to light through either absorbing or emitting it, the signal at the detector changes abruptly. Spectral transitions appear as narrow spikes (hence the use of the word "line" to describe them). Each line in a spectrum corresponds to a specific transition of the molecule. Figure 2 shows an example spectrum.

In the FIR, researchers observe rotational lines from small molecules, which contain about 2–10 "heavy" atoms, primarily

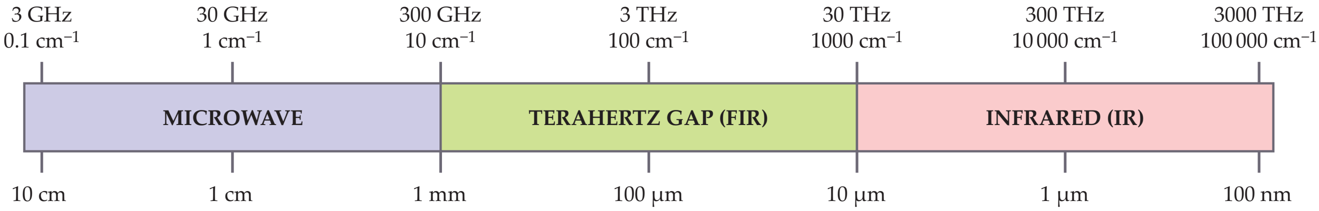

FIGURE 1. A GAP in the collection of molecular spectroscopic data has long existed between the microwave and IR wavelength ranges of the electromagnetic spectrum. Now technological advances are equipping far-IR (FIR) astronomers with the instrumentation they need to fill the terahertz gap.

carbon, nitrogen, oxygen, and associated hydrogens. For larger molecules, they observe rovibrational lines, which arise from changes in both rotational and vibrational energies. The specific energies of rotational transitions are related to a molecule's structure. As such, each rotational spectrum is molecule specific. If several lines for a given molecule are observed, the temperature and density in a sample of gas can be quantified by comparing the lines' relative intensities.[3] Molecules, therefore, are routinely used as probes of the physical properties of objects in space. For astrochemists, the molecular information gained through such measurements improves their understanding of how chemistry evolves as stars and planets form.

To study a particular molecule in space, one must first obtain a laboratory spectrum and assign the lines therein. Spectral lines are measured across a given frequency range and matched to a spectral prediction based on a quantum mechanical model of the molecule's energy levels. Usually not all of a molecule's spectral lines are measured. Frequency coverage, spectral sensitivity, and sample conditions all influence what lines can be observed in the lab and in space. But even with only partial spectral information from the laboratory, one can assign the spectrum and predict the rest of the lines. That's because the lines in a rotational spectrum follow a regular pattern that is linked to the molecular structure. With that information, spectroscopists can identify the molecule's transitions and determine its physical parameters.

Simple molecules require only a few parameters for a full spectral assignment. Complex molecules, however, demand dozens of parameters to achieve a level of assignment that leads to reliable predictions. If researchers collect sufficient information in the lab, they can determine the parameters with a high degree of precision. They can then use the information to extrapolate the spectrum to other frequency ranges at any temperature. Astronomers use this lab information to analyze observational spectra.

The spectrum that is collected during telescope observations contains all the lines from every molecule in the source. When a molecule is identified, its spectral features are matched to those predicted from the laboratory spectral assignment. Matching requires knowledge of not only the spectrum for the molecule of interest but also the spectra for all the molecules in the source. Astrochemists can then connect each line to a molecule and sort out any ambiguities by recognizing the patterns from known laboratory measurements. If enough spectral lines are observed that can be uniquely assigned to a given molecule and if their relative intensities match the expected physical parameters of the source, the molecule is said to be detected in space.

Such a process relies on laboratory measurements of spectra across the terahertz range so that the laboratory's spectral assignment can be matched to observations. Unfortunately, laboratory studies have been limited because of the challenges of filling the terahertz gap. Historically, researchers have lacked stable, high-powered, tunable light sources in the FIR regime and sensitive detectors that cover that part of the electromagnetic spectrum. IR spectroscopy, which covers 20–430 THz in frequency, or 15 μm to 700 nm in wavelength, is well established, and commercial spectrometers are a standard characterization tool in nearly every chemistry laboratory. Microwave spectroscopy, covering 300 MHz to 300 GHz in frequency, or 1 m to 1 mm in wavelength, is not as widely used as an analytical tool. But it is just as powerful as IR spectroscopy and is a well-established field of research dating back to the development of radar during World War II.

FIR spectroscopy, however, has not been widely pursued. Of all the high-resolution spectroscopy research laboratories in the world, around 10 have spectral access from 300 GHz to 1 THz. The number of labs with high-resolution spectral access above 1 THz can be counted on one hand. But with the development of new FIR observatories has come new technological capabilities, and many of the historical limitations in the FIR range have been overcome. A deluge of astronomical spectra is now arriving from FIR telescopes. My research group and the handful of others who work at the millimeter-to-micrometer wavelengths are striving to develop laboratory techniques to keep up with the quantity of data.

Laboratory challenges

The simplest and most straightforward way to obtain terahertz spectral data in the laboratory is to conduct what is called a direct-absorption experiment. When light is shone into a molecular sample, a detector records the amount that passes through it. Spectroscopists then reference the input light to the output light to determine how much the sample absorbed. By scanning the input light across frequency steps that are smaller than the width of a spectral line, they can piece together an absorption spectrum.

To extend measurements beyond the simple direct-absorption method requires borrowing techniques used to gather data in the IR and microwave regimes. In the IR, light sources that include lasers and optics based on ground glass with mirrored coatings are used. In the microwave, radiation is generated by crystal oscillators, like those used in a watch and car radio, and circuitry directs it to the sample. The FIR is often called the quasi-optical regime because it draws methods and equipment from both approaches. A FIR lab uses Teflon lenses, beamsplitters made of thin sheets of Mylar, mirrored focusing optics, and diodebased frequency multipliers. Combining the two types of experiments into one system that works for all wavelengths in the FIR is complicated and technologically challenging.

Unfortunately, the challenges of FIR experiments do not stop there. Once a system is established for generating light and directing it into the sample, a detector that is sensitive enough to measure the signals is required. Although some room-temperature devices cover the longer-wavelength end of the FIR regime, anything above roughly 300 GHz requires a custom-built detector cooled with liquid helium. Unless kept at extremely low temperatures, the detector elements that have the best response at FIR wavelengths are flooded with thermal background noise.

Helium boils at a temperature of 4.2 K, and keeping a detector at that temperature requires routine cryogen fills, which greatly complicates the logistics of experiments. In addition, the natural supply of helium on Earth is rapidly dwindling, and using helium-dependent devices is increasingly expensive (see PHYSICS TODAY, April 2019, page 26, and "Helium shortage has ended, at least for now," PHYSICS TODAY online, 5 June 2020). Detector manufacturers are now implementing closed-cycle cooling systems that use helium recirculation to better conserve the supply. But those detectors are not readily available to every spectroscopy laboratory.

Once a source and detector are set up, the next step is to deliver the molecular sample into the system. Rotational spectroscopy requires gas samples for analysis because the molecules have to be free to rotate and will not do so as a liquid or solid. For stable molecules, spectroscopists can fill a cell with gas and record the spectrum. For molecules that are highly reactive or unstable, however, they need to devise ways to produce the molecule and keep it sufficiently isolated to avoid its reaction or decomposition while recording spectra. Most options require sources that continually flow or pulse the gas mixture through the system. Those sources introduce complications for gas handling because they require large pumps and vacuum fittings, windows, and other hardware to couple the spectrometer to the gas cell.

Another challenge astrochemists face has to do with the nature of the molecules. In the low density of space, molecules react slowly because they take tens of thousands of years to collide. Their reaction rates speed up considerably when an ion is involved because its charge attracts molecules. But ions are difficult to produce in the lab at sufficient quantities to study their spectra. Plasmas are used to make the ions, and then the gas sample is expanded into a vacuum, which leads to cooling and stabilization of the products. But even with the most efficient ion sources, only 1 in every 10 000 molecules gets ionized, and once expanded into the vacuum, the gas sample is even further diluted.

Remarkably, detecting some ions in the lab is more difficult than in space. Fortunately, now that the technology is available to ease the design problems associated with FIR spectrometer instruments, several creative production techniques for producing molecular ions have been implemented and are leading to great advances in their study.

Once all those challenges are overcome and a spectrometer is constructed and signals are optimized, it may take anywhere from a few days to many months to record the spectrum of interest. Traditional techniques scan step-by-step at small frequency increments to capture all the molecular lines. Some techniques are designed to increase data-acquisition speed, but most are limited to the microwave regime. Fortunately, the development of more advanced telecommunications devices is now enabling complementary techniques for the FIR. But such extensions are limited by the available technology, and many techniques used in other frequency ranges that involve more sophisticated detection schemes are not yet applicable in the FIR. Most FIR instruments in the laboratory, therefore, are still focused on simple direct-absorption techniques.

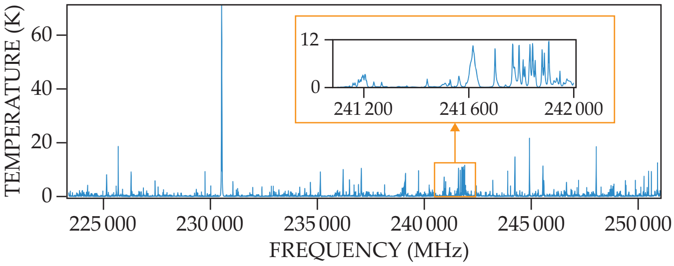

FIGURE 2. THIS SPECTRUM of the Orion molecular cloud was measured using the Caltech Submillimeter Observatory. The inset features spectral lines from methanol.[12] (Courtesy of Caltech/NSF, AST-0838261.)

Collecting astrochemistry data

Much of the equipment used in telescope observatories is similar, if not identical, to the equipment used in spectroscopy laboratories. Signal collection with a radio telescope, however, is more complicated than it is with a spectrometer in the lab because of heterodyne receivers used to detect the weak signals from space. Those receivers mix the observed light from space with a well-known local-oscillator frequency. The slight offset of the signal frequency from the local-oscillator frequency results in a beat frequency, which corresponds to the difference between the two. ALMA uses a collection of antennas, some seen in figure 3, to capture signals.

Telescope receivers are designed such that the beat frequency falls within standard radio bands. Researchers can then use powerful signal amplifiers commonly found in radar, cellular phones, televisions, radio transmitters, and other RF devices. The radio signal can be rescaled to the correct frequency range after all the signal-processing steps are completed at the higher signal power. Heterodyne techniques are thus incredibly sensitive and enable researchers to detect weak signals from space that would otherwise be indistinguishable from background noise.

Unlike the absorption spectra collected in the lab, observations typically consist of emission spectra. Molecules in space absorb light from nearby stars and then emit light at FIR wavelengths as they cool to their lowest energy states. That molecular emission thermally stabilizes an interstellar cloud during star formation. To observe the emission, astronomers tune their telescope receivers to the wavelength of a particular molecular transition previously measured in the lab and collect a signal to see whether any sign of emitted light rises above the background. Figure 4 shows some of the pieces of an ALMA telescope receiver that are used to collect molecular-emission measurements.

In the past, the bandwidth of heterodyne detections was so

FIGURE 3. THESE ANTENNAS are part of the Atacama Large Millimeter/Submillimeter Array, a radio telescope located in Chile and used for far-IR observations. (Courtesy of ESO/S. Guisard, www.eso.org/~sguisard.)

small that astrochemists had to target narrow frequency windows and match spectral signatures to molecules one line at a time, one molecule at a time, and one source at a time. But the new generation of FIR observatories employs novel broadband receiver technology to rapidly collect broad swaths of spectral information. The advances have prompted researchers to change their approach to data acquisition and allowed them to observe a wealth of molecular information. For perspective, the spectrum shown in figure 2 was collected in blocks of spectral data 4 GHz wide. The generation of receivers that were in use just a few years ago offered a maximum spectral bandwidth of 500 MHz. Receivers now offer bandwidths of up to 12 GHz.

In just the past few years, astronomical data sets have increased in size by a factor of 10–20, and the number of molecular lines in each spectrum has increased from a few to thousands, which has led to a wealth of new information. The *Herschel Space Observatory* had several key programs that were dedicated to broadband, high-resolution molecular-line surveys of clouds in various stages of star formation. The publicly available *Herschel* data archive is full of spectra from 600 GHz to 3 THz and contains thousands of unidentified spectral lines.[4] SOFIA routinely observes spectra at frequencies above 1 THz, where lab information is limited.[5] And the ALMA telescope has pushed data collection to the next level; for a week of observations, it can provide about 300 TB of terahertz-frequency spectral data.[6]

Few research laboratories have instruments that cover the entire terahertz gap, so only a few molecules have been fully characterized across that frequency range. That means that astronomers cannot analyze much of the spectral information gained from the new astronomical observations. Many astrochemists choose to focus on the molecules that have already been characterized, which are typically stable molecules that are good tracers of physical conditions in space. But what information could we glean from observations if we had the laboratory information with which to compare it?

Filling the terahertz gap

With the recent technology advances, laboratory spectroscopists are beginning to catch up with the influx of FIR observational spectra. Sources that offer enough power to drive absorption spectrometers in the FIR spectral regime are now available as off-the-shelf components that operate at frequencies of up to 3 THz. Detectors that provide the necessary sensitivity are now also commercially available. Increases in data-acquisition speed, driven by the telecommunications industry, are leading to the development of new broadband spectrometers. Based on those technology developments, research groups with spectrometers that cover the terahertz gap are now developing new techniques that offer increases in detection sensitivity, spectral acquisition speed, and spectral coverage. The improvements provide researchers with the means to study new molecules at an increased rate, make new identifications in space, and advance our chemical understanding of the universe.

Coupled with the advances in technology is a recent push to automate spectral assignments. Three main spectral catalogs are publicly available: the Jet Propulsion Laboratory Molecular Spectroscopy database,[7] the Cologne Database for Molecular Spectroscopy,[8] and the National Radio Astronomy Observatory's Splatalogue platform,[9] which combines information from the other two databases with information from several private catalogs maintained by laboratory groups. The databases maintain a list of molecules for which laboratory studies are available and provide catalogs that list all the assigned and predicted spectral lines and their associated frequencies and intensities. Such catalogs are incomplete for most molecules, but concerted efforts have been made to keep them up to date, at least for the most abundant molecules and for those that contribute the most lines to observational spectra.

The work is seemingly never-ending and, unfortunately, is not often supported by funding agencies. But fortunately, a few tireless heroes in the field have dedicated some of their time to maintaining those catalogs. The rest of us in the community are incredibly grateful for their work. Once a molecule has a catalog, either downloaded from a database or constructed by the group that does the laboratory analysis, the next step is to com-

FIGURE 4. ANTENNA COMPONENTS used in the Atacama Large Millimeter/Submillimeter Array (ALMA) telescope include **(a)** a cryostat, here being assembled by technician Patricio Escarate. It cools 10 receiver cartridges. The **(b)** cold receiver cartridges are paired with **(c)** warm receiver cartridges. Together, the assemblies are used to make observations in the 35–50 GHz frequency range. (Panel a courtesy of ESO/Max Alexander; panel b courtesy of ASIAA; and panel c courtesy of G. Siringo, ALMA, ESO/NAOJ/NRAO.)

pare the catalog entries with observations. A few software packages enable users to overlay on the spectra the information from the catalogs and perform a mathematical comparison. That analysis requires that one has mastered the nuances of laboratory spectroscopy and the technical details of observational astronomy.

