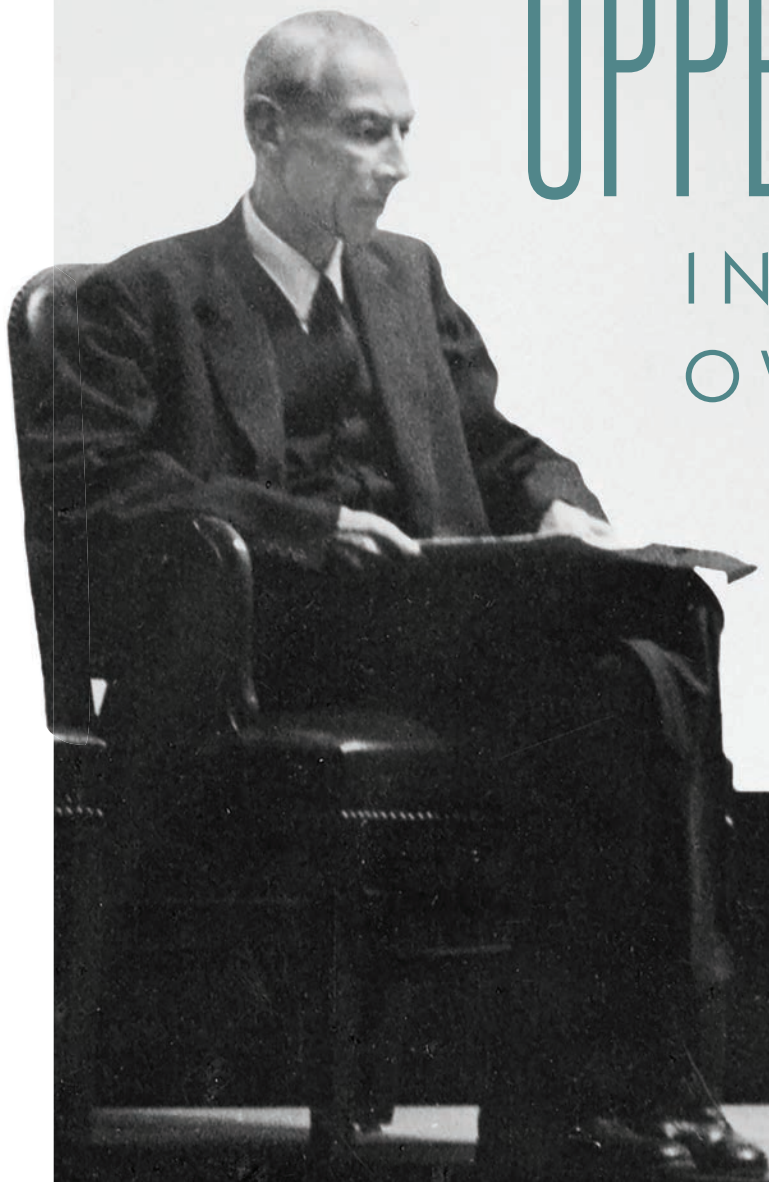
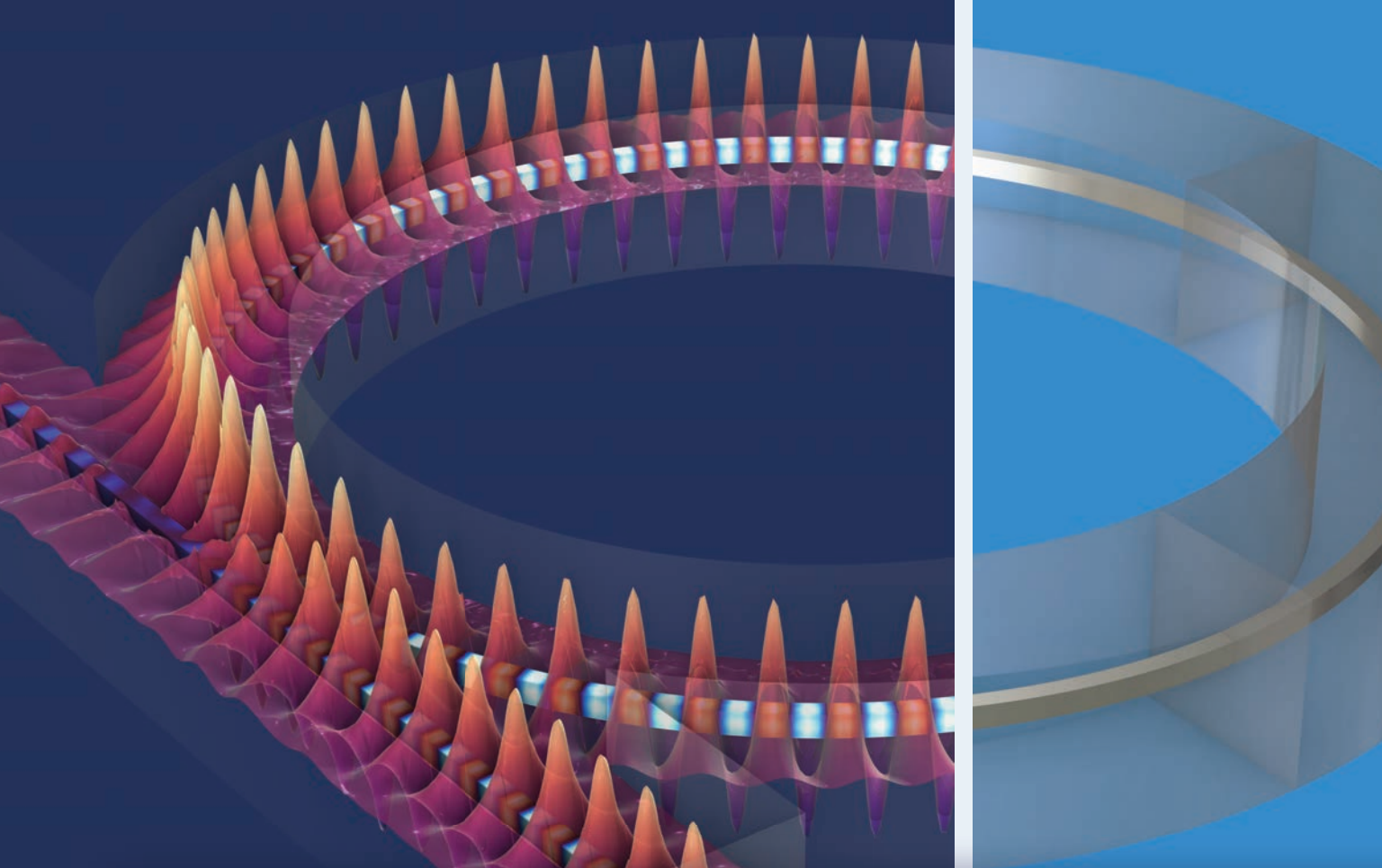


OPPENHEIMER

IN HIS
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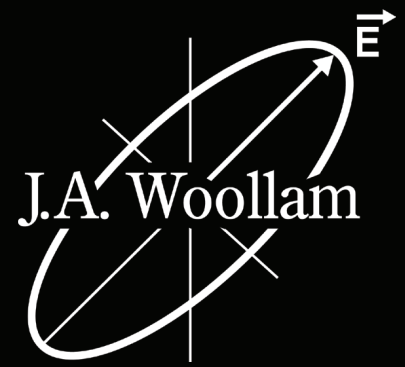


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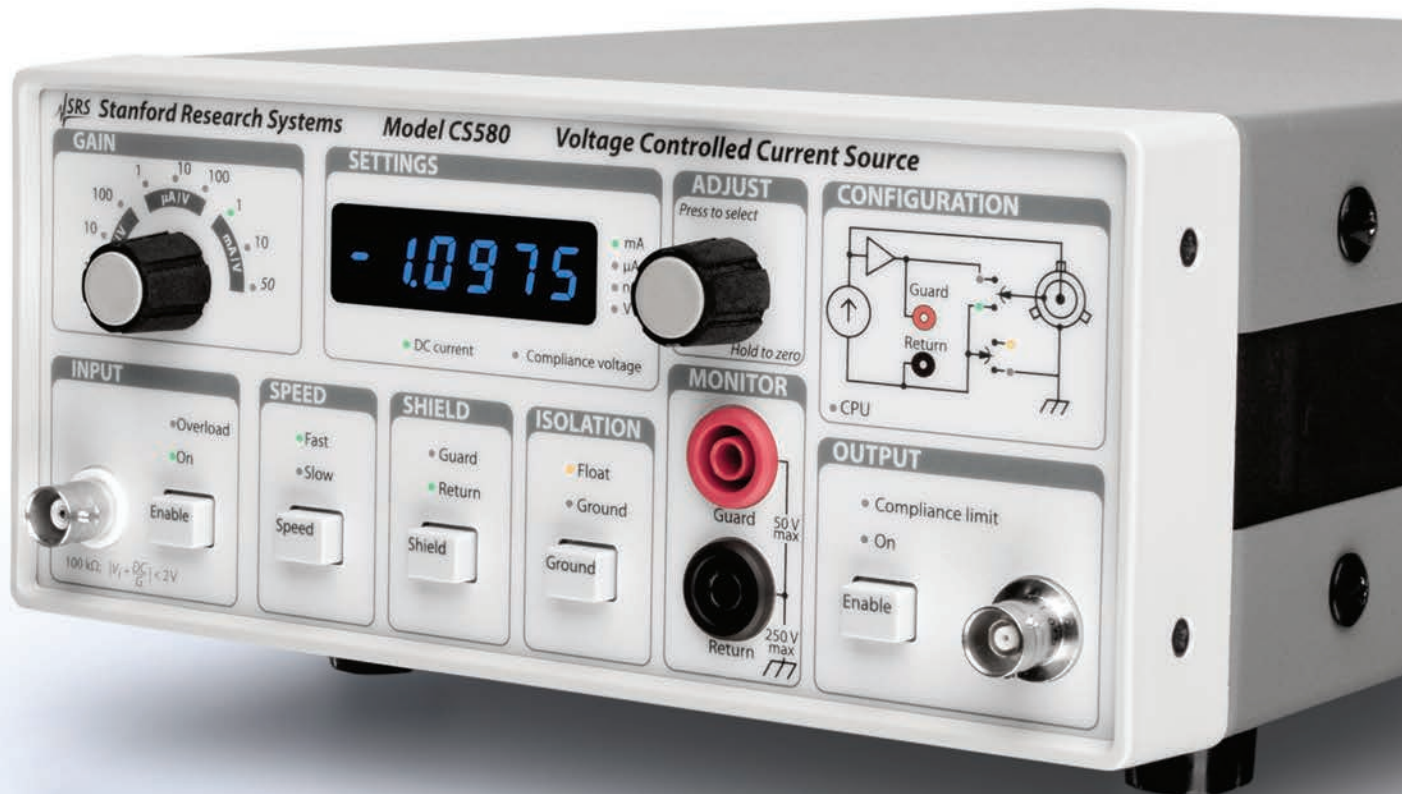
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FEATURES

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Oppenheimer reflects on his early career

Ryan Dahn

Interviews now available to the public bring the famed physicist's lesser-known early years to life.