Ideally, an automated process would exist that could reliably compare the database information with the observations being produced. The greatest strides in the field over the past few years have focused on that goal. Automated spectral-assignment routines based on statistical analysis and in some cases machine learning are now being developed. It's an enormous step forward for the field and one that's still in its infancy. Several teams are working on various aspects of the huge undertaking, with goals of combining methods once each aspect has been developed. When fully optimized, researchers may finally be able to process all the information coming from FIR telescopes without assigning the individual spectral lines by hand.

Automated spectral analysis may be a promising horizon for the field of astrochemistry, but researchers will still rely on laboratory efforts to supply the spectral information to which such programs can be applied. Technology once again leads to a gap. The next step in filling the terahertz gap is to bring the advances of FIR observatories to the laboratory. Telescope receivers are intricate, custom-built, and expensive pieces of equipment. They are designed to sit at a particular wavelength and perform long integrations in search of weak spectral features from distant molecular clouds. Building one for laboratory studies is not financially feasible because a full implementation of one device requires both custom-built equipment and support for a PhD-level expert for at least a year or two. That expense stretches beyond the budget of a laboratory managed by one investigator who relies primarily on government funding to support their students and technical staff.

Observatory funding is a different story: All observatories have highly trained technical staff who spend their time developing such devices. The only spectroscopy groups that have access to them are the ones that have close ties to observatories. Typically, both observatory and laboratory staff work at the same institution or are affiliated with the same larger research infrastructure. Generally, such research groups purchase or borrow the used and out-of-date receivers after a major facility updates its equipment. Even in the best-case scenario, the equipment being used for laboratory spectroscopic studies is one generation behind the state-of-the-art technology. Of the small number of laboratory groups working in the field, only two thus far have developed laboratory instruments using telescope receivers. The tantalizing results from their first experiments show great promise for future developments.[10,11]

Despite all the challenges associated with working in the terahertz gap, astrochemists have made major strides over the past two decades to provide the laboratory information needed to guide FIR observations of molecules in space. With the new capabilities that are now available in terms of instrumentation and data analysis, the terahertz gap is being filled. Because of the explosion of FIR observational capabilities, we are now rapidly expanding our understanding of the molecular universe. It is an exciting time to be an astrochemist!

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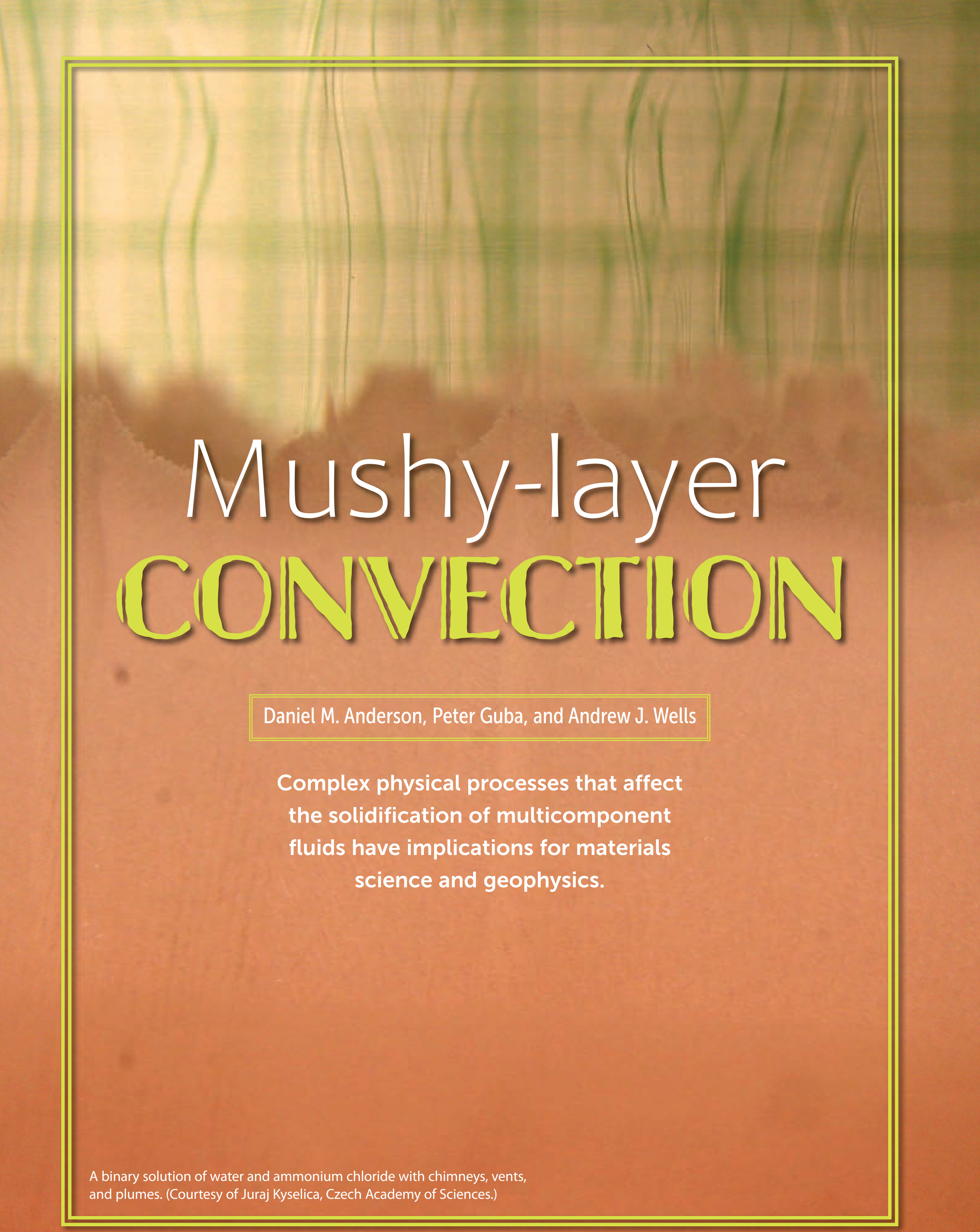
Mushy-layer CONVECTION

Daniel M. Anderson, Peter Guba, and Andrew J. Wells

Complex physical processes that affect the solidification of multicomponent fluids have implications for materials science and geophysics.



A binary solution of water and ammonium chloride with chimneys, vents, and plumes. (Courtesy of Juraj Kyselica, Czech Academy of Sciences.)

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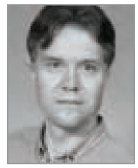


Sea-ice formation in freezing polar oceans and defect development in metal alloys may seem like disparate processes, but they share one important feature: a so-called mushy layer. Such porous media host complex fluid mechanical activity, thermal and chemical transport, phase transformations, nonlinear dynamics, and pattern formation. And the effects can be dramatic: Mushy-layer dynamics are implicated in the demise of industrially cast turbine blades and dynamics of the global climate.

Directly observing real-world mushy layers is a challenge. Industrial alloys, for example, are cast from high-temperature melts that pass through a porous, or mushy, state as they cool, and crystallization patterns that form during cooling control the material properties. But the materials are opaque, so their internal features remain inaccessible to visual inspection until they are cooled and sectioned.

Under quite different thermal conditions, sea ice forms when water freezes in the inhospitable polar oceans. Although the expanse of polar ice can be imaged remotely by satellites, directly probing dynamics inside the sea ice is a formidable challenge for even the most intrepid field researchers.

Earth's mantle and core have their own phenomena linked to mushy layers, but the deepest parts of our planet remain unreachable to direct exploration. Observations rely on inverse techniques, such as interpreting the propagation of seismic waves.

This article aims to provide a physical understanding of mushy layers by describing the mechanisms behind their convective processes. The synergy between analytic models, laboratory experiments, and computational simulations has been instrumental in developing a comprehensive picture. We feature two ubiquitous examples—one from Earth's cryosphere and another from metallurgy—and conclude by highlighting new insights into convective phenomena in ternary systems. But first, we explain how mushy layers form.

Reactive porous media

A mushy layer is a mixed-phase region composed of a solid matrix surrounded by a melt phase. When a solid–liquid interface freezes, such layers can appear as a result of the Mullins–Sekerka instability, in which constitutional supercooling—the cooling of a multicomponent fluid below its local equilibrium freezing temperature—drives perturbations on the interface to grow.[1] Small perturbations develop into dendritic structures that form a porous region of solid crystals in the parent liquid phase. The mushy layer is reactive in that the solid matrix will melt, dissolve, or grow in response to its local thermal and chemical environments.

Buoyancy forces tied to the fluid density's dependence on temperature and composition drive the motion of the interstitial fluid. The resulting heat and solute transport can cause the solid matrix to melt or dissolve, even to the point of complete local erosion. A striking consequence of that erosion is so-called chimney convection, shown in the opening image, in which fluid flow is strongly focused into channels devoid of solids.

Chimney convection during the industrial casting of an alloy can cause macrosegregation—the macroscale redistribution of the alloy's components. It can also lead to the appearance of chains of equiaxed grains known as freckle defects that punctuate the final solidified product. Freckle defects and other chemical inhomogeneities can weaken materials used in, for example, high-performance aeronautical turbine blades (see figure 1). It is therefore necessary to understand and prevent their formation in solid manufacturing processes.

Sea ice solidifies because of heat loss to the atmosphere at the sea surface.[2] Its chimneys are known as brine channels and, importantly, provide a direct source of salt flux into the underlying ocean.

To understand mushy layers in metallurgical and geophysical systems, one must come to grips with their phase diagram. Figure 2a shows a phase diagram for a simple binary alloy of components A and B with composition C and temperature T. Typically, A represents a solvent, such as water; B represents a dissolved solute, for example, salt; and C is the mass fraction of B in the system. Here we consider the case where the melt's density increases with C.

Two features of the phase diagram become immediately apparent: the liquidus, a line above which the system is entirely liquid, and the eutectic, a line below which a mixed solid forms. The liquidus temperatures of the components simultaneously reach their lowest values at the so-called eutectic concentration C_E. Between the liquidus and the eutectic exists a two-phase equilibrium mixture of solid dendritic crystals and interstitial fluid. The initial liquid composition determines which of the two chemical components forms the solid matrix: an alloy with subeutectic composition $C < C_E$ yields a mushy layer with solid A, whereas a supereutectic composition produces a mushy layer with solid B. At a given temperature, the liquidus defines the composition of the interstitial liquid.

The dendritic mushy layer has large surface-area-to-mass ratio, so pore-scale transport and internal phase transformations act rapidly to maintain thermodynamic equilibrium. Phase transformation is critical for maintaining the thermal and solutal balances in the mushy layer.

Buoyancy, instability, and convection

Because of density variations in the interstitial liquid, gravity can generate flows during mushy-layer solidification. Consider, for example, a common scenario in which the liquid density increases strongly with concentration and decreases weakly with temperature over the relevant ranges. A solidifying subeutectic alloy cooled from below (see figure 2b) generates a solute-enriched interstitial fluid, thereby developing temperature and concentration fields that are both stabilizing; the cold solute-rich fluid near the mushy bottom is denser than the warm solute-poor fluid above, so no convection occurs.

By contrast, a supereutectic alloy cooled from below (see figure 2c) releases solute-depleted fluid. The stabilizing thermal field is overcome by a much stronger destabilizing concentration gradient—the solute-poor cold fluid below is less dense than the solute-rich warm fluid above—and the interstitial fluid in the mush undergoes composition-driven convection.

The tables are turned when cooling occurs from above. In the case of sea ice, for instance, both the thermal and compositional fields drive convection in the mush. As the brine is cooled from above, the growing ice rejects salt, which makes the interstitial fluid denser.

The above classification can be guessed on purely static grounds, but dynamics must be considered to explain the onset of convection. The process is usually delayed until the density drop across the mush reaches a dynamically predicted critical value.[3] Potential energy must be released from the background state faster than it is dissipated to allow instabilities to grow and fluid to flow.

Quantitative representations of the critical conditions use the Rayleigh number, a dimensionless parameter that represents the ratio of buoyant mechanisms to dissipative ones. The liquid adjacent to the mush may also be prone to convection, and the different rates of heat and solute diffusion may drive double-diffusive fingering convection, known to oceanographers as salt fingers (see box 1). Interestingly, double diffusion plays no role in binary mushy layers because the liquidus constraint—the maintenance of phase equilibrium in the mush—prevents the temperature and the solute concentration from evolving independently. Related double-diffusive-type mechanisms for convection, however, are a necessary part of the conversation about ternary systems.

A conceptual tool known as a parcel argument (see box 2) explains a mechanism behind the formation of liquid inclusions, or nascent chimneys, in configurations like the one in figure 2c. The mechanism lies at the heart of all studies of near-onset convection regimes. Using techniques of bifurcation theory, Grae Worster at the University of Cambridge and one of us (Guba) found that positive nonlinear feedback can focus flow to form liquid inclusions. The feedback is associated with a decrease in the solid fraction and leads to increased permeability to fluid flow. The findings also demonstrate how experimental conditions—namely, the freezing speed and initial solution concentration—control the various stable convective flow patterns in mushy layers.[4]

Although they show only the near onset of chimney flow and not fully developed chimneys, the findings do hint at the experimental parameters one might tune to stimulate or avoid the emergence of chimneys. The phenomenon is highly nonlinear, so modelers have turned to approximate nonlinear models and simulations.[5,6] Numerical studies in which a single liquid inclusion or a chimney was isolated have helped explain convection in steadily propagating mushy layers.[7] Single-domain enthalpy methods for simulating flows and phase changes during mushy-layer evolution serve as versatile, less

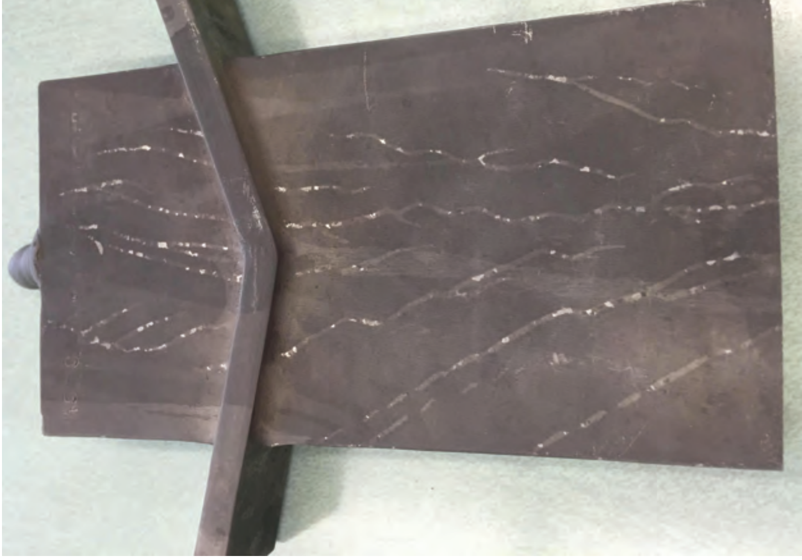


FIGURE 1. A TURBINE BLADE can be weakened by defects like those in this test cast. The growth direction of the freckle defects shown here is right to left, which was against gravity during the growth process. (Courtesy of Boyd Mueller of Howmet Aerospace and William Boettinger of NIST.)