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The Princeton period

Abraham Pais

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October 1967

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Planning reactions to the Oppenheimer security-clearance review

Allison Buser

Cognizant of their role within the scientific community, scientific societies had to weigh how to respond to the actions by the Atomic Energy Commission.

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OPINION

Does nuclear stockpile stewardship's science diminish global security?

Stewart Prager and Denisse Córdova Carrizales

The answer is relevant to the physics community, especially for scientists who are choosing their research paths.



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VERSION "B"

The Council of the American Physical Society is de-authorized by the decision of the AEC (or Loyalty Review Board, as it may be) in withdrawing the clearance of Dr. J. Robert Oppenheimer. Many members of the American Physical Society have worked with Dr. Oppenheimer for many years and as a result of this association have great confidence in the soundness and integrity of Dr. Oppenheimer.

From the very beginning, two features of the original charges against Dr. Oppenheimer have caused much concern to the Council, which believes that repeated use of charges with such specificity would be harmful to the best interests of the Society.

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Hans A. Bethe



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ON THE COVER

Three interviews given by J. Robert Oppenheimer in the 1960s were recently made publicly available by the Niels Bohr Library & Archives at the American Institute of Physics. Starting on **page 26**, *PT*'s Ryan Dahn discusses what Oppenheimer said—and didn't say—about his early career during one of the interviews.

(Image from Los Alamos Scientific Laboratory, courtesy of the AIP Emilio Segrè Visual Archives, *Physics Today* Collection.)

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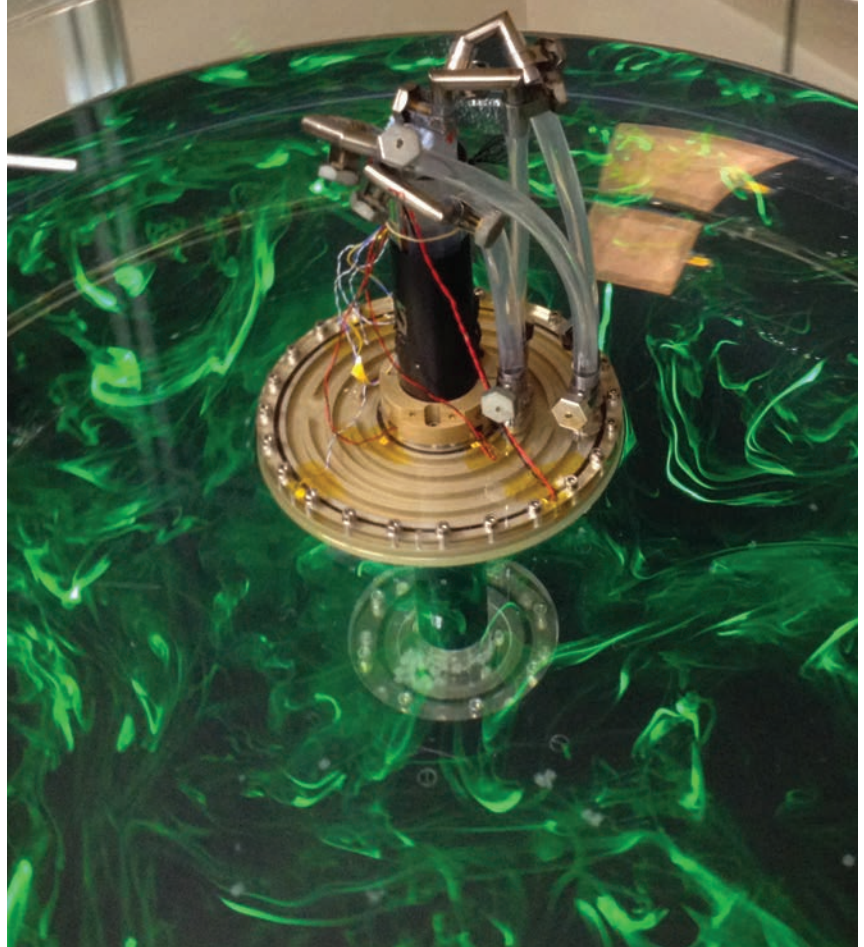
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TO READ ABOUT A SMALL YET MIGHTY TURBULENCE MODEL, TURN TO PAGE 14

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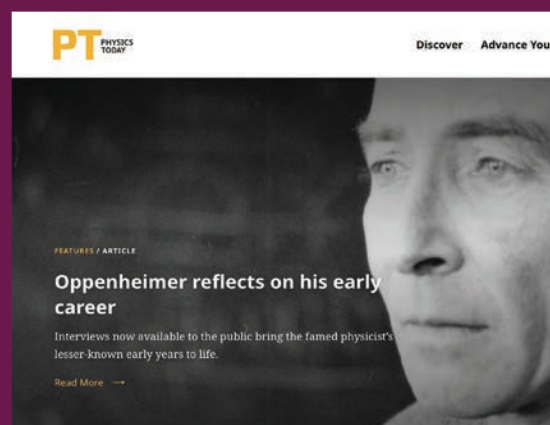
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Snapshots of Oppenheimer

By Richard J. Fitzgerald

Much has already been written about J. Robert Oppenheimer, perhaps most familiarly in Kai Bird and Martin Sherwin's 2005 biography, *American Prometheus: The Triumph and Tragedy of J. Robert Oppenheimer*. That book and other Oppenheimer biographies draw heavily on a lengthy transcript of an interview he gave in 1963 that is in the collection at the Niels Bohr Library & Archives (NBLA is part of the American Institute of Physics, publisher of *Physics Today*).

Before this past April, those resources were readily available only to researchers and only through explicit permission of the Oppenheimer family. But in coordination with the family, NBLA has now made the interview—along with two others Oppenheimer gave that are lesser known—publicly accessible for non-commercial, not-for-profit use. (For a panel discussion about the interviews, featuring Bird, members of the Oppenheimer family, and historian David Kaiser, visit <https://bit.ly/4dnt9jnM>.)

In this issue, *PT* takes a cue from the interviews and explores Oppenheimer's role in science through a variety of lenses.

Starting on page 26, *PT*'s Ryan Dahn explores what a 1963 interview with Oppenheimer reveals—and doesn't reveal—about his early career. Oppenheimer carried out doctoral and postdoctoral work in Europe in the mid and late 1920s, just as modern quantum mechanics was taking shape. In the interview, he shares his recollections of the time and how he came to be an evangelist for the new quantum theory in the US. Dahn also shares parts of the other two newly released interviews: one from 1960 on the Trinity nuclear test and one from 1966 focusing on Enrico Fermi.

Following Oppenheimer's death in February 1967, *PT* ran a special commemorative issue in October that featured four articles by eminent contemporaries who looked back at different aspects of his life and contributions. On page 34, we feature one of them: Abraham Pais's recounting of Oppenheimer's time at the Insti-



tute for Advanced Study in Princeton, New Jersey, where he became director in 1947.

It was while Oppenheimer was at the institute that the Atomic Energy Commission revoked his security clearance, an action that triggered strong responses from the physics community. Not only was the loyalty of a preeminent physicist being questioned, but the fundamental relationship between government and the scientific community was being drawn into question. Starting on page 44, you can read letters about how the American Physical Society and AIP considered their responses to the commission's action.

One issue that fueled the campaign to revoke Oppenheimer's clearance was his postwar concern for preventing an arms race. For example, in his farewell speech to the Association of Los Alamos Scientists on 2 November 1945, shortly after he resigned as director of the Los Alamos Laboratory, Oppenheimer said, "I think it is true to say that atomic weapons are a peril which affect everyone in the world, and in that sense a completely common problem." On page 51, Stewart Prager and Denisse Córdova Carrizales place that issue in a modern setting: the US nuclear Stockpile Stewardship Program. Although it is designed to maintain the US arsenal using science rather than weapons tests, the authors argue that the advancing science could actually further the development of new weapons and that ethical choices like those faced by Oppenheimer and other nuclear scientists of the era continue today. **PT**

J. Robert Oppenheimer

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For the first time, three rare oral history interviews are publicly available offering insight into one of the most influential figures in modern science.

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Experiment closes in on a second critical point of water

Precision heating of amorphous ice allows researchers to make tricky measurements of supercooled water.

By Sarah Wells

Water may be ubiquitous, but it's not conventional. Many properties of water, such as low compressibility and high surface tension, make it stand out from its peers. Water's behavior in a supercooled state—when it remains liquid at temperatures below its freezing point—is particularly unusual. The compressibility and heat capacity of most liquids shrink in the supercooled regime, yet water undergoes a transformation at specific combinations of temperature and pressure that causes its compressibility and heat capacity to surge.

To explain the behavior, researchers have proposed that a special phase transition, known as a critical point, exists in the supercooled region of water's phase diagram. At this point, two yet-to-be-detected phases of water were predicted to merge and become indistinguishable. Water's first critical point, between the liquid and gas phases, appears at about 647 K and 221 bar. Once controversial, the idea of the existence of a critical point between two liquid phases of water has gained consensus, and researchers have attained evidence of the two supercooled phases, high- and low-density liquids. But that second critical point has never been directly observed.

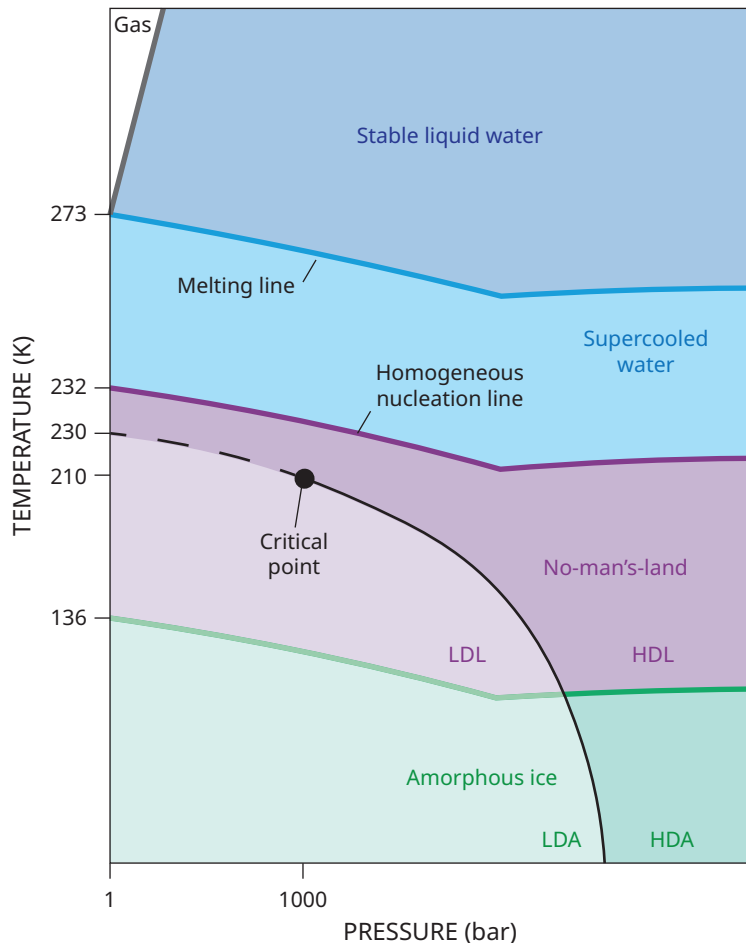
Now Anders Nilsson from Stockholm University in Sweden, Kyung Hwan Kim at Pohang University of Science and Technology in South Korea, and colleagues have found evidence of a liquid–liquid critical point (LLCP) in supercooled water.¹ Using an IR laser, the team conducted precision melting of ice samples formed below 136 K and used an x-ray free-electron laser to measure the molecular properties of the resulting liquid. The new work is the closest that an experimental result has come to directly measuring the location of the critical point, says Francesco Paesani, of the University of California, San Diego, who has conducted simulations of supercooled water.

Part of what makes LLCP research so difficult is

that it requires keeping water liquid at low temperatures and high pressures. Water cooled beyond its freezing point can maintain its liquid state only if it is carefully prepared without imperfections, such as dust or gas bubbles, that can act as nucleation sites for crystallization. And in the region known as no-man's-land (see the graph), which at standard atmospheric pressure has a threshold temperature of 232 K, random molecular motion is enough to trigger rapid crystallization. It's within that region that the LLCP is suspected to exist, but measuring the liquid state of the supercooled water before it crystallizes has been extremely challenging. Nilsson and colleagues have made many attempts, including in 2017 when they used x-ray scattering to measure the behavior of evaporatively cooled microdroplets (see the *PT* article "Supercooled water goes supercritical").

Rather than trying to glimpse the behavior of supercooled water as it's cooled, Nilsson and colleagues entered no-man's-land by melting an even colder form of water called amorphous ice. When water at standard atmospheric pressure is rapidly cooled to temperatures below 136 K, it freezes such that its molecules maintain their liquid configuration. When warmed into the supercooled regime, the water behaves like a liquid for up to microseconds before recrystallizing.

The researchers prepared samples of high- and low-density amorphous ices under pressure in a cryostat vacuum chamber and used pulses from a nanosecond IR laser to heat them and melt them into the two supercooled liquid phases. The team then used an x-ray free-electron laser to take measurements of the molecular and density states of the resultant transient liquids via small- and wide-angle scattering. By varying the energy per unit area of the laser, the team was able to systematically control the temperature of the liquids to search for spectral signatures of a liquid–liquid transition at conditions above and below recent estimated values of the LLCP.



◀ The liquid-liquid critical point is theorized to be found in a region of water's phase diagram called no-man's-land, which is difficult to access with standard experimental techniques. By melting samples of high-density and low-density amorphous ices (HDA and LDA, respectively), researchers found evidence that a critical point where high-density liquid (HDL) and low-density liquid (LDL) phases of water become indistinguishable lies at around 210 K and 1000 bar. (The figure is not to scale.)

As the researchers took measurements of the samples at different temperatures and pressures, they identified a region in no-man's-land that exhibited characteristics consistent with proximity to an LLC. They observed enhanced density fluctuations between the two liquid phases and a crossover from abrupt phase changes, consistent with a jump between discrete high- and low-density water phases, to the smooth changes predicted as the liquid phases become indistinguishable. They also observed a plateau in the liquids' temperature increase despite more heat being added, suggesting a rise in heat capacity consistent with proximity to

an LLC. The team inferred the location of an LLC at 210 K and 1000 bar, which is in alignment with other recent estimates, including simulation results from Paesani and colleagues.

Despite the progress toward nailing down the location of the LLC, questions remain. For example, Nilsson and colleagues were unable to make an estimate of the samples' correlation length, a measure of local molecular influence that grows alongside compressibility and heat capacity and that is predicted to diverge toward infinity at an LLC. Small variations in the amorphous ice samples made it difficult to measure their internal

structure using very small x-ray scattering angles. Increasing the homogeneity of the samples could be one way to solve the problem, Nilsson says.

"To me, this work does not close the subject on the LLC," says Paesani, "but it changes the subject from 'Does this exist at all?' to 'How precisely can we now characterize it?'"

PT

Reference

1. S. You et al., "Experimental evidence of a liquid-liquid critical point in supercooled water," *Science* **391**, 1387 (2026).

Brightness of the night sky is volatile

By analyzing daily satellite observations, researchers identified rapid and localized brightness changes caused by human activity.

By **Alex Lopatka**

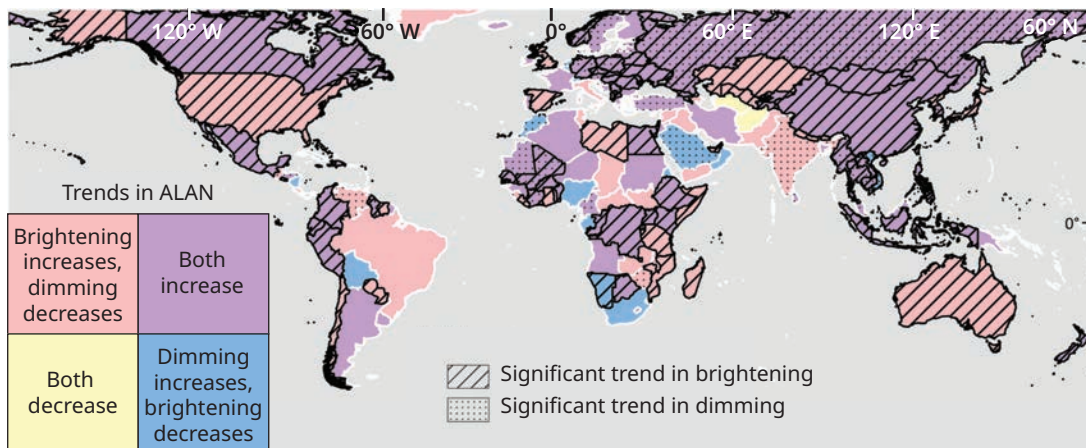


▲ In this image of Earth, yellow indicates areas that have experienced short-term events that primarily increased the brightness of nighttime artificial light from 2014 to 2022. Purple denotes areas where such events led to a sustained brightness decrease, and white means that some events in the area brightened the night sky across the time period and others dimmed it. (Image courtesy of Michala Garrison/NASA Earth Observatory.)

Satellite-based measurements have shown that the night sky above much of Earth's population has brightened over time. Measurements of changes in radiance of nighttime artificial light have been based on observations with annual or multiyear temporal resolution. But human-related activities that take place on shorter time scales—including construction events, power outages from natural disasters and disruptions from war, and changes in public policy—affect local artificial lighting and thus whether the night sky brightens or dims.

In new work, Zhe Zhu of the University of Connecticut and colleagues have identified frequent fluctuations in the brightness of nighttime artificial light across the globe.¹ Using data from NASA's Black Marble project, which employs a radiometer aboard the *Suomi National Polar-Orbiting Partnership* satellite, the researchers obtained nightly signals of brightening and dimming from 2014 to 2022 and corrected for atmospheric effects, lunar illumination, and viewing geometry. Then, they used a detection algorithm to track when the radiance of artificial light in a location increased or decreased, how intense the light was, and whether the change was abrupt or gradual.