BOX 1. DOUBLE-DIFFUSIVE CONVECTION IN BINARY FLUIDS

A classic example of double-diffusive convection occurs when a layer of warm, salty water is adjacent to one of cold, fresh water.[16] The underlying instability can be traced to the different rates of heat and solute diffusion, hence the term double-diffusive convection.

If the warm, salty layer is above the cold, fresh water, a parcel of fluid displaced upward warms rapidly because its thermal diffusivity is large relative to its solute diffusivity. The parcel is fresher and therefore lighter than its surroundings and continues to rise. By the same argument, a parcel displaced downward would continue to fall. The potential energy in each case is supplied by the unstable liquid-density stratification generated by the destabilizing process of thermal diffusion. Such double-diffusive convection occurs in what is often referred to as the finger-ing regime. Salt fingers influence the dynamics of such natural hypersaline environments as the Dead Sea.[16]

In the reverse situation—cold, fresh water on top—a parcel of fluid displaced upward cools but retains its salt content. Being heavier than its surroundings, the parcel falls back toward its original position. But a temperature lag allows the parcel to return with more inertia than it had before, and an overstable oscillatory motion persists against the stable compositional stratification. The regime is usually referred to as diffusive, and the mechanisms are fundamentally the same as those seen in nonreactive porous media.[17]

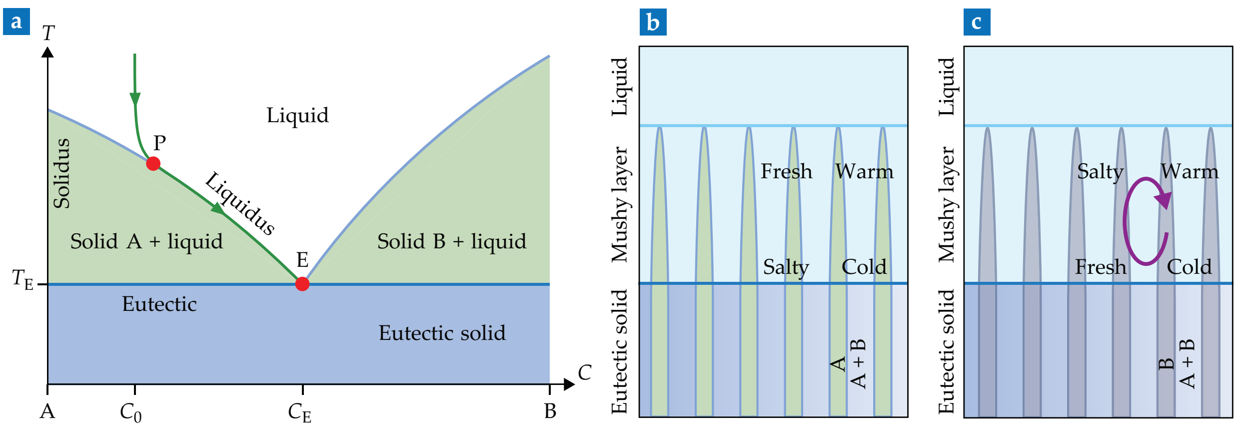


FIGURE 2. A BINARY EUTECTIC ALLOY with components A and B can be understood using a two-dimensional phase diagram. **(a)** A solution with initial composition C_0 lower than the eutectic composition C_E follows path P–E along the liquidus as it gradually cools. **(b)** If $C_0 < C_E$, the residual liquid is denser than the initial melt and the mushy layer is stable. **(c)** If $C_0 > C_E$, the residual liquid is lighter, which drives convection in the mushy layer.

computationally expensive alternatives to the classical front-tracking approach and have been applied to study solidification of metals and sea-ice dynamics.[6] Still, a complete picture remains elusive of how liquid inclusions develop into chimneys in time-evolving mushy layers.

Sea ice and brine channels

Sea ice is a geophysically important mushy layer formed by freezing seawater. More than 10^7 km^2 of Earth's polar oceans freeze over each year (see the article by Ron Kwok and Norbert Untersteiner, PHYSICS TODAY, April 2011, page 36). Convective motions in the mushy layer are crucial for understanding the salt flux to the underlying ocean, which affects the water's buoyancy and has implications for circulation and water-mass transformation. Desalination and convective flow also affect the material properties of the porous sea ice. Further, the liquid-filled pores provide a natural biogeochemical reactor that supports life, such as photosynthetic algae, in sea ice. (See references 2 and 6 for broader reviews.)

Brine channels, the convective chimneys in mushy sea ice, are the primary conduits for saline water expelled from sea ice into the upper ocean. Convection is suppressed in thin mushy layers, but it is initiated above a certain thickness, thereby driving brine-channel growth and gravitational drainage through high-salinity plumes. That behavior is consistent with the idea of a critical Rayleigh number and the layer storing increasingly more potential energy until it exceeds its convective-stability threshold. The brine-channel pattern evolves in space and time as a sea-ice layer grows (see figure 3), with extinction of flow in some channels and a coarsening of their spacing.

It is natural to wonder about what controls the selection and evolution of the convection pattern in such a nonlinear dissipative system. John Wettlaufer, Steven Orszag, and another of us (Wells) postulated a variational principle by which the brine-channel spacing maximizes the outward flux of potential energy in response to buildup driven by cooling, ice growth, and brine segregation in the pore space.[8] Several groups have used that principle to build simplified models of mushy-layer convection with brine channels to predict salt fluxes from ice and flow patterns.[6] The results agree with laboratory observations over relatively short time scales on the order of days.

Longer-term observations of sea ice are more challenging, and researchers have historically relied on *in situ* techniques, such as collecting ice-core samples and inferring attributes from electromagnetic properties.[2] Alternatively, computational simulations with an enthalpy method can be used to evaluate the complexities caused by permeability evolution as ice desalinates.

In addition to affecting the surrounding ocean water, salt fluxes influence the physical and biogeochemical properties of polar ice. Many biogeochemically active tracers, such as nitrates and phosphates, are rejected from the solid-ice matrix and segregated into the liquid-brine-filled pore spaces alongside other salts. That process can lead to chemical concentrations much higher than those in the ocean, and the ice can therefore act as a substrate for significant biogeochemical processes.[2] When convection occurs, the turnover continually replenishes pore water with nutrients. The pores can thus provide a habitat for bacteria, photosynthetic algae, and other life.

Freckle prediction in metallurgy

Sea ice has been freezing and thawing for eons. Metallurgical history spans millennia. But understanding their link is a modern development. A little more than half a century ago, metallurgists working at Bell Labs in Murray Hill, New Jersey, recognized the utility of using transparent compounds as proxies for metals in solidification experiments.[9] The researchers studied solidification in transparent aqueous systems, such as ammonium chloride solutions, because they were more easily managed and visualized in the laboratory. Other metallurgists from the University of Oxford, MIT, Pratt & Whitney Aircraft Company, and other institutions successfully used the systems to trace the origins of macrosegregation in cast alloys, along with freckle and other channel-type defects, back to interdendritic convection during growth.[10] The juncture was also notable because those metallurgists appear to have coined the term "mushy" to describe mixed-phase solid–liquid regions.[11]

Experiments, modeling, and simulations of aqueous systems have since been used extensively to identify conditions under which defects can be avoided and to explore such mitigation strategies as rotation, application of magnetic fields, and forced convection. One strategy involved adding a third component—zinc chloride—to a solution of water and ammonium chloride.[12] In that case, the added component increased the density of the fluid released upon solidification. The denser fluid promptly shut off the convective instability and the related formation of unwanted freckles.

Although adding an extra component to a metallurgical process may make forming a solid product easier, the most important consideration is whether that product still has the desired properties. Thus, to make quantitative predictions for multicomponent alloys of metallurgical interest, one must address their increasingly complex phase diagrams. That need led metallurgists at NIST to team up in the 1990s with researchers at the University of Iowa and develop the freckle-predictor criterion, a Rayleigh number–based measure for predicting whether freckles will form in different nickel-based superalloys.[13] Because of their complexity, multicomponent systems are typically studied using continuum models[14] based on conservation of mass, momentum, energy, and species, all coupled to phase transformations. The models are amenable to computer simulations like the one shown in figure 3.

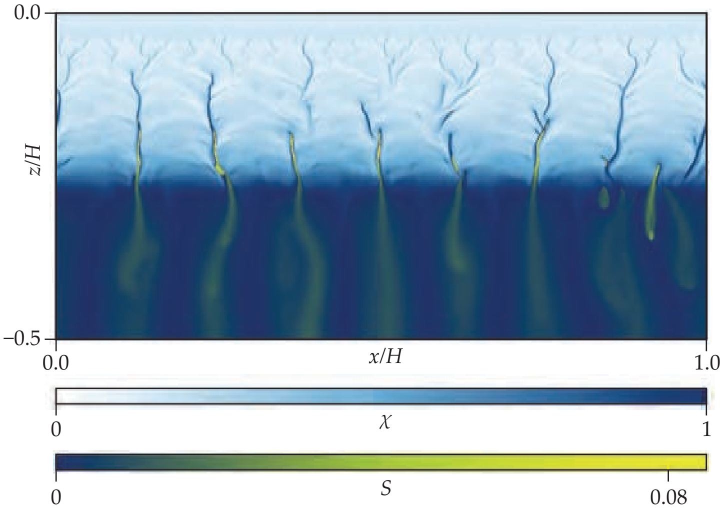


FIGURE 3. SEA-ICE GROWTH is simulated here using an enthalpy method in an effectively two-dimensional Hele-Shaw cell of depth *H*. The cell is cooled from above.[15] Salt-enriched plumes (yellow) with dimensionless salinity *S* drain from brine channels in sea ice with porosity *χ* into the underlying liquid (blue).

Ternary systems and distinct mushy layers

Research on aqueous ternary systems constitutes a small but important step toward understanding complex multicomponent systems. Recent studies of systems with relatively simple phase diagrams have revealed new, and in some cases unexpected, mechanisms associated with convection in mushy layers.

As with binary systems, the first ingredient for understanding ternary-mixture solidification is the ternary phase diagram. The sketch in figure 4a is for a system with components A, B, and C. Suppose that A represents a solvent, such as water, and B and C two solutes, such as salts. Upon cooling from below, A solidifies at point P to form single-phase dendrites in a primary mushy layer, shown in figure 4b, with B and C left in the liquid. The liquid mass fractions of both B and C increase with depth in the primary mushy layer as A is removed from the liquid phase to form the dendrites. At point S, components A and B solidify together, forming two-phase dendrites in a secondary mushy layer, with component C rejected. The liquid phase in the secondary mushy layer is further enriched in component C and depleted in component B.

Even for the relatively simple phase diagram shown in figure 4, one can also envision adjusting the initial liquid compo-

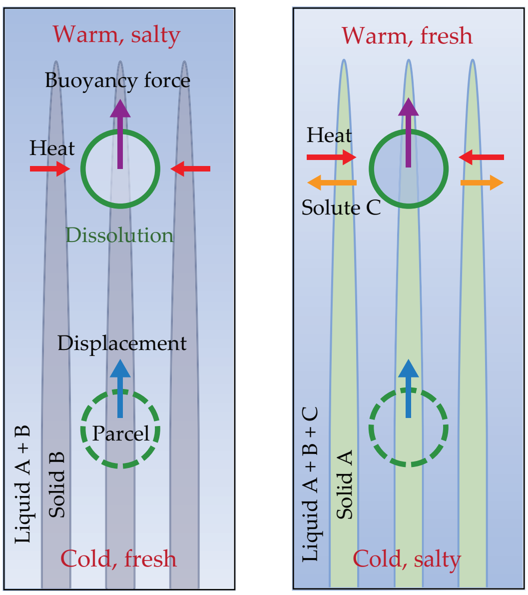
BOX 2. PARCEL ARGUMENTS

Consider a binary mushy layer with cold, fresh water sitting below warm, salty water, as shown in the left diagram. The layer is thermally stable and solutally unstable, a typical situation in supereutectic growth. The lighter component is water, or solvent A, and is released upon solidification; the heavier component is salt, or solute B, and forms dendrites. Assume that heat diffuses much faster than solute B.

An upwardly displaced fluid parcel warms rapidly in response to its new environment. To maintain thermodynamic equilibrium and achieve the composition required by the liquidus constraint, the parcel dissolves some of the surrounding matrix. Such dissolution may lead to a nascent chimney; the accompanying permeability increase, although secondary to the solid-fraction erosion, generates nonlinear focusing of the flow into narrow buoyant plumes.

Now consider a ternary mixture whose primary mushy layer is thermally and solutally stable—specifically, the bottom is cold and rich in two salts, solutes B and C, as shown in the right diagram. Assume heat diffuses much faster than solutes and that solute C diffuses much faster than solute B. For simplicity, suppose that buoyancy forces act only with respect to solute C.

An upwardly displaced fluid parcel warms rapidly but remains relatively rich in the slowest-diffusing component, solute B. Thermodynamic equilibrium—the ternary liquidus constraint—is maintained by a relative depletion of solute C through solutal diffusion. The parcel is thus fresher in solute C and lighter than its local environment, so it experiences an upward buoyancy force that drives an instability, despite the apparently stable background stratification.



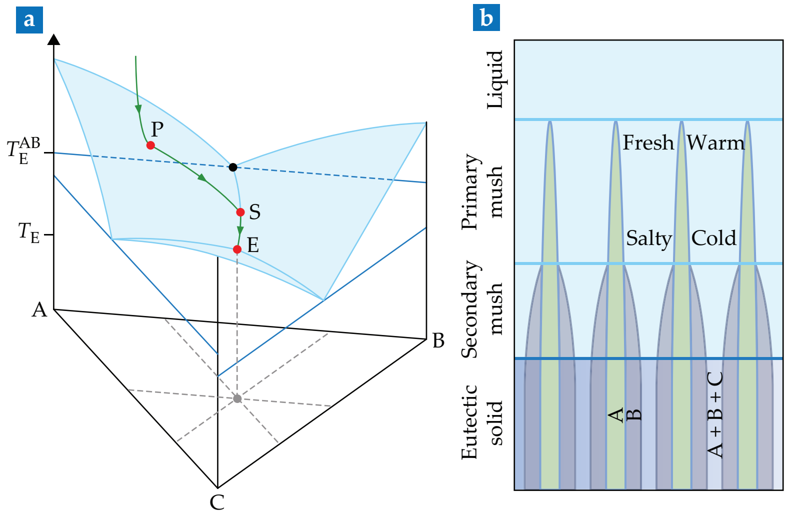


FIGURE 4. A TERNARY EUTECTIC ALLOY with components A, B, and C can be understood using a three-dimensional phase diagram. **(a)** The temperature *T* is plotted on the vertical axis and the composition is represented on the triangular base. Each corner represents a pure component. Points on the sides correspond to binary alloys. Points in the triangle correspond to ternary alloys. Liquidus surfaces from the binary vertical sides meet at a ternary eutectic point E. Points P and S represent the thermodynamic states in the primary and secondary mushy layers formed by the ternary alloy. (Adapted from ref. 5.) **(b)** This schematic shows the dendritic microstructure in primary and secondary mushy layers. A novel mechanism behind the unexpected convection that can occur in the primary mush is explained in box 2.

sition to instead produce a secondary mush with solids A and C. Whereas a binary eutectic system could be characterized into subeutectic and supereutectic cases, the simple ternary eutectic system has six such categorizations, two for each of the three corners of the phase diagram.