Some key results are shown in the map. The researchers found



◀ This country-level map shows trends in brightening and dimming of artificial light at night (ALAN) and whether the trends are significant over the 2014–22 study period. (Image courtesy of Tian Li and Zhe Zhu/University of Connecticut.)

that variations in radiance were frequent, sometimes abrupt, and often subsequently reversed in the same region. Globally, brightening events contributed to a 34% increase in radiance of artificial light relative to the 2014 baseline, but that was offset by a radiance decrease of 18% from dimming events, so the result was a net brightening of 16%. The new analysis, with its high spatial and temporal resolution, could help provide a consistent framework for understanding the drivers of change in artificial light at night across the

globe. Researchers may, with nightly observations, be positioned to study various effects, such as how policy changes curb light pollution or how economic volatility affects human activity. **PT**

Reference

1. T. Li et al., “Satellite imagery reveals increasing volatility in human night-time activity,” *Nature* **652**, 379 (2026).



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A tabletop model of atmospheric turbulence

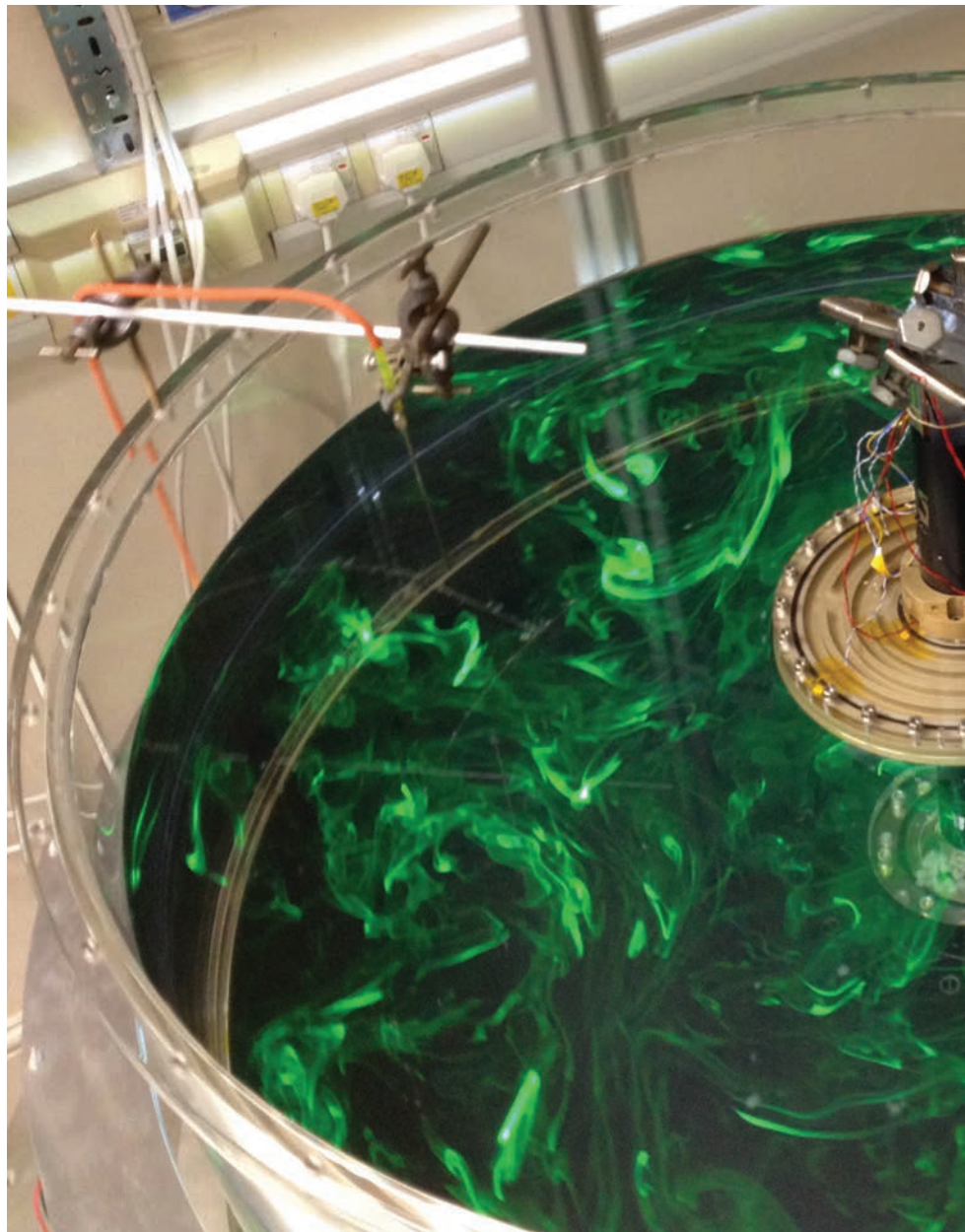
A meter-sized lab experiment offers new insight into how energy is transferred between turbulent flows of different sizes, from small eddies to large-scale weather events.

By **Sarah Wells**

Contributing to damaging weather events such as polar vortices, midlatitude storms, and tropical cyclones, turbulent flow in Earth's atmosphere plays a large role in climate dynamics. Atmospheric turbulence can be understood, in part, by its kinetic-energy spectrum, which describes energy cascades between eddies of different length scales. The scales can range from tens of meters to thousands of kilometers, and energy flow between the eddies contributes to weather events such as tornadoes or large, merging storms.

Yet how to describe the underlying processes that create the atmospheric structure has been a long-standing subject of debate among atmospheric scientists. Theories based on idealized or simplified conditions predict a flatter spectrum for large length scales and a steeper drop-off for small length scales, whereas observational data from aircraft show the opposite. Now Peter Read from the University of Oxford and colleagues have created a scaled-down, tabletop model of Earth's atmosphere that can realistically

Inside a tank filled with a dyed solution of water and glycerol, turbulent eddies of different length scales are generated through the use of variables like the speed of rotation and differences in temperature. (Photo courtesy of H el ene Scolan.)



re-create those atmospheric energy dynamics more accurately than previous models.¹ Such experiments can offer a new understanding of the kinetic-energy spectrum and of large-scale turbulence on Earth and other planets.

Despite its small stature, the team's model emulates large-scale, planetary atmospheres by exhibiting comparable values for key dimensionless parameters derived from the rotation speed, fluid density and viscosity, system size, and

other properties. The model consists of a meter-wide tank filled with a water-glycerol mixture, and it features a heated ring at the bottom of the tank and a cooling plate at the top surface of the fluid to imitate the effects of solar radiation at the equator and radiative atmospheric cooling at high latitudes. The researchers rotate the fluid system at speeds between 0.5 and 10 revolutions per minute to account for Earth's rotation. The model also includes a cone-shaped

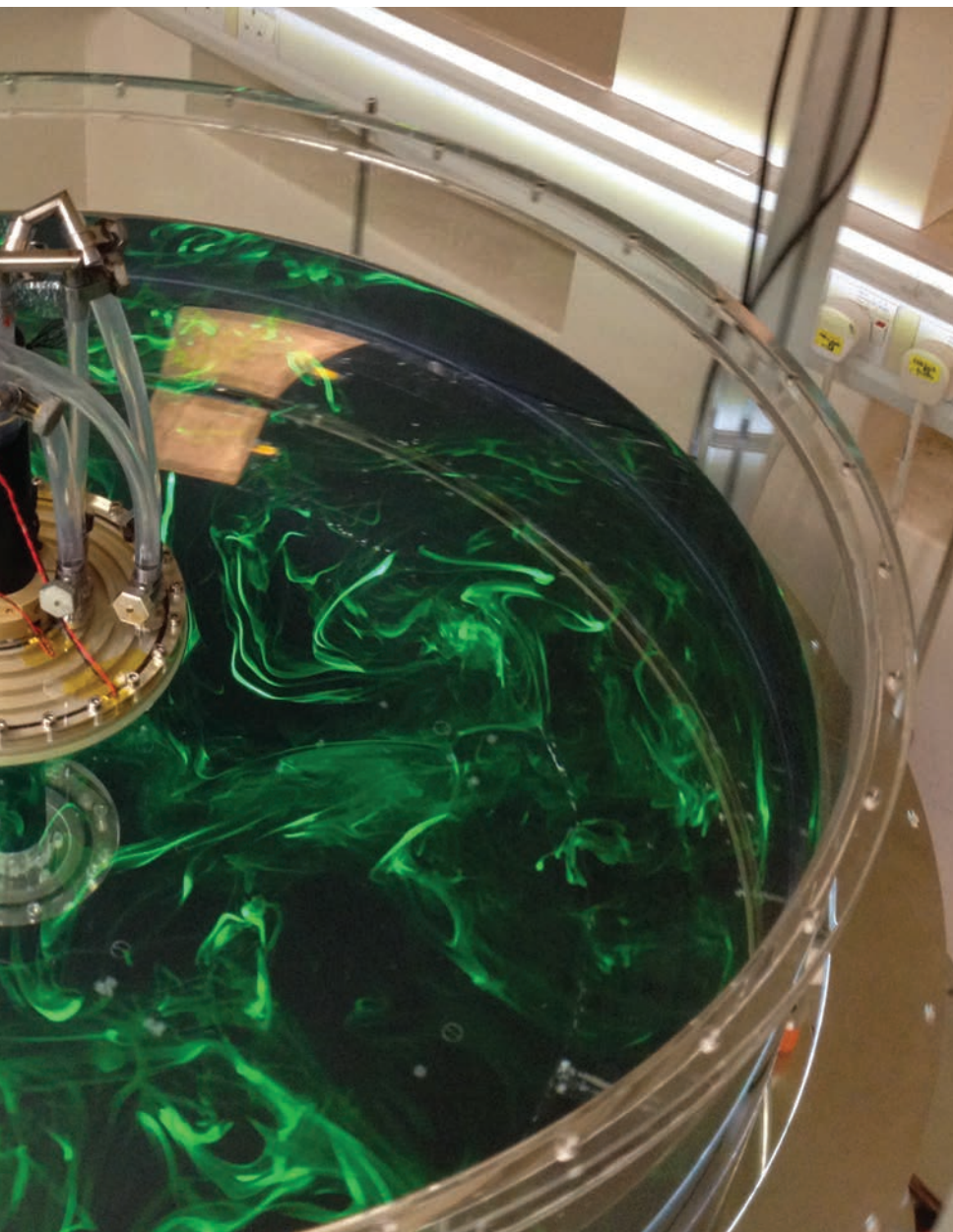
floor to imitate how the effect of Earth's rotation depends on latitude. Altogether, the temperature differences in the fluid and rotation of the tank generate convective motion that creates turbulence. The team visualizes the turbulence by using a camera mounted above the tank to capture the motion of particles seeded in the fluid, which can be seen in the figure.