As with the binary-alloy case, the preferential rejection of one or more components upon solidification generates potential energy that can fuel buoyancy-driven convection. A hypothesis based on the static density profile in a ternary mixture is that convection could be triggered in either, neither, or both of the mushy layers. Exploration has begun in laboratory experiments and in analytic and computational models. Still, the interaction between convection in primary and secondary mushy layers is far from being completely understood.[5]

Even in isolation, however, the primary mushy layer of a ternary system reveals new features and convective-instability mechanisms distinct from any known to operate in binary mushy layers, and the ternary liquidus constraint plays a central and somewhat unexpected role. As outlined earlier, the local composition and temperature are directly linked in a binary mushy layer. In the primary layer of a ternary system, only the combination of two solute compositions is linked to the temperature.

The additional degree of freedom afforded to the temperature and composition in the ternary system calls back into question the possibility of double-diffusive-type instabilities driven from inside the primary mushy layer. Indeed, convective instabilities are predicted when temperature and composition fields have different diffusion rates and make opposing contributions to an otherwise static density profile. More surprising are the instabilities observed in models without any destabilizing contribution to the static density profile when differences in diffusion rates, solute rejection rates, or other imbalances related to the solute fields are present. The mechanism driving such instabilities is outlined for a special case in box 2. Further details can be found in reference 5.

Over the past half century, convection in mushy layers undergoing multicomponent solidification has developed from a hypothesis to a well-documented phenomenon. Careful laboratory experiments have revealed its striking features, mathematical models and analyses have cemented a physical understanding of mushy-layer dynamics and the mechanisms that trigger convective processes, and computer simulations have quantified fully developed chimney convection. With their importance in metallurgy and geophysical systems, the multiscale, multiphase, multicomponent, multiphysics systems that host mushy layers continue to offer exciting opportunities for physics-based research.

Peter Guba acknowledges the support from the Slovak Research and Development Agency under grant APVV-18-0308.

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PT

FINDING THE RIGHT PROGRAM FOR YOU

Samantha Pedek, graduate student, University of Iowa; co-chair, Physics Congress 2022 Planning Committee

Find Your People and Grad Program at the 2022 Physics Congress

Join hundreds of physics undergrads, grad school reps, and physics luminaries

Samantha Pedek, 2022 Program Co-chair

Samantha Pedek

Networking is one of the most important aspects of being a young professional. We've all heard the spiel about how networking can have positive impacts on future educational and career-related opportunities, but many of us struggle with making the initial contact that can lead to lasting connections.

In 2016 I attended the Physics Congress (PhysCon), the largest gathering of undergraduate physics students in the United States. Every few years, PhysCon brings together students, alumni, and faculty members for three days of frontier physics, interactive professional development workshops, and networking. It is hosted by Sigma Pi Sigma, the physics honor society, and anyone interested in physics can attend.

Networking at PhysCon was unlike any other professional development experience I had as an undergraduate physics student. The sheer number of like-minded people was daunting—hundreds of physics and astronomy undergraduates, representatives from graduate schools and summer research programs, employers from all over the country, and well-established professionals at the height of their careers were all under one roof for three days.

The Physics Congress is a high-energy, hands-on weekend designed explicitly for undergraduate physics students. Photo courtesy of SPS National.

PhysCon has continued growing in attendance, scope, and opportunities, and you won't want to miss the next one! In celebration of the 100th anniversary of Sigma Pi Sigma, an extra-special PhysCon is planned for October 6–8, 2022 in Washington, DC. With a little preparation, you'll have the chance to narrow down your graduate school search, meet potential employers, and make lasting connections with people heading down similar career paths.

The most direct opportunity to meet with representatives from physics and astronomy grad programs and potential employers occurs during the Expo, which encompasses both a grad school fair and a career fair. During the Expo, attendees can visit booths to learn more about a program, company, or undergraduate research experience as well as get tips and advice on applying. When I attended, seeing the wide variety of vendors enabled me to start thinking about my life after col-

NETWORKING TIPS

Before you attend a networking event, craft and practice your **elevator pitch**—a 30-second narration of who you are professionally, what you've accomplished, and where you hope to go in the future.

If you're attending an in-person event as a prospective student or employee, **business cards** (or contact cards) show that you're serious about your future and make it easy for new contacts to connect with you.

BE AN SPS INTERN

The Society of Physics Students summer internship program offers 10-week, paid positions for undergraduate physics students in science research, education, communication, and policy with various organizations in the Washington, DC, area.

www.spsnational.org/programs/internships.

lege, and I was blown away by the versatility that a degree in physics can provide.

A more subtle opportunity to build your network as a young professional is to engage with attendees you don't already know, between events or at meals. Shuffling between workshops, plenaries, and banquets will be hundreds of people with lived experiences similar to yours. Be adventurous and sit at a meal or workshop table with strangers! You might find yourself next to a professor from a graduate school you're interested in, or even from a school you didn't realize you should be interested in. A quick conversation can leave a lasting impression.

A straightforward way to meet students and professionals is to go to the poster sessions, as a presenter or an attendee. These are excellent opportunities to have one-on-one interactions with others and to learn about new topics. Seeking out posters in subfields you're doing research in or interested in studying in grad school is a great way to form connections and learn about current research in the field. My favorite question to ask a presenter is "Can you tell me more about your research?" They likely have an answer prepared, which can be a bridge to more natural conversation.

2019 Physics Congress attendees visit one of the many graduate school booths in the exhibit hall to learn about the program and check out physics demonstrations. Photo courtesy of SPS National.

The physics and astronomy community is quite small, so if you meet people at PhysCon, you're likely to run into them again. Almost a year after I attended PhysCon 2016, I was a Society of Physics Students intern. Of the 14 of us, over half had met previously, largely at PhysCon. Having that shared experience helped me connect with the other interns right from the start. We even looked back at old PhysCon photos and tried to spot one another in the background, which was wildly entertaining.

Attending PhysCon is the networking gift that keeps giving. I have met others who attended in different years and we're still able to bond over our shared experiences. You are bound to find someone with similar interests and goals in a sea of over a thousand physics students, mentors, and advisers. Preparation is the key to successful networking, so practice your elevator pitch, make business cards, and I'll see you in 2022! GSS

Water makes its mark on GPS SIGNALS

Clara Chew is a soil hydrologist and project scientist at the University Corporation for Atmospheric Research in Boulder, Colorado.

Clara Chew

In addition to being a navigation tool, GPS signals are helping scientists observe Earth's hydrologic cycle.

Gone are the days of asking for directions. Now anyone with a smartphone can quickly find the location of the nearest coffee shop, closest gas station, or the fastest way out of town. Runners can stay on pace, or not, and they can know how far, or how little, they have traveled, thanks to their GPS watches. The use of the global positioning system has become so ubiquitous that some researchers are worried that humans are losing their sense of direction because of it.

Despite GPS's popularity, few are aware of an unintended use of its signals. Aside from providing location information, GPS signals can be used to glean information about Earth's hydrologic cycle. They can distinguish whether the surface is wet or dry, how much water is contained in the soil and vegetation, and how much snow is on the ground.

Although GPS satellites were first launched in the late 1970s, their use as a remote-sensing tool was not explored until the mid 1990s. Since then, multiple ground and airplane experiments have shown transmitted GPS signals to be sensitive to a host of geophysical variables, such as near-surface soil moisture, snow depth, flood-inundation extent, sea-ice concentration, and ocean-surface winds. Now researchers are expanding their efforts to investigate how GPS signals recorded by satellites could revolutionize remote sensing.

Trash or treasure?

Earth is constantly bathed in GPS signals. Some of them are directly intercepted by the receivers located in cell phones and watches. Others first bounce off the ground, buildings, or anything nearby before being picked up by a GPS receiver. Those ground-reflected, or multipath, signals are normally a nuisance; they introduce errors and noise into the positioning estimate and are partly responsible for GPS being less reliable in cities with a lot of large buildings. Many GPS receivers have special algorithms that suppress those multipath signals. And the GPS antenna itself can be designed to block them.

Yet multipath signals can still creep in. In 2008, researchers at the University of Colorado were studying how to suppress multipath signals in GPS antennas and receivers. Those installations, like the one shown in figure 1, were designed to monitor the movement of tectonic plates, with antennas that are surrounded with metal rings that physically block multipath signals. But some multipath signals were still present in the data. Moreover, the signals appeared to change in intensity on a somewhat regular basis, especially for receivers located in fields and rangelands far from buildings and structures known for causing significant reflections.

When the researchers approached a hydrologist at the university, he recognized that the changes in the multipath signals looked eerily like a time series of soil moisture—regular and predictable signal increases during and shortly after rainstorms, with a subsequent slow decrease, indicative of the soil drying out.

The Colorado research group began investigating whether the ground-reflected signals could be

FIGURE 1. THE GPS ANTENNA under this hemispherical dome was designed to monitor the movement of tectonic plates. Ground-reflected GPS signals can be used to infer the soil moisture content near the antenna.

used to infer the moisture content of the soil. Their goal was to effectively repurpose the GPS antennas into soil moisture sensors, which could help monitor droughts and validate data from satellites that are designed to retrieve soil-moisture data. The task, however, wasn't as simple as directly correlating the multipath signals with observations of soil moisture. Seasonality in the time series indicated that the ground-reflected GPS signals were also likely affected by water in overlying vegetation.

By combining numerical modeling and analysis of hundreds of field samples, the Colorado group successfully derived an algorithm that would estimate soil moisture near a geodetic GPS antenna. More than a thousand of those antennas were scattered throughout the western US and Alaska as part of the Plate Boundary Observatory network funded by NSF. Hundreds of the antennas could be used to derive soil moisture with a resolution of about the area of a football field. The outcome was a new array of GPS soil moisture sensors—one of the largest such networks in the world.[1]

A different kind of radar

In retrospect, it should not have been so astonishing that GPS signals are sensitive to water in the soil. After all, microwave radar had been used for years to detect changes in soil moisture and surface water. And GPS is a type of microwave radar system, albeit with a different scattering geometry. In traditional radar, both the transmitter and the receiver are located on the same platform, which means the transmitter sends out a signal, and the receiver records it after it bounces back to the platform. GPS satellites, however, have only a transmitter, not a receiver. Receivers are normally located in cell phones, on towers, or in airplanes.

Although the scattering geometry is different, GPS signals behave much like any L-band microwave signals, which lie in the 1–2 GHz frequency range. They are sensitive to water in the soil and on the surface because of the large change in dielectric constant between a dry and a saturated soil; a similarly large difference in the dielectric constant exists between a saturated soil and water. Wetter soils have higher dielectric constants, which causes the surface to reflect the incoming GPS signals more strongly.

In ground-based systems, the surface-reflected signal interferes with the direct signal, which travels from the GPS satellite straight to the antenna. The extent of the interference depends on the difference in path lengths that the two signals have traveled and on the properties of the reflecting surface. By measuring changes in the frequency, phase, or amplitude of the interference pattern relative to a bare, dry reference state, one can infer changes in the surface, be they from soil moisture, vegetation, or snow.

In many ways, GPS signals are ideal for remotely sensing the terrestrial hydrologic cycle. Because the circularly polarized L-band signals are unaffected by cloud cover or sunlight, they can see the surface no matter the time of day or atmospheric conditions. In addition, the wavelength of L-band signals—19 or 24 cm in the case of GPS—is relatively long compared with those of other microwave frequencies, such as the C or X band. That's important because the wavelength is directly proportional to how much vegetation a signal can penetrate. Longer wavelengths can better sense the surface conditions beneath a canopy.

Although L-band signals are less affected by vegetation, they are still attenuated by traveling through the canopy. The roughness of the surface can also greatly affect how reflective the surface is. Smooth surfaces produce much stronger reflections than rough surfaces, which can scatter the signal in directions away from the receiver. Those confounding factors are by no means unique in the remote-sensing world, although they can and do complicate the analysis of GPS reflections.

Capturing reflections in space

Surface-reflected GPS signals don't just bounce around incessantly from buildings to trees to cars. A fraction of the signal eventually finds its way back into space. Despite the relatively weak transmitted signal, ground-reflected GPS signals can be observed from low Earth-orbiting satellites with receivers specially designed to record the reflections. Given the success of ground-based GPS receivers in capturing soil moisture and other variables, it is natural to wonder whether the retrieval could be done from space, as data from satellites could increase the spatial coverage from point measurements to global observations.

Scientists have known for years that GPS signals reflecting off the ocean surface can be recorded by satellites and used to infer the roughness of the water, which itself is related to the surface wind speed. The first robust demonstration came from the Disaster Monitoring Constellation's UK satellite *UK-DMC1* in the mid 2000s. The satellite carried an experimental receiver designed to capture GPS reflections, although many researchers were skeptical it could actually work. They were wrong, and *UK-DMC1* proved that ocean-reflected signals could indeed be consistently recorded by a downward-looking GPS antenna onboard a satellite.[2]

The signals' sensitivity to roughness and, by extension, wind speed motivated NASA to fund a new mission in which a constellation of eight satellites would collect GPS reflections. The Cyclone Global Navigation Satellite System (CYGNSS) was launched in December 2016 to measure hurricane wind speeds, with the ultimate goal of learning how to better predict the storms' intensities.[3] Since its launch, CYGNSS data have been successfully used to map winds during numerous hurricanes, including Harvey and Irma. Those data have been assimilated into numerical weather prediction models to improve forecasts of a storm's track and intensity.

Even though CYGNSS was designed for collecting data over the ocean surface, the satellites also collect information over land. Before CYGNSS, there had been hints as to what GPS reflections would look like over land. The *UK-DMC1* experiment produced a handful of observations over Nebraska[2] in the mid 2000s. A subsequent satellite, the UK's *TechDemoSat-1*, showed in 2014 that discernable reflected signals could be obtained over a wide variety of land cover types and surfaces.[4] The data were still much too sparse to fully image the land surface, but they left researchers hopeful, although with only inklings of what the true potential of the new technology could be.