The researchers use that velocimetry data to compute the kinetic-energy spectrum of the tank turbulence and find that its dependence on length scale more closely agrees with observational data captured by aircraft than with the idealized calculations. They also use the velocimetry data to calculate the cascade of vorticity, a measure of atmospheric fluid rotation that's important for weather forecasting. The team found that whereas energy largely cascades from small to large length scales, the cascade of vorticity goes in the opposite direction and dominates at both large and small length scales. That observation helps explain the steep slope of the energy spectrum observed at large length scales, but the exact mechanism that connects these opposite cascades is still being explored, Read says.

The team plans to use the model to study how the kinetic-energy spectrum might look different for gas giants and other planets that have atmospheres unlike Earth's. For example, using faster rotation speeds and greater variations in the tank's fluid depth can create effects similar to parallel jet streams, which are connected to the generation of zonal banding on Jupiter and Saturn. **PT**

Reference

1. S.-S. Ding et al., "Stratification-dependent enstrophy-controlled regime in geostrophic turbulence," *Phys. Rev. Lett.* **136**, 114101 (2026).



arXiv sets out on its own

In search of funding and autonomy, the preprint service is launching as a nonprofit.

By **Jenessa Duncombe**

The go-to website for preprints in physics, arXiv, will become an independent nonprofit organization starting in July, with the goal of providing long-term stability for the platform. The open-access repository will depart from its longtime home at Cornell University. The search for a CEO and members for a board of directors is underway, and 26 eligible current employees are being offered roles in the new company.

arXiv's leadership says it has no plans to change the platform's central mission. "Our assessment was that we were going to open up more support so that we wouldn't have to turn against the sort of ethos and the mission of arXiv," says Greg Morrisett, the dean of Cornell Tech, the university's applied sciences and engineering campus in New York City. Morrisett oversees arXiv at Cornell Tech.

arXiv is a global service for preprints, which are non-peer-reviewed scientific manuscripts, and postprints, which have been accepted by a refereed journal. Researchers post to arXiv to share early results and solicit feedback from their peers. Many also submit the preprints for publication in scholarly journals, a process that can take months. arXiv has no paywall or advertisements, and it does not monetize its content.

The service was in part inspired by an email list started by string theorist Joanne Cohn at the Institute for Advanced Study in Princeton, New Jersey, in 1989. She sent unpublished manuscripts typed in the math software TeX to other string theorists eager to see what their peers were up to. (See the 2021 *PT* article "Joanne Cohn and the email list that led to arXiv.") Theoretical physicist Paul Ginsparg recommended to Cohn at a conference that she automate the management of the email list, and she told him to give it a try. He did so in 1991 and created a web repository two years later. Ginsparg brought it to Cornell in 2001 when he accepted a professorship at the university. Initially held in the university's library, arXiv moved to Cornell's College of Computing and Information Science in 2019 and then to Cornell Tech later that same year.

arXiv
by the numbers

Founded

1991

Total submissions

3 million

Total downloads

6 billion

Top submitted
disciplines

**Computer
science,
physics,
and math**

Expenses (FY 2025)

\$6.7 million

(Data from arXiv.org.)

As the service gained popularity, arXiv's leadership grew increasingly convinced that Cornell would not be the long-term base of operations, says Morrisett. arXiv grew from around 3000 monthly submissions in 2001 to over 30 000 submissions in March 2026, and its subjects have branched out beyond physics into mathematics, computer science, statistics, and other disciplines. Ginsparg, who serves in various formal advisory roles for arXiv, says that the mission of arXiv to provide a free exchange of ideas among scientists at that scale is not a central part of the mission of a university, which must primarily serve its students, faculty, staff, and alumni.

The decision to become a nonprofit is in part financially motivated. arXiv's expenses in fiscal year 2025

were about \$6.7 million with a deficit of \$297 000. Cornell began tightening its own budget last year while facing funding cuts and challenges from the Trump administration. The arXiv budget deficits “were being covered by Cornell Tech,” says Morrisett. “And we’re just not going to have the funding to do that going forward.”

arXiv was supposed to live on its own dime through contributions from the Simons Foundation and Schmidt Sciences, research grants from NSF and NASA, and institutional membership fees. Institutional membership fees are not required, but some universities, libraries, research labs, and consortia choose to donate to make the service better for everyone, says Ginsparg.

As the need for additional funding has grown, arXiv’s affiliation with Cornell was inhibiting potential donors from giving money, Morrisett says. “Some organizations, especially in Europe or Asia, might be less happy about sending a check to Cornell University and hoping that it was deployed appropriately for arXiv, versus sending it directly to a nonprofit,” he says.

arXiv has raised enough money to cover all its anticipated funding needs for its first three years as a

nonprofit, says Ivan Oransky, a special adviser on scientific publishing at the Simons Foundation. The foundation has funded arXiv since 2011, and Oransky serves on arXiv’s advisory board. The Simons Foundation and two other foundations have made long-term commitments. (Oransky declined to share the names of the other foundations while details are being finalized.) “The Simons Foundation believes very much in the importance of the arXiv and how critical it is to science and math,” he says. The foundation’s support is committed for at least the next five years, says Oransky.

Going independent could allow for arXiv to further modernize its web services. “Universities are not used to paying the kind of rates that you need for good software engineers, and we’ve had to pull strings to get the talented people we have,” says Morrisett. Engineers at arXiv have been migrating the repository’s 3 million articles to the cloud and converting the legacy Perl code to Python. Ramin Zabih, arXiv’s executive director, says that one new user-facing capability that will be considered in the next few years is personalizations based on subscriber interests.

PT

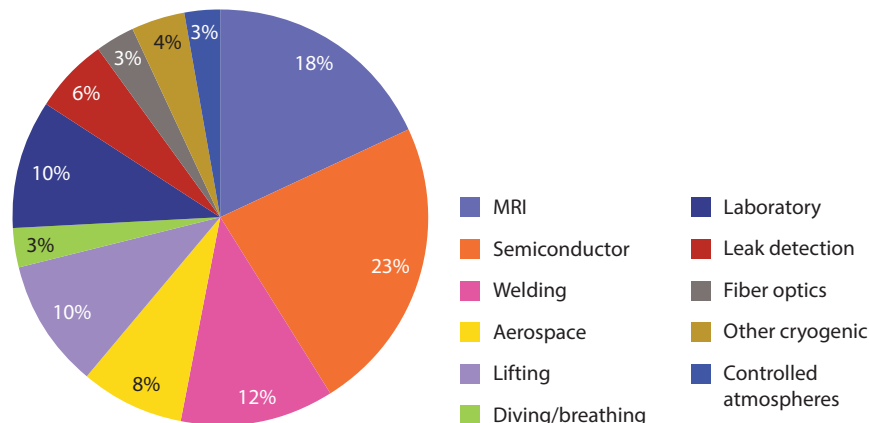
Helium users brace as shortages begin

Recycling systems are keeping many researchers afloat as prices rise and some suppliers ration helium.

By **Toni Feder**

“We hope we are cushioned this time,” says Jeffrey Filippini, who, as associate head for facilities, oversees the helium liquefier for the physics department at the University of Illinois Urbana-Champaign. His department was lucky to accept a delivery of helium in February, just before the US and Israel attacked Iran. Now, with liquefied natural gas plants shut down in Qatar and the Strait of Hormuz nearly unpassable as of press time, it may be a while before helium is again predictably available.

Qatar supplies about 30% of the global helium market. The other main sources are Algeria, Russia, Ukraine, and the US. Helium is obtained primarily as a byproduct



▲ Worldwide helium consumption by usage area for 2025. Semiconductor manufacturing has surpassed medical MRI as the largest consumer of helium. Low-temperature physics, chemistry, biomedical, and other research represented about 10% of the total use. (Chart adapted from Kornbluth Helium Consulting.)

from natural gas processing. “A significant amount of the world’s helium comes from places that are not geopolitically stable, which makes it

susceptible to ‘black swan events,’” says helium market consultant Phil Kornbluth. “The war in the Middle East is a classic example.” (For a



◀ A 22.3-tesla NMR magnet at the Technical University of Munich vents its helium in February 2024 after part of the superconducting coil became resistive. Often, the rate and volume of gas escape in such quenches are too large for recovery systems to handle; in the case shown, the gas could have filled a small blimp. (Photo courtesy of Matthias Brandl.)

report on a recent helium crisis, see *PT*'s 2023 story "Helium prices surge to record levels as shortage continues.")

Semiconductor manufacturers and medical imaging facilities are the largest users of helium (see chart on page 17), and they are at the top of the pecking order for allocations, Kornbluth says. Researchers are lower down in priority, along with party balloon sellers. Applications for helium include cooling superconducting magnets for NMR materials studies and, in Filippini's case, cooling balloon-borne detectors for studying the early universe.

The helium deficit will be most severe during the next few months, before other sources can be integrated into the global supply, says Kornbluth. Even when the conflict subsides and the Strait of Hormuz reopens, he says, it will take months to get liquid natural gas and helium production back up to capacity.

After previous helium crises, many institutions invested in equipment to recycle helium. Where they could, researchers also switched to mechanically cooled systems that don't consume liquid helium. "Driven by prices and the choking off of supplies, there have been changes in technology," says Stuart Brown, chair of physics and astronomy at UCLA. "We are buying a small fraction of helium compared with what we would have bought 5 or 10 years ago."

But recycling systems and alternatives to liquid helium are not compatible with all experiments: Such helium-saving systems are too heavy for balloon studies, and their vibrations interfere with measurements using scanning tunneling microscopes and high-field NMR spectroscopy. They can also be pricey and power hungry. As a result, many researchers still need helium for their work.

Reduce, recycle, stockpile

Many researchers and facilities managers tell *Physics Today* that they are not "yet" having difficulty obtaining helium. They point to protection through recycling, stockpiling, and existing long-term contracts with suppliers. "The time scale for response in the market as we see it as users is quite long," says William Halperin, physics professor and cryogenics facility director at Northwestern University.

Early in the war, Messer, an industrial gas company that supplies Halperin's facilities, raised prices by about 14% to more than \$31.70 per liter. Halperin says he is concerned that Messer will declare force majeure, a suspension of contract that often results in buyers having to pay more to secure helium from other suppliers.



◀ Apala Chaudhuri places clinical samples into Olaris's NMR spectrometer. Any interruption in helium would translate to an interruption in patient care, CEO Liz O'Day says. (Photo courtesy of Liz O'Day.)

ing the stable operation of these shared facilities and strengthening their infrastructure and support systems have become urgent priorities." He notes that Japan will likely become more dependent on the US for helium imports.

Liz O'Day hasn't felt the effects of a helium shortage yet. But if it comes to that, patients will suffer, she says. Her company, Olaris, uses NMR for discovery and clinical diagnostics, including measuring metabolites in the urine of donor-kidney recipients to non-invasively evaluate the health of their grafts. Helium is essential, O'Day says. "Any disruption would cause a pause in our work." She has not installed helium recovery equipment because of the up-front cost and the required space. But the current shortage has her thinking about "scalability and sustainability."

In past helium shortages, researchers have been known to leave a dewar of helium outside on a loading dock, and the dewar "would be 'magically' removed and taken to someone across town to save a magnet that was about to run out of helium," says Hayes. "There are also stories of buying helium gas from a welder and taking it to a liquefaction system to save someone's magnet," she says. "The research community looks out for each other."

"I am hearing of allotments being cut in half, and prices are all over the map," says Sophia Hayes, vice dean of graduate education and a chemistry professor at Washington University in St Louis. "The uncertainty is highly distressing for researchers."

Other helium users in the US and abroad report similar uncertainty. At the Athinoula A. Martinos Center for Biomedical Imaging at Massachusetts General Hospital in Boston, a magnet used for preclinical imaging of rodents will have to be shut down if the center can't get helium, says Jerome Ackerman, a scientist there who also looks after helium. The center's helium supplier, Linde, declared force majeure and said that for now, it cannot provide any liquid helium to the center, Ackerman says.

In February, the UConn Health NMR facility acquired a second-hand NMR machine from the Leibniz Research Institute for Molecular Pharmacology in Berlin. "We need about 2000 liters to cool this thing down," says facility director Jeffrey Hoch. The university's supplier sources helium from Qatar and declared force majeure. Hoch says that he and his colleagues found an alternative source but will pay twice the price.

Yohei Miyanoiri, of the Institute for Protein Research at the University of Osaka, says that facilities in Japan that lack reliquefying systems "have increasingly been forced to shut down their experimental instruments." Consequently, he says, research has become concentrated at user centers such as his. "Ensuring

PT

Q&A: Ken Ono feared AI. Now he trains it

The mathematician wants AI to help researchers focus on creativity.

By **Jenessa Duncombe**

“Am I doing a better service to science by writing 20 more papers that only people in my field will read or by participating in this movement?” Ken Ono asked himself last year. At the time, Ono was an endowed chair at the University of Virginia. In the following months, he’d take a leave of absence from the university, move to Silicon Valley, and become the founding mathematician at an AI startup, Axiom Math.

Axiom is one of several companies focused on developing AI tools to verify mathematical proofs. In the future, similar tools could be applied to check AI-generated computer code, a potentially lucrative service now that AI tools can write lines of code faster than any human can debug them. Startups Harmonic and Math Inc as well as Google’s DeepMind are targeting similar AI-powered verification tools.

Axiom has attracted investor attention, reaching a valuation of \$1.6 billion earlier this year. (Ono says that he has shares in the company and that he receives a salary that is similar to his former compensation at Virginia.) His interests, he says, are in helping researchers use AI to think in more-creative ways and across more disciplines.

The following interview has been lightly edited for length and clarity.

Let’s rewind to last year. What were you doing at the University of Virginia?

I have been your prototypical math researcher for around 30 years. My work as a number theorist has been

useful for classical number theory and applied problems. Perhaps the most notable for the *Physics Today* community is that I was one of the main authors in a paper that proved the umbral moonshine conjecture. The conjecture offers a potential road map for understanding the underlying architecture of quantum gravity and string theory. I’ve advised 35 PhD students. In addition to being known for my research, I’m kind of viewed as an ambassador for the mathematics community.

You were invited to a May 2025 conference in Berkeley, California, for FrontierMath, a project supported by the nonprofit research institute Epoch AI. What did you think going in, and what did you learn there?

To be honest with you, I was very skeptical that AI could be useful for research in mathematics. Earlier versions of ChatGPT would say 9.11 was larger than 9.8. Then, last year, these large language models [LLMs] were close to performing at the gold medal-level on International Mathematical Olympiad problems. Many mathematicians took notice and figured we should engage. Our goal at the FrontierMath conference was to assemble a list of 50 very challenging research-level math problems to test AI models.

At that meeting, I discovered that ChatGPT o4-mini had remarkable access to the accumulated knowledge of the fields that I knew well. I could ask it a research-level problem, and ChatGPT might not get the right answer, but it said the right things and it knew the right

papers. If I were talking to a beginning graduate student, it would take three or four months, maybe a year, for our conversation to get to that level. And here, the computers could just do it.

How did you feel about that?

I was depressed last June and July. I was thinking, What is my future in science when my bread and butter seems accessible with just a few keystrokes? The model had read all my papers. I felt like I’d spent 30 years of my life writing them. And let’s face it, the next paper I write is largely a function of what I’ve thought about for the last 30 years.

I took some comfort in the fact that to nail a theorem to finish a paper, there’s a last 3–5% of effort where you really need to bang your head against the wall to either find an elegant new argument or carry out a difficult calculation that an LLM can’t look up. But I was thinking, Has my career come down to finding problems where that’s all I could do?

You have now joined the AI industry. What changed?

At the end of the day, the crafting of solutions in mathematics is 90% of our effort cognitively. Maybe that’s only one-third of the research paper. The other two-thirds is regurgitating or framing what’s already been known to the community. AI can significantly lighten the load in terms of writing lemmas, which are smaller theorems used to prove a bigger theorem, or making sure I don’t miss out on a reference in the literature. Even though LLMs



▲ Ken Ono (Photo by Matt Riley, UVA.)

are well known to hallucinate, I can check their work.

When I finally understood that, I recognized that this is not the end of mathematics. The computer should not be replacing us as scientists, but maybe it's replacing a large part of the heavy lift that was routine to us anyway. When you get to that conclusion, it gives you not only a sign of hope, but it gives you a new mission, a new purpose. That's why I decided to consider roles in Silicon Valley. I had a number of offers, and I ended up in Palo Alto working with one of my former students, Carina Hong.

How is Axiom working on the verification problem?

We are developing tools that can take an informal proof, formalize it in a computer language called Lean, and check if the proof is correct. I'm not advocating that humans be removed

from the adjudication process, but I want this to be a tool that gives absolute confidence that a mathematical statement is or is not correct.

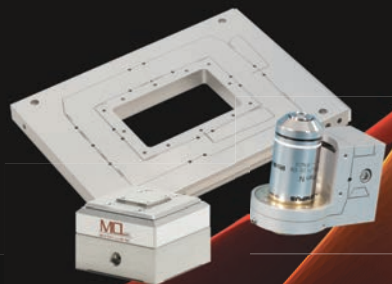
Give us an example of the type of work you do as the founding mathematician.

I'm not an engineer. I can't write the code. But I've been learning quite a bit of what goes on under the hood. Last week, I wrote three internal papers for our engineers. I spend a lot of time thinking about how successful practices in mathematics might translate to executable code. I help engineers understand how mathematicians perform their craft.

In what ways can researchers use AI? And what role does AI play in that collaboration?

There are at least three different kinds of AI that we should talk

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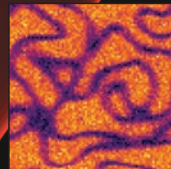


Nanopositioning Systems

Closed Loop, Piezo control
Low Noise, Picometer precision
UHV & Custom design

Micropositioning Systems

Precision motion
Intelligent control = no drift
Nanopositioner compatible



Force Microscopy

MadAFM[®] Multimodal AFM
Resonant Probe AFM
DIY Quantum Microscope

**Single Molecule
Microscopy**

RM21[®] Microscope
Unique MicroMirror TIRF
Adaptable design



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about. First, LLMs today are essentially the most awesome librarians you could ever face. They have access to the accumulation of all human knowledge. They're stochastic parrots. But do you want your librarian to be your neurosurgeon? Although they are very reliable for a large percentage of queries, they make mistakes.

The second kind of AI is verification, and that's a large part of what we're doing at Axiom. How does one know that an informal scientific argument is correct? I like to think of Lean and the formalization part as the math teacher.

The third part of AI is, How do you deploy state-of-the-art machine learning and reasoning and advances in AI to discover or find glimpses of patterns that humans just cannot spot? This is perhaps where AI has hit its home runs in science and academia. An example is Google DeepMind's AlphaFold and its advances in protein folding. In March, we released a tool called Axlplorer, for scientists who are studying mathematical datasets and may be wondering, Maybe there's a needle in the haystack, the glimpse of something, but how do I look for it?