After the launch of CYGNSS, researchers quickly began mapping the reflections coming from the land surface to determine whether the data were at all responsive to changes in surface hydrology. To their surprise, the data appeared to be incredibly sensitive to extremely small surface-water features. For instance, researchers easily imaged the Amazon River's tributaries, some as small as 25 m wide, using data from CYGNSS, as shown in figure 2. And they observed significant sensitivity to soil moisture when they compared the data with retrievals from operational soil moisture satellites.[5]

That finding was surprising because before the launch of

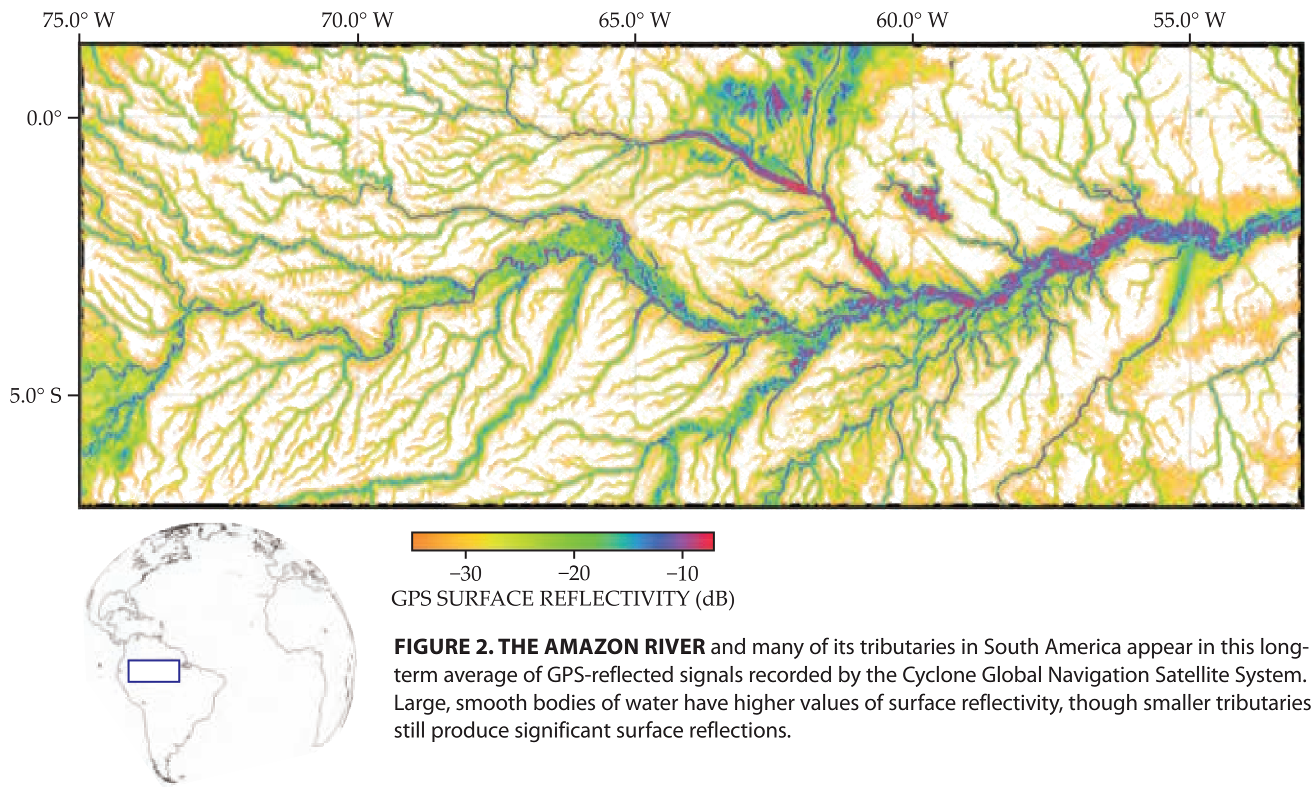


FIGURE 2. THE AMAZON RIVER and many of its tributaries in South America appear in this long-term average of GPS-reflected signals recorded by the Cyclone Global Navigation Satellite System. Large, smooth bodies of water have higher values of surface reflectivity, though smaller tributaries still produce significant surface reflections.

CYGNSS, the vast majority of the research pertaining to spaceborne GPS-reflection data came from theory and modeling that assumed a rough ocean as the scattering surface. The roughness produces a weakly scattered signal coming from an area of about 25 km × 25 km. Most researchers had assumed that the land surface would be much more electromagnetically rough than the ocean surface. Surely, they thought, hills and trees were rougher than the average ocean wave, and they had anticipated even weaker reflected signals as a result. What they found instead was that inland water bodies sheltered from the wind are smooth enough to produce coherent reflections, which result in a strong signal from a relatively small area, about 0.5 km^2.

Cost and constellations

The discovery that the land surface can produce powerful reflections at a relatively high spatial resolution has spurred interest in how GPS-reflected signals recorded by CYGNSS or future satellites like it could map flooding, changes in soil moisture, and other variables, such as the freeze-and-thaw state of the soil[6] and even sea-ice extent.[7] Several other remote-sensing satellite techniques and instruments can retrieve the same information, but the GPS reflection technique stands apart for its cost-effectiveness. Because the technique essentially recycles signals that already exist, no expensive transmitters need to be built, and their absence decreases the size and mass of each satellite.

Other microwave instruments, including passive radiometers and active radar, cost hundreds of millions of dollars to launch in a single satellite. For example, in collaboration with the Indian Space Research Organisation, NASA is scheduled to launch the *NASA–ISRO Synthetic Aperture Radar* (*NISAR*) spacecraft in early 2023. *NISAR* will fly a combined L- and S-band active radar and cost approximately $1.5 billion. By comparison, CYGNSS cost a total of $150 million for the eight satellites.

The financial benefit alone is compelling, given the always uncertain funding for Earth science. But the relatively economical nature of the technique opens the door for launching constellations of instruments, as CYGNSS has already demonstrated. Constellations of satellites decrease the temporal repeat period: You get data from one particular spot more often with many satellites than with only one. For many applications, having frequently updated data is key. In the case of flooding, affected communities require rapidly updated flood maps to know where and how to get resources. Because floods are usually associated with significant cloud cover, they are often mapped using data from microwave instruments. (See the box on page 47 for an example.) Currently, the instruments with the fastest repeat time are passive radiometers, which collect naturally emitted microwave radiation from the surface. The repeat time, once every three days, comes at the expense of spatial resolution, which makes it difficult to pinpoint where the flooding actually is.

On the other hand, active microwave radar instruments, such as *NISAR*, have a high spatial resolution, on the order of tens of square meters. Their temporal repeat period, however, is quite long—more than 10 days—which implies a significant risk of the instrument missing the entire flooding event. And even if the satellite doesn't miss the entire incident, the snapshot of data it collects may not capture the maximum flood stage.

Launching constellations of either passive or active microwave instruments to decrease the temporal repeat period is an expensive proposition. For example, the European Space Agency currently has in orbit two C-band radar satellites, which make up the Sentinel-1 constellation. And it plans to launch two additional satellites in the coming years at a cost of more than €200 million ($226 million) per satellite, or more than €800 million altogether for the four-satellite constellation.

Unique obstacles

Although launching constellations of inexpensive GPS reflection satellites is an attractive proposition, the technique is not without its own challenges. The collection strategy characteristic of spaceborne GPS reflection observations may appear a bit strange to those familiar with traditional remote-sensing data. Usually, satellite remote-sensing missions are designed to collect observations over a particular area at a particular rate. Someone interested in soil-moisture data for Dallas, Texas, for example, can have confidence that NASA's *SMAP* (*Soil Moisture Active Passive*) satellite, an L-band radiometer, will provide those data every three days at 6:00am central time. The timeline for spaceborne GPS reflection data, however, is murkier. Because the positions of the GPS transmitters and GPS reflection receivers are constantly changing, so are the reflection points on Earth's surface.

The result is a set of observations pseudo-randomly positioned across the landscape, as can be seen in the box figures on page 47. Over Dallas, two subsequent GPS reflections might be collected within a few hours of each other, followed by several hours or days without data. The temporal gaps, however, can be shortened with the addition of more low-cost satellites. Recording data from the other constellations of navigation satellites, such as the European Union's Galileo or Russia's GLONASS, could also increase the density of observations without the need to launch more satellites. GPS reflection receivers that do that are already in development.

In addition, one of the greatest advantages of the GPS reflection technique—its use of freely available transmitted signals—comes at a cost: a lack of signal control. Despite being widely used by the civilian population, the constellation of GPS transmitters is fundamentally a military operation. And the military can and does change the power of its transmitted signals. A more powerful transmitted signal will result in a more powerful reflection. But without knowledge of the changes in transmission power, changes in the reflection power could be mistaken for a change in the surface hydrology. Those jumps in power level can be mitigated by observing the power of the direct signal, which travels from the GPS transmitter to the receiver without first reflecting off the ground. Future GPS reflection satellites will likely perfect that mitigation strategy.

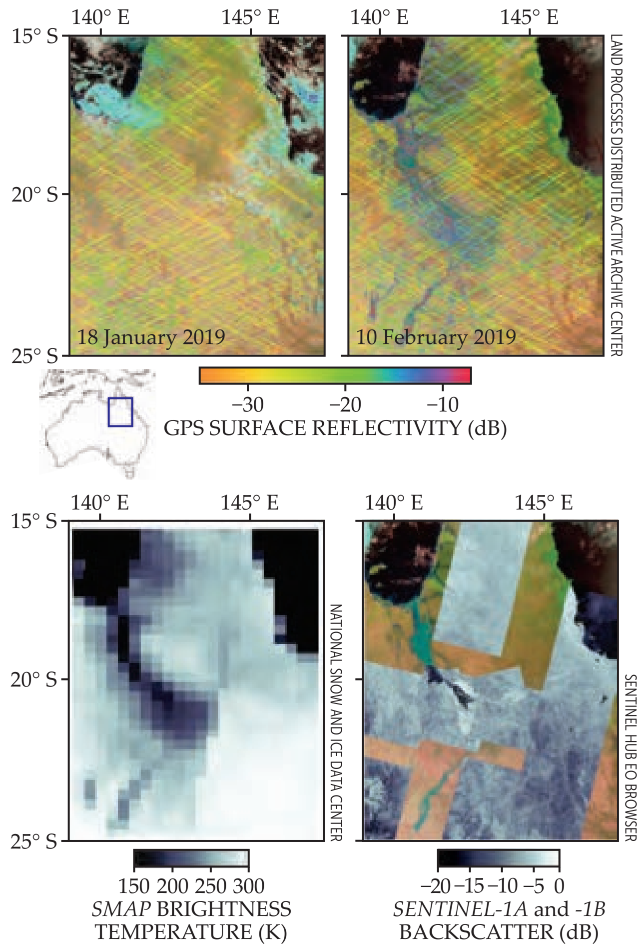
Carving out a niche

The unique advantages of the GPS reflection technique still do not make it a one-stop shop for every hydrologist's remote-sensing needs. The superior spatial resolution of active radar data is useful for mapping inundation in a single neighborhood, for example. And the repeatable swaths of measure-

IMAGING A FLOOD

Heavy rain in late January 2019 brought wide-scale flooding to the state of Queensland in northeastern Australia and helped to end a long drought. Ground-reflected GPS signals recorded by the Cyclone Global Navigation Satellite System (CYGNSS) constellation captured the extent of the flood, as shown in the top panels. Researchers used cloud-free images from the MODIS (Moderate Resolution Imaging Spectroradiometer) instruments aboard the *Terra* and *Aqua* satellites to confirm the flooded area. CYGNSS data (superposed as colored stripes) in the flood's boundary show a significant increase in the power of the reflected signal (right) relative to that observed before the flood (left). Large increases in the reflected signal strength could ultimately be used to map flooding at spatial and temporal scales not currently available with other methods.

The CYGNSS satellites were not the only microwave instruments to record data during the flood. Images from an L-band microwave radiometer on NASA's *SMAP* (*Soil Moisture Active Passive*) satellite and a pair of C-band radars on the European Space Agency's *Sentinel-1A* and *Sentinel-1B* satellites are shown in the bottom panels. Each satellite can provide complementary information when creating a timeline of a flood. At left, the *SMAP* satellite captured average brightness temperatures on 8–12 February 2019 during the Queensland flooding event. Although *SMAP* data cover the region entirely, its resolution is quite coarse. At right are aggregate data recorded by *Sentinel-1A* and *Sentinel-1B* during the same time period. Those satellites captured less area, but their record is richly detailed.



ments and consistent, global coverage of radiometer observations make them well suited for assimilation into numerical weather and climate models.

Instead, GPS reflection technology can provide data that are complementary to those that already exist from other microwave instruments, and it can help fill a gap in our knowledge of how hydrologic events evolve over short time scales. For instance, scientists could map short-term changes in soil moisture in environments more heterogeneous than a typical 36 km radiometer pixel, and the CYGNSS data have already shown promise in that regard. Recently, data from CYGNSS were used to help map high-resolution soil moisture in East Africa during a severe locust outbreak. Locusts tend to hatch in environments with a specific soil moisture range, and by mapping the current soil moisture conditions, scientists were better able to identify the location of the locusts' likely breeding grounds.[8]

What's more, satellites that record GPS reflections have the potential to offer moderate (0.5 km^2) spatial-resolution maps of flooding within a matter of days of the event. If more low-cost GPS reflection satellites are launched, the gaps in observations, as highlighted in the box, could be filled, so that maps akin to the one shown in figure 2 could be available daily. The improvement could revolutionize how satellite data are used—not only to monitor but also to respond to events in near-real time.[5,9]

Whether significant investment into GPS reflection technology will actually be made by government agencies remains to be seen. The recent announcement of *HydroGNSS*, a reflection-satellite concept, as the second European Space Agency scout mission is certainly encouraging. And if recent investments into reflection research by commercial satellite companies are any indication, the field is likely to continue growing. It is only a matter of time before the full potential of GPS signals is realized, and given the field's rapid advances in just the past five years, we may not have long to wait.

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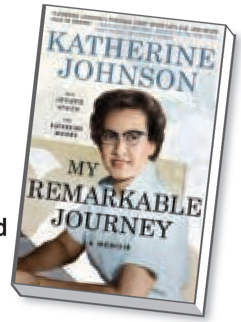
The mathematician Katherine Johnson at her desk in NASA's Langley Research Center in 1966.

BOB NYE/NASA

A hidden figure tells her story

My Remarkable Journey
A Memoir



Katherine Johnson with Joylette Hylick, Katherine Moore, and Lisa Frazier Page
Amistad, 2021. $25.99

Although she was well known in her local community of Hampton, Virginia, the mathematician Katherine Johnson (1918–2020) was absent from popular and scholarly accounts of the US's space program until the release of the 2016 film *Hidden Figures*. Based on a book of the same name by Margot Lee Shetterly, which was published that same year, the film depicts how Johnson and her colleagues in the West Area Computing Unit at NASA's Langley Research Center calculated spacecraft trajectories for the US human spaceflight program in the 1960s. It rocketed Johnson and the West "computers," who were some of the few Black women employed in technical roles at NASA during that era, to late-in-life (or, in some cases, posthumous) fame.

In her memoir *My Remarkable Journey*, written with the assistance of her beloved daughters Joylette Hylick and Katherine Moore and the writer Lisa Frazier Page, Johnson reflects on the trajectory of her life and career. She invites readers to join and learn from her journey, which brought her from rural West Virginia to the national spotlight and transformed her into a role model and American icon.

Johnson details how her training in advanced mathematics at West Virginia State College—a historically Black college—and West Virginia University, along with her focus and curiosity, enabled her to make important contributions to US aviation and space activities over her 33 years at NASA and its predecessor, the National Advisory Committee for Aeronautics. In addition to researching and calculating trajectories for crewed missions, including Project Mercury and the space shuttle program, Johnson also published NASA reference books and technical studies in support of Mars exploration. Her success challenged contemporary prejudices about which people were best suited to working in mathematics and related fields—prejudices that persist today, as women and people of color continue to be underrepresented in STEM (science, technology, engineering, and mathematics) jobs.

In the book, Johnson recounts how she pushed against workplace practices and policies that she found personally demeaning and detrimental to her research. For example, she questioned her colleagues—who were all white men—about the exclusion of "computers" from engineering group meetings. Motivated by a commitment to collaboration as well as an unshakable belief that she was "as good as anybody else," Johnson overcame her colleagues' inherent biases by appealing to their sense of pragmatism: She successfully argued that her attendance would enable the entire team to operate more effectively.