How might these different types of AI apply to the physical sciences?

LLMs could be helpful for every physicist. Verification tools could be useful for folks working on general relativity and in black hole physics who want to ensure that the mathematical foundation of their work is airtight. And discovery AI tools could be indispensable for sifting through petabytes of collision data to identify an important bump in a plot, or for materials scientists predicting new material structures.

Will using AI erode scientists' skills?

If you say, Here's a question, here's the answer, and that's the end of

the story? That's a huge erosion of skills. We've got scientists using AI to publish three times the number of papers as researchers who do not use AI. I don't champion that. When I say AI can amplify and augment scientists, these are not the metrics I'm talking about. I'm talking about asking the deeper questions and having the right to spend more time on the creative part because the bar is lowered not only for the grunt work but also for ease of entry to a field.

In my years in the provost office, one of the things I wanted to do was support interdisciplinary science. How do I get scientists to break out of their silos? One night recently, I was having a hard time going to sleep, and I started engaging with an LLM: "Tell me about who's at Stanford who uses mathematics and neuroscience? Does it relate to anything I do?"

An hour later, I'm reading about new kinds of brain cells that people have discovered that help us navigate. These brain cells are arranged in a virtual hexagonal lattice. I have thought deeply about lattices as a number theorist, never thinking that the same features that excite me as a mathematician are somehow embedded in the brain. I started reading *Scientific American* articles, then *PNAS* articles, and now I'm up to the textbooks in that field. It is exciting to know that in science, we don't have to be siloed.

You mentioned earlier about discovering that ChatGPT had read all your papers. How do you feel about companies feeding your research into models without your permission?

I freely share my research on arXiv, and so I consider it a contribution to the global knowledge commons. I don't mind when it is used in training. However, my commercial books represent a distinct category of intellectual prop-

erty where the rules of fair compensation must apply. One of my books is officially part of the \$1.5 billion Anthropic settlement, which establishes a vital precedent for remunerating creators. It's a step toward a future where AI progress respects the financial and legal rights of authors.

You're a member of the Mathematical Sciences Education Board at the US National Academies. AI is quickly shifting the educational landscape. How can education keep up?

I don't think any of us agree that the current models of education make sense. They are built around traditions that depend on a certification and grades. We live at a time when knowledge has become cheap. The fact that knowledge has become cheap means that we really need to rethink education. What are the tools that we want? I don't accept that manual trades like plumbing are the only safe bets. I think that's cheap. Maybe there is a lot of truth to that. But I think that's giving up on our young people. We still need humans to set the dials and adjudicate in science, law, and policy and any role where human judgment and accountability remain irreplaceable.

If you've had children, you know your daughters and sons would sing out loud, even if they had no talent, because they love music. Where did we lose that? What AI is giving us, when implemented and deployed properly, is a tool for us to expand our creative horizons.

We need a call to action, not just to physics or math professors. This is a call to action to university presidents and provosts. Instead of trying to preserve the current system, act now and prepare for the future, because our young people demand it. Rethink your curriculum so that what is truly human is what we are training.

PT

IAEA tracks unauthorized incidents involving radioactive material

Many thefts occur during authorized transport.

By **Toni Feder**

The International Atomic Energy Agency (IAEA) tallied 4626 incidents from 1993 through 2025 in which nuclear and other radioactive material was not under regulatory control. Such incidents include theft, illegal possession, attempted sale, smuggling, and unauthorized disposal of material.

According to a 23 March fact sheet from the IAEA's Incident and Trafficking Database (ITDB), 359 (nearly 8%) of the reported incidents were likely connected with trafficking or malicious use. The remaining incidents were likely not connected to those motives (68%) or were of undetermined intent (24%).

Over the first roughly 15 years, the number of incidents reported to the agency by 145 member countries trended upward, but since 2007, it's fluctuated around 180 incidents a year. The majority of materials reported as lost, stolen, or missing involved radioactive sources used in industrial, medical, or material-analysis applications.

In the past decade, nearly 70% of reported thefts occurred during authorized transport.

▼ An expert participates in a field exercise on transport security of nuclear and other radioactive material. The course took place in Karlsruhe, Germany, in 2017. (Photo by Dean Calma/IAEA.)



“Nuclear and other radioactive material remains vulnerable to security threats during transport, and data from the ITDB underscores the continued need to strengthen security,” Elena Buglova, director of the IAEA’s division of nuclear security, said in a press release. In more than half the transport-related thefts, the stolen radioactive materials have not been recovered, according to the press release.

Some 14% of the incidents involved nuclear material, including uranium and plutonium; 60% involved other radioactive material; and 26% involved radioactively contaminated or other material. The agency reports a long-term decline in incidents involving nuclear material and an increase in those involving non-nuclear materials. Those trends appear to be associated with improved detection capabilities, reporting practices, and international cooperation in nuclear security, according to the fact sheet.

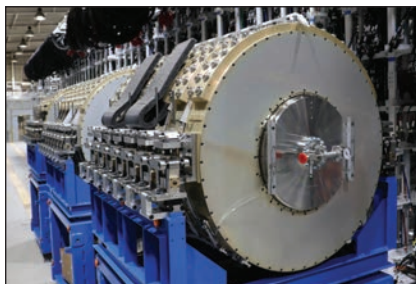
Of reported thefts, nearly 4% were confirmed to be related to trafficking, defined in the ITDB framework as intentional unauthorized movement or trade of nuclear or other radioactive material, in particular with possible or proven criminal intent. Some thefts involved nonradioactive materials, which perpetrators may present as radioactive to deceive prospective buyers.

Most trafficking incidents are opportunistic, “as demonstrated by ad hoc planning and a lack of resources and technical proficiency,” the fact sheet says. But over the past decade, a few incidents have been reported to the agency that appeared “more organized” and “better resourced” and that “involved perpetrators with a track record in trafficking nuclear/radioactive material or other criminal activities.”

Most seizures of nuclear material that potentially could be used in weapons involved gram quantities, but a few—most recently in 1994—involved kilograms. The number of successful sales of nuclear or other radioactive material is unknown, and it is “difficult to accurately characterize an actual ‘illicit nuclear market,’” according to the fact sheet. For cases where a motive was determined, financial gain was a principal incentive.

Among incidents in which there was no trafficking or malicious use, the majority involved unauthorized disposal or shipment of radioactive material or discovery of uncontrolled sources. Examples include radioactive sources being shipped across international borders or entering the scrap metal or waste recycling industries. The latter can result, for example, in the manufacture of goods contaminated with radionuclides, such as cobalt-60.

PT



The Bruno Rossi Fellowship offers a highly competitive salary and up to \$250K in startup funds for:

- Equipment
- Research consumables
- Conference travel
- The opportunity to hire a postdoc, grad student, or research associate

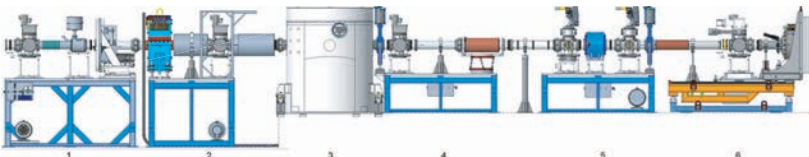
Fellows will also have access to an NNSS mentor and state-of-the-art facilities and technology.



The Nevada National Security Sites is proud to announce the Bruno Rossi Distinguished Postdoctoral Fellowship in Science and Technology, established in honor of Dr. Bruno Rossi, an experimental physicist who developed novel instrumentation to capture extremely fast physics with the limited electronics of his time. This prestigious fellowship aims to inspire the next generation of researchers to drive advancements in national security.

The Bruno Rossi Distinguished Postdoctoral Fellowship is up to a three-year program for recent PhD graduates (within five years of graduation) with expertise in accelerator physics and a passion for applying data science, artificial intelligence, and machine learning to model, control, and optimize complex systems. The Rossi Fellow will be instrumental in developing and demonstrating next-generation capabilities for the Scorpius accelerator and allied radiographic systems.

Specific initiatives include advances in the theory, computational modeling, and/or machine learning applications; strong focus will be placed on computational efforts aligning with electron-beam target interactions and/or other accelerator beam physics.



The Downstream Transport (DST) of the Scorpius accelerator handles critical safety, protection, and diagnostic functions while converting the electron beam to x-rays. Its sections perform debris mitigation (1), specialized beam transport (2), safety stops (3), transport to final focus (4), in-flight imaging and diagnostics (5), and final focusing onto the target (6).

For more information on this year’s Rossi Fellowship and to learn how to apply, scan this QR code.



Trump fires National Science Board

By **Jacob Taylor**

President Trump fired the entire National Science Board (NSB) in late April. The board advises Congress and the president on scientific issues and has traditionally played a major role in shaping NSF policy.

The White House did not formally announce the 22 firings, nor did it initially provide a rationale for them. News slowly trickled out as board members learned that they had been terminated.

Several days after the firings, the White House said the board had been dismissed because of “constitutional questions” raised by a 2021 Supreme Court ruling that limited the power of federal officials who are appointed without going through the Senate confirmation process. The Trump administration contends that the 1950s statute that created the NSB runs afoul of that ruling. “We look forward to working with the Hill to update the statute and ensure the NSB can perform its duties as Congress intended,” a White House spokesperson said.

NSB committee members are scientific experts who are selected by the president and serve six-year terms in a part-time capacity. NSB chair Victor McCrary and vice chair Aaron Dominguez were elected to lead the board last August after former chair Darío Gil left to lead the Department of Energy’s Office of Science.

As of press time, NSF has been without a confirmed director since April 2025 and has shed roughly a third of its staff since the start of 2025. The White House proposed halving the agency’s budget last year, and it has made a similar proposal for the next budget cycle. The proposed cut would also reduce NSB’s budget from \$5 million to \$3 million.