She also writes that, unlike in the film adaptation of *Hidden Figures*, she "hadn't paid attention" to the racially segregated restrooms at Langley. She suspects that her "fair skin complexion" may have enabled her to move in those spaces without challenge from her white peers.

Johnson's passion for her work was equaled by her enthusiasm for every other area of her life. She was a student; public school teacher; partner to James Goble and later James Johnson; parent to children Joylette, Constance, and Katherine; and a dedicated and active member of her community, church, and treasured Alpha Kappa Alpha Sorority. In many ways, *My Remarkable Journey* is a love letter to the people who brought meaning to her life and enabled her to pursue her goals. She writes with particular warmth about the educators who sparked her curiosity and supported her learning, including her mother Joylette Coleman and William Schieffelin Claytor, a mathematics professor at West Virginia State College who was one of the first Black Americans to receive a doctorate in his field.

Johnson and her coauthors excel at placing her actions, decisions, and experiences in historical context, which makes it possible even for readers unfamiliar with 20th-century US history to join Johnson on her life's path. The most compelling of those discussions highlight moments that deeply impressed Johnson and shaped her worldview. For example, background information on the 1957–58 International Geophysical Year serves as a foundation for understanding Johnson's attitudes toward early US space activities. Although the year was ostensibly a global effort to study Earth sciences, it also became an arena for Cold War competition when the Soviet Union launched *Sputnik 1* in October 1957 and jump-started the space race.

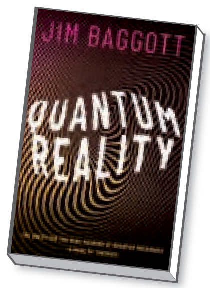
Recalling the night she and her three daughters viewed the Soviet satellite from the front yard of their home, Johnson writes, "I felt that competitive American spirit rise in me." Spurred by the feeling that the US couldn't afford to lag behind its Cold War rival, she would soon become an integral part of the American response to the Soviet challenge in space.

Johnson's accessible memoir will engage readers of all ages and interests. It is a welcome addition to the bookshelf of anyone keen to know Johnson and learn more about Black women's contributions to both the US space program and the exploration and understanding of our universe. For young people aspiring to STEM careers, Johnson offers inspiration for navigating discrimination and self-doubt. For STEM professionals, her story underscores the importance of creating and maintaining equitable and inclusive learning and work environments so that everyone can pursue their own remarkable journeys.

Emily A. Margolis
National Air and Space Museum
Washington, DC

Although the "Copenhagen interpretation" of quantum mechanics may be a postwar invention, the Danish capital was indeed a major site for intellectual exchange during the quantum revolution of the 1920s. Pictured here is the lakeside street of Sortedam Dossering, which features some of the oldest neon lights in the city.

How I learned to stop worrying and love metaphysics



Quantum Reality
Jim Baggott
Oxford U. Press, 2020. $25.95

Anyone who has ever strolled through the science section at a Barnes & Noble knows that popular books on quantum mechanics abound. Jim Baggott, a prolific science writer with a PhD in chemical physics, has himself already written several successful popular texts dealing with quantum theory. Seeing that Baggott has now written another book on the topic, *Quantum Reality*, one might ask: Why? What makes Baggott's newest book—one more in a long list of attempts to introduce the public to philosophical issues within quantum mechanics—stand out?

Fortunately, *Quantum Reality* quickly justifies its existence. Part 1 provides an entertaining yet compact introduction not just to the most important physical and formal features of quantum mechanics but also to the ways in which that physics opens itself—inevitably and irrevocably—to philosophical inquiry. Indeed, certain passages almost serve as tasty amuse-bouches for the entire field of philosophy of science, and in that way Baggott's book achieves broader appeal than its competitors.

The necessity of engaging with philosophy during the scientific process is nicely illustrated by the book's central metaphor: scientific theorizing as a ship navigating the treacherous waters between Charybdis, representing the shores of metaphysical reality, and Scylla, the isle of empirical reality. How one chooses to navigate that metaphorical strait says much about which interpretation of quantum mechanics one finds particularly appealing or explanatory.

Part 2 introduces the different interpretations of quantum mechanics. Baggott groups the interpretations with respect to whether their adherents consider quantum mechanics to be complete. He discusses the interpretations in relation to the sailing metaphor and measures them against several neatly articulated "realist propositions." Which of those propositions one is inclined to take as axiomatic and how one answers the completeness question will indicate which interpretation—or class thereof—one finds most appealing. That is a new way of tackling a very old question, and it helpfully foregrounds the costs and benefits of kindred approaches vis-à-vis the twin criteria of realism and completeness.

Among the less realist views Baggott discusses are relational interpretations, consistent (or decoherent) histories, and information-theoretic views like quantum Bayesianism. Those are important approaches typically left out of popular accounts. The chapters progress toward increasingly realist views and focus on "completion attempts" like Bohmian mechanics, spontaneous-collapse theories, and even views incorporating the agency or consciousness of the observer. Everettian approaches get the last word, but somewhere in the mix Baggott takes time to discuss pivotal aspects of the interpretational debate that are too often neglected, including the role of decoherence, the differing types of probabilities at work in various views, and the array of interpretations fitting under Hugh Everett III's umbrella.

I also appreciate the seriousness with which Baggott both motivates and explains less realist approaches. (I cringe at the term "antirealist.") For although physicists have little patience for discussing such views and are quick to appeal to a comfortable realist stance, I suspect information-theoretic and relational views do a lot more work than they receive credit for and provide particularly useful ways of thinking about relativistic quantum theories—precisely the arena where the more familiar, more realist interpretations flounder.

The moments in *Quantum Reality* covering well-trodden terrain are relatively minimal. Unfortunately, they tend to be the same areas where popular accounts frequently go furthest astray: sections in which authors who are not credentialed in history nevertheless present as factual largely anecdotal narratives concerning the theory's rich (and richly documented) historical and philosophical background. For example, Baggott—like many—continues to talk about the "Copenhagen interpretation." But by now it should be well known that that approach was a postwar invention by Werner Heisenberg created for the express purpose of restoring his name and reputation after his dubious wartime activities.

Heisenberg reconstructed a history in which his early views aligned more closely with those of Niels Bohr, who, by contrast, emerged from the war as a scientist hero. Not only did Heisenberg, Bohr, and others disagree on key interpretational issues in those early years, but the points on which they did agree directly contradict two supposed features of the Copenhagen interpretation: the physical collapse of wavefunctions and the distinction between the classical and quantum domains. Bohr and Heisenberg—along with Grete Hermann, an early philosopher of quantum physics—were quite clear in their pre–World War II lectures, papers, and correspondence that an actual collapse cannot occur lest certain physical problems arise: A mechanism that instantaneously localizes a potentially broadly spatiotemporally diffused wavepacket, for example, will necessarily involve superluminal processes.

Heisenberg, Bohr, and other supposed Copenhageners were also adamant that there is no distinct classical world. Although at a certain scale one switches to classical mechanics for ease of calculation, events and apparatuses at those scales are still more accurately described with quantum mechanics. And the reverse is impossible: There is a point at which classical mechanics breaks down. It was thus widely appreciated by the early 1930s that certain assumptions in classical theories, such as the simultaneous testability of the full state of a system in complete isolation, were revealed by quantum mechanics to be in principle untenable.

Happily, those problematic bits are outshined by the aspects of *Quantum Reality* that set it apart from similar projects. In those moments, Baggott's unique, smart-alecky-professor voice keeps you turning the pages, and you regret that the book wasn't around when you were a precocious teenager grappling with the mysteries of physics.

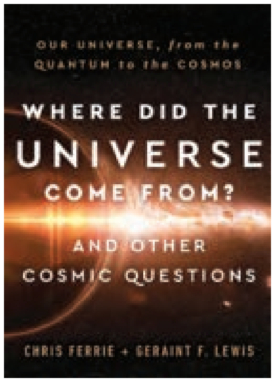
Elise Crull
City College of New York
New York City

NEW BOOKS & MEDIA

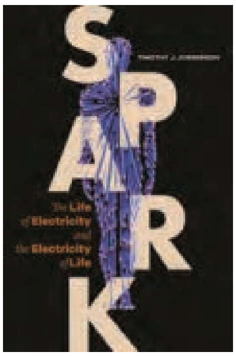
Where Did the Universe Come From? And Other Cosmic Questions

Our Universe, from the Quantum to the Cosmos

Chris Ferrie and Geraint F. Lewis
Sourcebooks, 2021. $17.99



Quantum physicist Chris Ferrie and astrophysicist Geraint Lewis have teamed up to discuss the formation and evolution of the universe, both on the tiniest of scales and on the grandest. Aimed at the general reader, the book explains in conversational, nontechnical language two theories that form the basis of modern physics—quantum mechanics and general relativity—and uses them to address such difficult topics as how matter was created and how long the universe will last. Although a grand unified theory has yet to be proposed, the authors show how the two theories are intricately intertwined and work together, despite their vast separation in scale. —CC



Spark

The Life of Electricity and the Electricity of Life

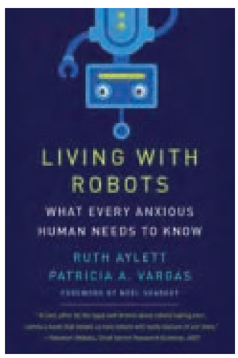
Timothy J. Jorgensen
Princeton U. Press, 2021. $29.95

Did you know that the word "electricity" derives from a Latin word meaning "amber-like"? Or that giraffes are particularly susceptible to lightning strikes? Those are just two of the diverse and diverting topics touched on in *Spark*, authored by Timothy J. Jorgensen. A professor of radiation medicine and biochemistry, Jorgensen focuses not on electricity as a power source for appliances and electronic devices, but rather on its role in biology. After first explaining what electricity is and how humans discovered it and began experimenting with it, he moves on to its present-day use in medical research, such as in developing neuroprosthetic limbs and treating mental disorders like depression. Written for a general audience, *Spark* is intended to both educate and entertain. —CC

Living with Robots

What Every Anxious Human Needs to Know

Ruth Aylett and Patricia A. Vargas
MIT Press, 2021. $27.95

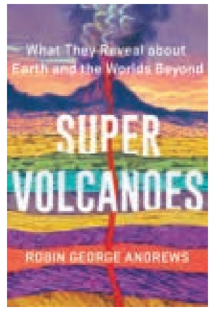


Given the technological advances of the last decades, should we fear robots? Or are they simply helpful companions? In *Living with Robots*, Ruth Aylett and Patricia A. Vargas, two roboticists, provide readers with an overview of the different types of such machines, including industrial robots, household vacuum cleaners, and military and sex robots. On the one hand, they warn that we should be concerned about such dystopian possibilities as killer drones that operate without human control and sexbots that contribute to the objectification of women. On the other hand, roboticists still struggle to build machines that can perform simple human tasks like walking or holding a cup of coffee. Ultimately, the authors note, "We really cannot build a robot that is just like us." —RD

Super Volcanoes

What They Reveal about Earth and the Worlds Beyond

Robin George Andrews
W. W. Norton, 2021. $27.95

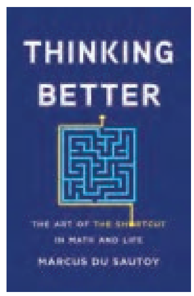


Although science journalist Robin George Andrews concedes that volcanoes can be incredibly destructive, he argues that they are "for the most part, good." Trained as a volcanologist, Andrews changed careers when he realized that he wanted to share stories about volcanoes rather than conduct scientific research. He succeeds in that task with *Super Volcanoes*, in which he takes a rollicking tour from Hawaii to Mars and demonstrates that volcanoes are scientific gold mines that tell us much about a planet's history. Along the way, readers learn many surprising things about the fiery cauldrons, including that scientists have only directly observed at most two underwater volcanic eruptions. Andrews's passion for volcanoes and his exuberant writing style make the book an easy recommendation. —RD

Thinking Better

The Art of the Shortcut in Math and Life

Marcus du Sautoy
Basic Books, 2021. $30.00



Whether creating an artistic masterpiece, starting an entrepreneurial venture, or simply plotting the best route from A to B, Marcus du Sautoy has a clever strategy, or shortcut, to facilitate the process. Each of the 10 chapters of the mathematician's book *Thinking Better* centers on a particular type of shortcut, such as patterns, probabilities, or networks. He begins by positing a puzzle and then, through a series of historical anecdotes and mathematical discussions, shows how he arrived at the solution. Using a humorous and conversational narrative style, du Sautoy presents some fairly complex mathematical concepts in a way that is both educational and entertaining. —CC PT

NEW PRODUCTS

Focus on test, measurement, quantum metrology, and analytical equipment

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

Automated silicon-photonics test system

Keysight's NX5402A Silicon Photonics Test System, integrated with its PathWave Semiconductor Test software technology, combines the company's multichannel optical and electrical test architecture and its optimized fiber alignment and positioning system. According to Keysight, the fully automated, high-throughput testing system maintains high accuracy, repeatability, and reproducibility and delivers advanced wafer-level photonic calibration and reliable performance monitoring with built-in system diagnostics. Its stable, repeatable test capabilities can enable semiconductor manufacturers to speed delivery of silicon-photonics wafer production. Silicon photonics' primary applications are in the data-center market, but they may in the future be used in areas such as optical and quantum computing, automotive lidar, and health care. ***Keysight Technologies Inc***, *1400 Fountaingrove Pkwy, Santa Rosa, CA 95403-1738, www.keysight.com*

Phase noise analysis

Rohde & Schwarz has launched its R&S FSPN for dedicated phase noise analysis and voltage-controlled-oscillator testing. According to the company, the R&S FSPN delivers high sensitivity, accuracy, and reliability for high-speed, real-time phase noise measurements. It is suitable for characterizing sources that require high stability in demanding applications, such as synthesizers, voltage-controlled oscillators, and oven-controlled crystal and dielectric resonant oscillators in R&D and production. The R&S FSPN comes in two models: One covers the frequency range from 1 MHz to 8 GHz and the other from 1 MHz to 26.5 GHz. They address radar and satellite applications in the C band, the X band, the K_u band, and the complete K band. Both models feature low-noise internal local oscillators coupled with real-time cross-correlation engines for increased measurement sensitivity. ***Rohde & Schwarz GmbH & Co KG***, *Muehldorfstrasse 15, 81671 Munich, Germany, www.rohde-schwarz.com*

Volatile chemical-species sampler

To provide analysts with an advanced yet easy-to-use instrument, Shimadzu has replaced its HS-20 headspace sampler with the HS-20 NX series. The new series uses the isolation gas flow to reduce carryover to 1/10 that of conventional models. It supports a wide range of volatile chemical species, including compounds with a high boiling point and high polarity. The proprietary isolation gas flow prevents sample diffusion from the vent channel, which reduces carryover of highly adsorptive compounds and eliminates the need for repeating blank runs. The HS-20 NX series provides high temperature capability: The vial oven and sample line can be set to 300 °C and the transfer line to 350 °C. The sample path is designed to be inert and at the shortest distance, which suppresses peak broadening and adsorption of analytes, including high-boiling compounds. ***Shimadzu Scientific Instruments Inc***, *7102 Riverwood Dr, Columbia, MD 21046, www.shimadzu.com*

Qubit controller for quantum computing

The Zurich Instruments SHFQC Qubit Controller offers a full room-temperature control system for up to six superconducting qubits in a single instrument. Integrated into the company's Quantum Computing Control System (QCCS), it adds fast local feedback to existing error-correction capabilities. The SHFQC supports control and readout frequencies of up to 8.5 GHz with no need for mixer calibration and provides a 1 GHz bandwidth. The six signal-generator control channels and single quantum-analyzer readout channel can be controlled and triggered individually. Using efficient pulse-level waveforms in their arbitrary waveform generators, the control channels can be programmed to generate complex gate sequences. The readout channel analyzes in real time up to 16 qubits, 8 qutrits, or 5 ququads—either serially or in parallel. Matched complex filters and tight integration with the SHFQC's control channels optimize the signal-to-noise ratio and readout latency. A single SHFQC can help simplify small qubit setups; for systems of 100 or more qubits, multiple SHFQCs can be combined with other elements of the QCCS. ***Zurich Instruments AG***, *Technoparkstrasse 1, 8005 Zürich, Switzerland, www.zhinst.com*

Humidity and temperature sensors

Two ultrahigh-accuracy versions of Sensirion's fourth-generation humidity sensors, the SHT41 and SHT45, offer improved relative-humidity (RH) and temperature (T) specifications: Typical accuracies have been honed down to ΔRH = ±1% RH and ΔT = ±0.1 °C. The sensors are built on Sensirion's new, optimized CMOSens chip that features ultralow power consumption. The CMOSens Technology provides a complete sensor system with a fully calibrated digital I^{2}C (inter-integrated-circuit) fast-mode-plus interface on a single chip. The sensors cover operating ranges from 0% to 100% RH and −40 °C to 125 °C. With the extended supply voltage range from 1.08 V to 3.6 V and an average current of 400 nA, the SHT41 and SHT45 are suitable for mobile and battery-driven applications. The very small size and robust housing enable integration into challenging designs and ensure high reliability. ***Sensirion Holding AG***, *Laubisrütistrasse 50, 8712 Stäfa, Switzerland, www.sensirion.com*

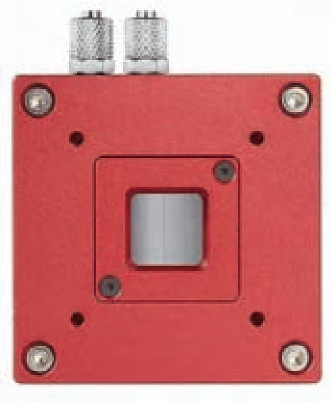
RF arbitrary waveform generator and transceiver

Tabor Electronics has recently added the RF Arbitrary Waveform Generator/Transceiver to its Proteus series platform. According to the company, the RF AWG/AWT delivers excellent phase noise and spurious performance for applications of RF- and microwave-signal generation and acquisition. It has a built-in in-phase and quadrature modulator with advanced capabilities for multichannel RF-signal generation, transmission, and analysis and the ability to scale up to hundreds of synchronized channels. Integrated digital up-converters allow for the generation of multiple signals simultaneously in up to four channels in a single unit; the channels feature independent phase and frequency control, over 2 GHz of modulation bandwidth, and excellent spectral performance. The compact, cost-effective RF AWG/AWT is offered in configurations of 2, 4, 8, or 12 channels with a sample rate of 9 GS/s and a resolution of 16 bits. ***Tabor Electronics***, *2327 Larkin St, San Francisco, CA 94109, www.taborelec.com*

Fiber-optic temperature monitoring

A new line of fiber-optic temperature sensors and monitors from Omega, a Spectris company, are suitable for surface or immersion applications where metallic probes cannot be used. Unlike traditional resistance temperature detectors and thermocouples, fiber-optic sensors use light for fast and reliable temperature analysis that is immune to RF interference, electromagnetic interference, and nuclear magnetic resonance. The fiber-optic temperature sensor allows measurements in small or precise locations. It has a temperature range from −200 °C to 250 °C and an accuracy of ±0.8 °C and requires no recalibration. The fiber-optic monitor operates in a temperature range from −80 °C to 300 °C. It can monitor up to eight channels and offers micro-SD and USB data-logging capabilities and RS-485 and USB output with Modbus. ***Omega Engineering Inc***, *800 Connecticut Ave, Ste 5N01, Norwalk, CT 06854, www.omega.com*

High-speed laser sensors



The Blink HS laser power and energy sensor from Laserpoint can provide accurate energy measurements for ultrafast lasers, detect fast instabilities in them, and monitor fast manufacturing processes in production lines. According to the company, Blink HS's patent-pending technology, which combines the high response speed of a photodiode with the broadband and high-power operation of a thermopile, makes it the fastest laser power and energy sensor currently available. The submicrosecond response time allows for the measurement of the energy of each pulse emitted by laser sources with repetition rates up to 1 MHz, pulse durations down to femtoseconds, and average power up to 20 W. An available high-speed meter with a sampling rate up to 500 MS/s can provide a precise energy measurement of each single ultrashort pulse. With a high damage threshold and efficient water cooling, the Blink HS can withstand energies up to 10 mJ. ***Laserpoint SRL****, Via Burona 51, 20055 Vimodrone, Milan, Italy, www.laserpoint.eu*

Three-in-one field probes

AR RF/Microwave Instrumentation has announced its FL8000 Series of electric field probes covering the 5 kHz–60 GHz frequency range. For automotive, aviation, military, and commercial applications, electromagnetic compatibility testing in a laboratory often requires measuring different types of electric fields. The FL8000 Series probes offer a three-in-one solution capable of measuring CW, pulsed, and modulated electric fields. According to the company, the probes' excellent linearity and dynamic-range performance enable the accuracy required for even the most demanding testing, and their versatility can help simplify the test laboratory. The probes use a laser to deliver power over fiber, which allows for continuous operation without recharging or replacing batteries. They are supplied in kits with all items needed for field-probe operation. ***AR RF/Microwave Instrumentation****, 160 Schoolhouse Rd, Souderton, PA 18964, www.arworld.us*

Asphere metrology

Zygo Corporation, a business unit of AMETEK, has expanded its Verifire series of laser Fizeau interferometers used to perform noncontact 3D metrology of aspheric surfaces. The new Verifire Asphere+ (VFA+) is designed to reduce the number of generation and measurement steps needed to achieve a highly precise and accurate final surface. Leveraging the benefits of Fizeau interferometry through precise, high-resolution, fast, and full-aperture metrology for axisymmetric aspheres, the VFA+ can enable optics manufacturers to produce a wide range of aspheric designs. An optional secondary stage integrated in the VFA+ accommodates a computer-generated hologram to further enlarge aspheric shape coverage, which includes free-form, cylinder, and off-axis conic surfaces. The flexible system can measure a range of aspheres with only the change of the reference optic and is adaptable to multipart automated measurement of trays of optics. ***Zygo Corporation**, Laurel Brook Rd, Middlefield, CT 06455-1291, www.zygo.com*

Semiconductor metrology

The new NX-Hybrid WLI semiconductor metrology tool from Park Systems fully integrates atomic force microscopy (AFM) with white-light-interferometer (WLI) profilometry for the first time, according to the company. Widely used for quality assurance in semiconductor production, white-light interferometry is a nondestructive, noncontact optical technique that can generate 2D and 3D models of surfaces. The Park NX-Hybrid WLI was developed for use in applications that require resolution and accuracy beyond the capability of a WLI alone. The combination of the WLI module and the atomic force microscope provides high-throughput imaging over a very large area and performs nanoscale metrology with sub-angstrom-height resolution. The atomic force microscope is based on the automated Park NX-Wafer AFM system for R&D, semiconductor and related devices, and quality assurance. ***Park Systems Inc**, 3040 Olcott St, Santa Clara, CA 95054, https://parksystems.com* PT

Richard R. Ernst

Nobel laureate Richard R. Ernst, the pioneer of modern nuclear magnetic resonance (NMR), died on 4 June 2021 in his birth town of Winterthur, Switzerland. He was the key player in transforming NMR from its roots in physics to an indispensable tool in chemistry and medicine. His many fundamental innovations not only propelled NMR into becoming the most versatile analytical method in structural chemistry and molecular biophysics but also were essential to the development of Fourier-transform (FT) magnetic resonance imaging (MRI), an exceptionally powerful tool in diagnostic medicine.

Ernst was born on 14 August 1933, the son of an architecture teacher. His parents fostered a love for music in him and his two sisters, with Ernst composing and playing the cello. His interest in chemistry was kindled by the discovery in his home's attic of a large box of chemicals left by his late uncle, a metallurgical engineer. Ernst went on to study chemistry at ETH Zürich but soon was disappointed by the enormous amount of memorization the curriculum required. After a two-year interruption for his obligatory Swiss Army training, he returned to ETH. In 1962 he completed his PhD in physical chemistry under the direct supervision of Hans Primas in Hans Günthard's laboratory, where he worked mostly on the development of NMR instrumentation. He also received rigorous training in quantum mechanics from Primas, who had been strongly influenced by lectures of Wolfgang Pauli at ETH.

Immediately following their marriage, Ernst and his wife, Magdalena Ernst-Kielholz, left for Palo Alto, California. There Ernst spent a postdoctoral period with Weston Anderson at Varian Associates, a world-leading company that introduced commercial NMR equipment in close collaboration with Nobel laureate Felix Bloch at Stanford University. Anderson and Ernst demonstrated the enormous gains in sensitivity and efficiency attainable by pulsed FT NMR, which became the cornerstone for all of Ernst's future technological breakthroughs.

In 1968 Ernst returned to ETH Zürich as a lecturer and was promoted to full professor in 1976. In his autobiography, which was published in German in 2020 and in English in 2022, he expresses the frustrations he felt after returning to Switzerland about the slow pace and muted interest in adopting FT NMR until Spectrospin (now part of Bruker), located near Zürich, produced the first commercial FT NMR spectrometer. Around the same time, a lecture by the Belgian physicist Jean Jeener about two-dimensional FT NMR inspired Ernst to break new ground and dramatically expand the scope of the technology by developing the foundation for a vast array of multipulse, multinuclear NMR experiments.

A gifted experimentalist, Ernst used his deep understanding of spin physics to become the first to fully exploit the rich molecular information contained in large networks of coupled nuclear spins. The full Liouville–von Neumann description of how such networks evolve in time is daunting to many practicing chemists—and even physicists. That prompted Ernst and his coworkers to introduce an elegant analytical treatment, known as product operator formalism, that remains key to virtually all modern solution NMR innovations. While developing multidimensional NMR spectroscopy, he proposed that the concept offered similar advantages in the then-fledgling field of magnetic resonance imaging. His classic 1976 paper, with Walter Aue and Enrico Bartholdi, in the *Journal of Chemical Physics* beautifully lays out the principles of both multidimensional NMR spectroscopy and today's FT MRI.

In a subsequent, highly successful endeavor, Ernst collaborated with Kurt Wüthrich to expand the use of 2D NMR to study the structure of proteins in solution. That work created the basis for Wüthrich's 2002 Nobel Prize in Chemistry.

In addition to the Nobel Prize, Ernst received many honors and awards. They include the Marcel Benoist Swiss Science Prize in 1986, the Ampere Prize in 1990, the Wolf Prize in Chemistry in 1991, and the Louisa Gross Horwitz Prize in 1991.

Despite all his scientific successes, Ernst remained a modest and humble person. Although invariably direct and sometimes outspoken, both in public and in private, he was a compassionate man and had an uncanny ability to touch people's lives. At memorial sessions that honored his life and work, those who had the privilege to know him personally shared such unforgettable special moments.

ROLF TSCHUDIN

Richard R. Ernst

In 1968, before returning to Switzerland from the US, Ernst and Magdalena visited Nepal, where they became enthralled by Himalayan art, religion, and culture. It was a passion Ernst retained for the rest of his life. Over time, he and Magdalena acquired an extensive collection of precious Tibetan thangkas (scroll paintings), which were displayed at their home in Winterthur. After he retired, Ernst used Raman spectroscopy to analyze with unabated scientific rigor those centuries-old thangkas for paint pigments to delineate their provenance. Through his appreciation for Buddhism, he became closely acquainted with the 14th Dalai Lama, Tenzin Gyatso.

With countless lectures to the general public and his writings, Ernst turned into a global ambassador of science who shared his passion for research, promoted its broad significance, and appealed to his colleagues to take on responsibilities for the benefit of humankind. With his death, the NMR field lost not only a founding father but also an exceptional human being. As a role model for many of us, Richard Ernst embodied the scientific conscience of our community.

Ad Bax
National Institutes of Health
Bethesda, Maryland
Rafael Brüschweiler
Ohio State University
Columbus

Arthur Poskanzer

Arthur Poskanzer, a groundbreaker in exploring extreme states of nuclear matter, died peacefully in his home in Berkeley, California, on 30 June 2021.

Art was born in New York City on 28 June 1931. Because of an illness, he could not attend school and was self-taught until sixth grade. He went to Stuyvesant High School and then Harvard University, where he received a BS with honors in chemistry and physics in 1953. Following graduation, Art spent the summer at Los Alamos Scientific Laboratory and worked on chemical separation of heavy elements. He separated 1 gram of americium—at the time a large fraction of the world's supply of the element—from plutonium.

In 1954 Art received an MS from Columbia University, where he worked with Jack Miller, and in 1957 was awarded a PhD from MIT. Advised by Charles Coryell, Art did his thesis on the chemical separation of heavy elements, his area of expertise. Art then joined the group of Gerhart Friedlander in Brookhaven National Laboratory's chemistry department and used accelerators to study exotic atomic nuclei. He measured the half-life of helium-8 and the properties of various isotopes that have delayed proton emission. Art's calcium-37 data were crucial for interpreting Raymond Davis Jr's Nobel Prize–winning solar neutrino experiment.

In 1966 Art moved to the Lawrence Radiation Laboratory (later Lawrence Berkeley National Laboratory) in Berkeley, California, where he remained for the rest of his career. Together with Joseph Cerny and Earl Hyde, he used the Bevatron proton beam and novel electronic detectors to discover numerous nuclear isotopes with an extreme imbalance of neutrons and protons, notably lithium-11. Study of such isotopes at the limit of nuclear stability remains at the forefront of nuclear-physics research.

Art used the newly commissioned nuclear beams of the Berkeley Bevalac in the mid 1970s to study nuclear matter at very high temperature and density. To measure such complex collisions, Art, Hans Gutbrod, Hans Georg Ritter, and their collaborators developed a novel instrument with a large solid angle and high granularity: the Plastic Ball detector. In analyzing the data it produced, Ritter, Art, and colleagues found that hot nuclear matter flows much like a liquid, with properties that are well described by calculations based on hydrodynamics. Their landmark result was published in *Physical Review Letters* in 1984.

Soon thereafter, CERN initiated plans for much-higher-energy nuclear beams in the Super Proton Synchrotron. For the program, Art and colleagues developed a new experiment, called WA80, with the Plastic Ball as a component.

The next step in the study of nuclear matter under extreme conditions, the Relativistic Heavy Ion Collider (RHIC) at Brookhaven, was approved for construction in 1990. The unprecedented complexity of RHIC collisions required new experimental approaches, and Art convened a community-wide discussion on the question. The consensus was to create an experiment based on a large-volume, high-granularity time-projection chamber in a solenoidal magnet, a concept developed by Howard Wieman. The resulting proposal, with strong leadership by Art, was approved and became the Solenoidal Tracker at RHIC, or STAR. STAR is still carrying out cutting-edge research, 30 years after its conception by Art and colleagues. The chamber at the ALICE detector at CERN's Large Hadron Collider can likewise be traced back to Art's pioneering vision for STAR.

STAR's construction required significant R&D, and Art organized Berkeley Lab's heavy-ion effort into the Relativistic Nuclear Collisions program for that purpose. Art and others from Berkeley joined the CERN NA49 experiment to prototype STAR technology.

Art also developed new techniques for flow analysis, in which he applied a novel Fourier-decomposition approach to NA49 data that definitively established the hydrodynamic flow of nuclear matter. That phenomenon remains an essential tool for studying the quark–gluon plasma. Art and Sergei Voloshin wrote an encyclopedic paper on flow-analysis techniques that is one of the most-cited papers in the field.

As the scientific director of the Bevalac and founder of the Relativistic Nuclear Collisions program at Berkeley Lab, Art was an effective administrator. His first love, however, was research. Art retired in 2002, but he did not slow down. In the 15 years after his retirement, he wrote a dozen papers on flow phenomenology and analysis techniques, and he was a principal author on 10 STAR publications.

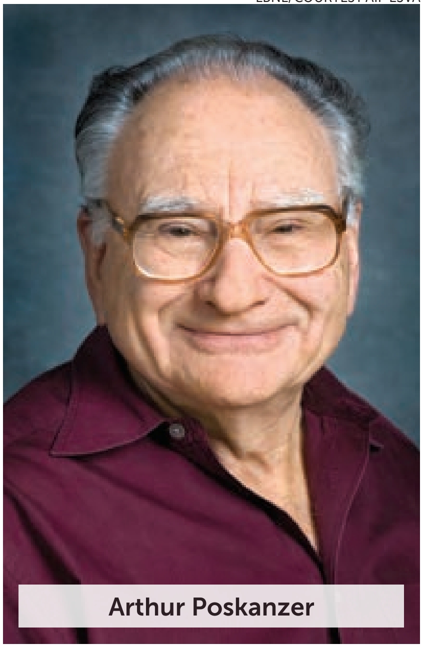
In 1980 Art received the Glenn T. Seaborg Award from the American Chemical Society for his contributions to nuclear chemistry. In 2008 he was awarded the American Physical Society's Tom W. Bonner Prize for the discovery of hydrodynamic flow of nuclear matter.

Art and his wife, Lucille, were well known for their online guide *Restaurants in the Berkeley Area*, which provided reviews of the local culinary scene. They started it in 1978 as a printed guide and put it online in 1995. Early editions also included reviews of local hot tubs, which, unfortunately, were later dropped.

A kind and generous collaborator, Art set a very high standard. His work has influenced multiple generations of scientists, and he leaves a legacy of friendship, leadership, and accomplishment.

Peter M. Jacobs
Lawrence Berkeley National Laboratory
Berkeley, California PT

LBNL/COURTESY AIP ESVA



Arthur Poskanzer

QUICK STUDY

Daniel Woodbury is a senior electro-optical engineer at Lockheed Martin, in Denver, Colorado. **Robert Schwartz** is a graduate student in physics, and **Howard Milchberg** a professor of physics and electrical engineering, both at the University of Maryland in College Park.



Extreme sensitivity charge detection

Daniel Woodbury, Robert Schwartz, and Howard Milchberg

To detect individual electrons in air, researchers are revisiting experiments from the dawn of the laser age with new technology.

After Theodore Maiman's demonstration of the laser in 1960, researchers quickly discovered that tightly focused laser pulses generated a bright spark of ionized air. The initial reports caught the physics community off guard; in the words of an early researcher, C. Grey Morgan, a "flash of laser light can set the air on fire!" Because each laser photon didn't have enough energy to knock an electron off an air molecule, it should have been impossible for the laser to ionize the air directly. Eventually, researchers realized that the extremely high electric fields at the laser's focus were driving an electron avalanche breakdown, an already well-known process using high static fields and high-power microwaves.

An initial population of free electrons gains energy by acceleration in the laser field, ionizing other molecules in a cascading, exponential process. The source of the initial population of electrons was a mystery, however, and it spurred pioneering theoretical work by Leonid Keldysh. In the quantum or multiphoton ionization (MPI) limit—at moderate intensity and short laser wavelength—of the theory, an electron is liberated when an atom absorbs many photons simultaneously. In the semiclassical limit (at high intensity and long wavelength), the laser's large electric field pulls electrons out of atoms by tunneling ionization.

With the basic process understood, researchers rushed to apply laser-driven avalanche breakdowns to such varied fields as breakdown spectroscopy, fast switching of high voltages, laser surgery, and laser machining. In this Quick Study, we recount the physics governing the laser-driven sparks and show how revisiting early experiments with new technology has uncovered the ability to pinpoint individual electrons in ambient gases.

Electron cascades

In a discharge induced by a static field or microwaves, breakdown begins with a single free electron—usually originating from cosmic rays or dust—that accelerates along the electric field until it collides with and ionizes a molecule. For air at standard temperature and pressure, the threshold field is about 3 MV/m.

In the electric field of a focused laser pulse—whose frequency is 10^4 times that of microwaves—electrons don't accelerate to a sufficient energy for ionization to happen before the field switches sign and accelerates them in the opposite direction. As the sinusoidally quivering electrons elastically scatter off air molecules, their driven motion loses coherence with the laser and they heat up.

Over many such collisions, an electron can gain enough kinetic energy to ionize a neutral molecule. An ionization cascade will develop if the laser-induced heating and ionization overcomes energy and particle losses from the heated volume. The greatly reduced acceleration time in each laser cycle demands a much higher peak electric field, on the order of 10 GV/m for a 1 μm (near-IR) wavelength laser. Such fields may seem extreme, but researchers have routinely generated them since the 1970s by focusing the output from commercial Q-switched lasers, which pack a modest amount of energy into a 10 ns pulse.

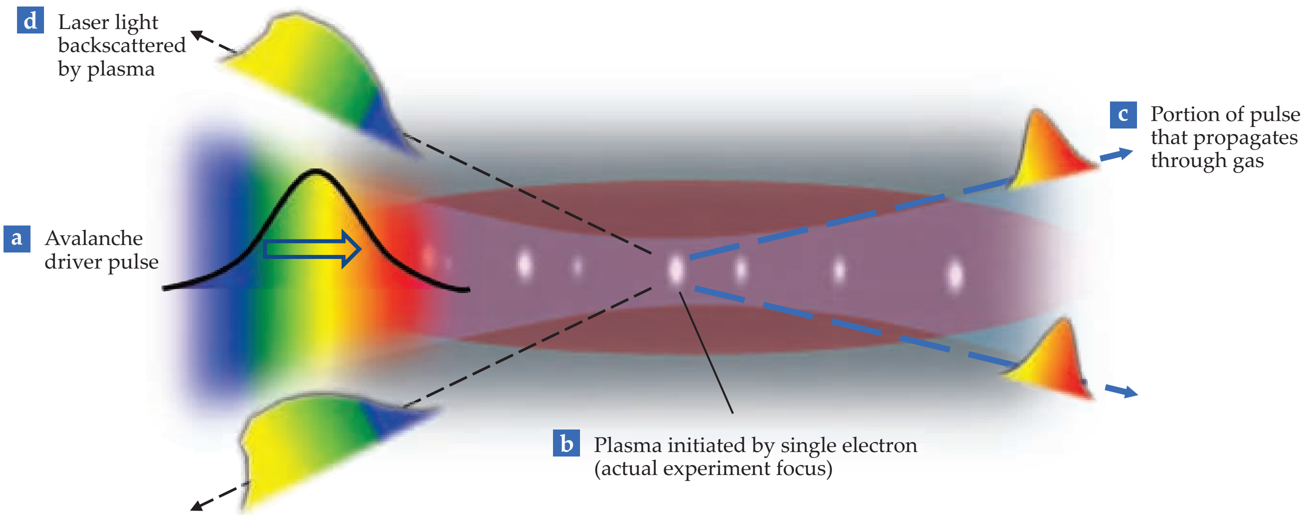
Unlike static or microwave breakdowns, which are centimeter-sized or larger, laser-breakdown plasmas can start off in the micron range. Laser-driven electrons in air oscillate in small orbits and randomly change direction as they collide with gas molecules. The rapidly growing free-electron population diffuses into a small blob around the location of the initial free electron that seeds the process. As long as the laser pulse is on, the local electron density continues to increase, accompanied by outward diffusion, until there are enough electrons in the heated volume to respond collectively in resonance with the laser and absorb energy even more rapidly. Eventually, the breakdown explodes outward as a bright plasma spark.

An IR breakthrough

The remarkable growth of a laser-driven breakdown suggests that avalanches might have been used to detect single free electrons. Early researchers, however, had no way to tell if the avalanche began with 1, 100, or even 1 million electrons. In the end, the breakdown would saturate to the same bright plasma spark, in which every molecule was ionized. More fundamentally, MPI of oxygen molecules in air could liberate many electrons early in the pulse and mask the effect of any seed electrons present. And with nanosecond laser pulses, air-breakdown plasmas can grow to the total volume of the laser focus, with an attendant loss of spatial resolution for locating seed electrons.

We found the solution to those problems while pursuing another topic—the remote detection of radioactive sources. All radioactive materials emit high-energy particles that can be directly detected by Geiger counters, scintillators, or spectrometers. As the high-energy particles travel outward from the source, they knock electrons off air molecules and leave behind a trail of ionized air.

Because of the combined effects of the inverse square drop-off with distance and attenuation by the air, however, the flux of high-energy particles becomes extremely weak. Constant



A LASER EMITS a short chirped pulse through air. **(a)** The red part of its spectrum precedes the blue. **(b)** Light at the laser's focus produces a plasma blob initiated by a single electron. The series of blobs pictured are experimental data. **(c)** Beyond the focus, a portion of the driver pulse—the early (red) part of the spectrum—continues propagating. **(d)** Another portion of the pulse is backscattered by the plasma. That spectrum is the main diagnostic and is collected by a spectrometer.

bombardment leads to a small population of free electrons and negative ions (on the order of a few thousand per cubic centimeter) in the air near the source. Although that level of ionization is far too low to generate enough optical emission to see from a distance, focusing a laser in that air could—you guessed it—drive a bright breakdown spark.

Our early experiments using near-IR lasers repeatedly failed to detect air ionization induced by an alpha particle source. Because of MPI, the exact same breakdowns occurred with or without the source present. Fortuitously, our lab had recently obtained an ultrashort-pulse, mid-IR laser (3.9 μm) intended for high-field nonlinear optics experiments, and we decided to try that laser as an avalanche driver by stretching its pulse to 50 ps. (That duration is long enough to grow the avalanche over multiple exponentiation times, but not so long that avalanche growth can easily be seeded by the "noise" of dust, cosmic rays, or background radiation.) And most importantly, MPI was expected to be strongly suppressed by the much lower photon energy.

The effect was immediate and distinctive: Without the radioactive source present, no avalanches happened, and with a low radioactive source flux, there appeared small, spatially discrete, and countable laser-driven breakdowns in the laser focus, seeded by individual electrons. By scanning the position of the radioactive source, we were able to reduce the initial electron density to the point where only one breakdown was seeded—by a single electron in the laser focus.

Although we diagnosed those laser-driven avalanches simply by collecting the total light emission from the plasma, the most sensitive and quantitative diagnostic for remote detection was the backward-scattered IR radiation from breakdown plasmas, as shown in the figure. By chirping the laser pulse so that redder wavelengths precede bluer wavelengths in time, the reddest part of the backscattered spectrum marks the onset time of an avalanche.

The time delay provides a quantitative measure of remote charge density and hence radioactive source strength: More free charges in the laser focus lead to a shorter avalanche delay and a redder wing in the backscattered spectrum. Such a single-shot measurement could never have been done prior to the 1990s—it had to await the development of IR-sensitive CCD cameras and superfast electronics.

A clear implication of this discussion is that a laser-driven avalanche is an ultrasensitive diagnostic of any source of free charge in a gas, including the charge induced by another laser pulse. To test theories of ultrashort-pulse laser ionization in dense gases, we recently used a laser-driven avalanche to measure the absolute ionization yield in air generated by an auxiliary ultrashort laser pulse over 14 orders of magnitude. That dynamic range is obtainable in no other way, and it corresponds to one ionization event for every 10^{16} gas molecules.

The extreme electron amplification in gases driven by IR-wavelength lasers can be viewed as the *in situ*, spatially resolved analogue of the photomultiplier tube and represents a long-neglected application of avalanches. By the early 1980s, ideal lasers for the application had developed—long wave carbon dioxide lasers with 100 ps pulse durations. But by that point, researchers considered avalanches a solved (albeit complicated and messy) problem, and they had moved on to study strong-field optical ionization in very dilute gases.

The development of modern, time-resolving diagnostics has rekindled our interest in the physics and applications of the laser-driven avalanche, an amazing effect observed from the earliest days of the laser.

Additional resources

▶ C. Grey Morgan, "Laser-induced breakdown phenomena," *Sci. Prog.* **65**, 31 (1978).

▶ L. V. Keldysh, "Ionization in the field of a strong electromagnetic wave," *Sov. Phys. JETP* **20**, 1307 (1965).

▶ R. M. Schwartz et al., "Remote detection of radioactive material using mid-IR laser-driven electron avalanche," *Sci. Adv.* **5**, eaav6804 (2019); D. Woodbury, R. M. Schwartz, H. M. Milchberg, "Measurement of ultralow radiation-induced charge densities using picosecond mid-IR laser-induced breakdown," *Optica* **6**, 811 (2019).

▶ D. Woodbury et al., "Absolute measurement of laser ionization yield in atmospheric pressure range gases over 14 decades," *Phys. Rev. Lett.* **124**, 013201 (2020).

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Mid-Atlantic snowfall

When the atmosphere's polar jet transports cold winter air from Canada toward the US East Coast, it meets warm, moisture-laden air transported north across the Atlantic Ocean by the Gulf Stream. The heat exchange brought about by the difference in temperature between the two air masses powers nor'easter winter storms. On Monday, 3 January, after an unseasonably balmy start to 2022, a nor'easter blew in to the mid-Atlantic region. This satellite photo, captured on 4 January by the Moderate Resolution Imaging Spectroradiometer aboard NASA's *Terra* satellite, shows the winter storm's snow band, which lingered over north-central Virginia and southern Maryland.

The Capital Weather Gang of the *Washington Post* reported that 5–10 inches of snow or more accumulated in the region, sometimes as fast as 2–3 inches per hour. The severity of the storm, they pointed out, was because of heavy, wet snow—made possible by the near-freezing temperatures—and strong gusty winds. The combination knocked down tree limbs, and many households lost power for hours or even days. Hundreds of drivers and their passengers on a stretch of Interstate 95 in northern Virginia were forced to a standstill. Some were stranded on the highway for more than 24 hours and slept in their vehicles until plowing and towing crews were able to reach them. (Image courtesy of Joshua Stevens, NASA Earth Observatory.) —AL

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