The NSB firings drew swift criticism from Democratic leaders. Zoe Lofgren (D-CA), the ranking member of the House

Committee on Science, Space, and Technology, released a statement implying that Trump may seek to replace the board with “MAGA loyalists who won’t stand up to him.” Maria Cantwell (D-WA), ranking member of the Senate Committee on Commerce, Science, and Transportation, called the firings “a dangerous attack on the institutions and expertise that drive American innovation and discovery.”

Scientific societies, including the Association of American Universities, the American Association for the Advancement of Science, and the Union of Concerned Scientists, also criticized the firings.

White House seeks to stop paying publishing fees

By **Lindsay McKenzie**

The Trump administration’s fiscal year 2027 budget request, released in early April, calls for a “government-wide prohibition on publishing and subscription fees.” The White House says the use of federal funds for “expensive subscriptions to academic journals and prohibitively high publishing costs” should be covered only if “required by Federal statute or approved in advance by a Federal agency.” The administration justifies the ban by saying that “research funded by taxpayers should be publicly accessible; yet many publications charge the Government to both publish and to access the same research study.”

At a mid-April hearing on the budget request, House investigations and oversight subcommittee ranking member Emilia Sykes (D-OH) said that the Trump administration’s proposal for the federal government to stop paying the fees “is an issue in need of a scalpel, and this decree is a sledgehammer.”

Sykes continued, “Cutting federal funds for publishing costs is only going to put a further strain on our

universities and researchers who are already under attack from this administration.” She noted, however, that she has doubts about the fairness of the publishing fees that journals charge. She praised the work of her state and its universities for their negotiated money-saving open-access agreements with major academic publishers.

Republicans on the committee did not weigh in on the proposed prohibition of subscription and publishing fees but expressed dissatisfaction with how the scholarly publishing industry operates. Rich McCormick (R-GA), the subcommittee chair, said that “what was once a straightforward process of peer review and dissemination has become a complex, commercialized marketplace with misaligned incentives and bad actors willing to exploit them.”

Asked by Sykes to comment on the Trump administration’s proposal to stop paying for subscriptions, Carl Maxwell, senior vice president for public policy at the Association of American Publishers, said preventing both federally funded and federally employed scientists from accessing the latest science is “self-defeating.”

Several media outlets reported last year that federal agencies had canceled their subscriptions to some academic journals, including those from high-profile publishers such as Springer Nature.

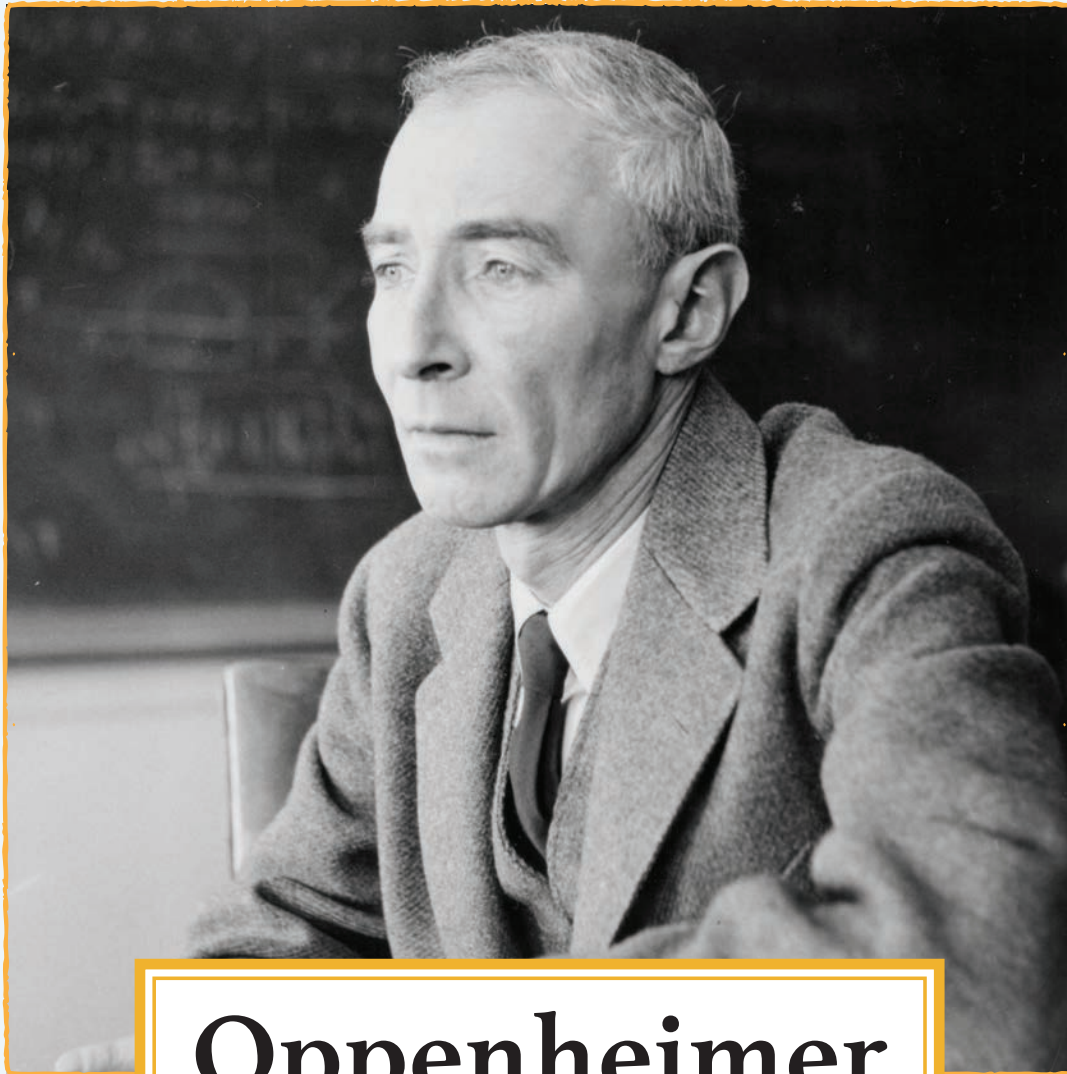
The National Institutes of Health announced last year that it intends to cap the amount it contributes toward publishing costs for NIH-funded research. The agency has declined to say when it plans to announce the details of that policy. **PT**

For up-to-date information on fiscal year 2027 funding for federal agencies that support the physical sciences, visit AIP’s Federal Science Budget Tracker at <https://aip.org/fyi/budget-tracker>. Each agency page has updated spending proposals, program-level budget details, and a timeline of legislative actions. Historical budget data are also available back to FY 2017.

Thomas Kuhn, noted historian and philosopher of science, interviewed J. Robert Oppenheimer as part of a project to document the birth of quantum mechanics. (Undated photo, courtesy of the MIT Museum.)



(Design by Freddie Pagani with artwork adapted from iStock.com artist o-che.)



Oppenheimer reflects on his early career

▲ J. Robert Oppenheimer, circa 1960. (Photo from the AIP Emilio Segrè Visual Archives, *Physics Today* Collection.)

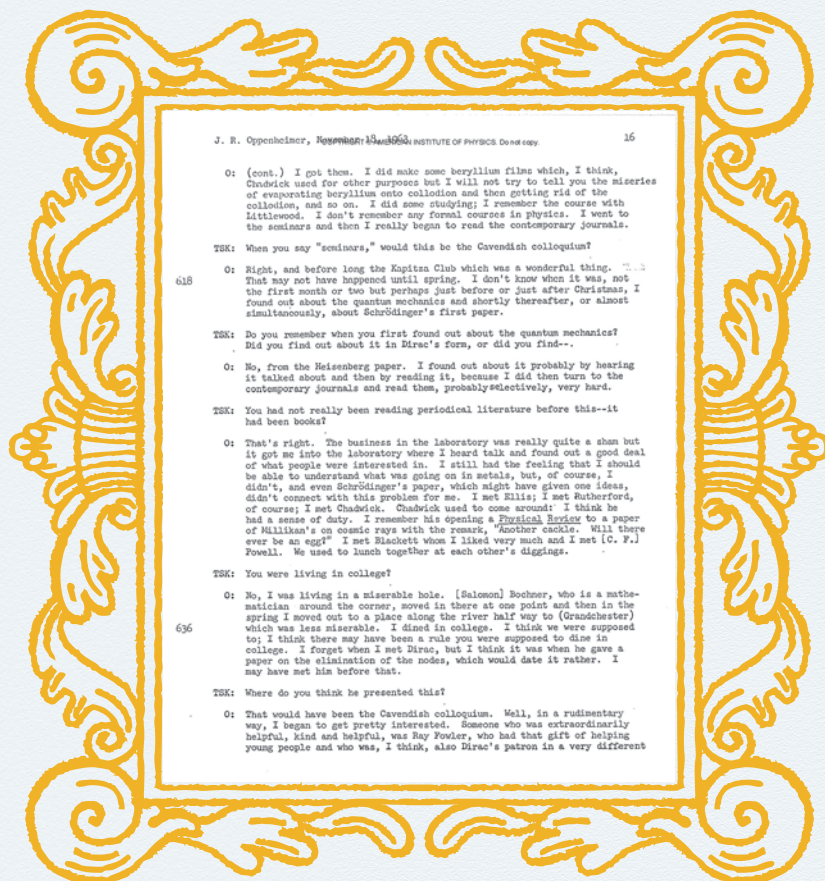
By Ryan Dahn

Interviews now available to the public bring the famed physicist's lesser-known early years to life.

On 18 November 1963, J. Robert Oppenheimer sat down at the Institute for Advanced Study in Princeton, New Jersey, for the first session of a two-part interview with historian and philosopher of science Thomas Kuhn; the second session was two days later. The historian had come not to interview Oppenheimer about his role in the Manhattan Project but to record his memories of a dynamic period in the history of physics that was beginning to fade from collective memory: the discovery of modern quantum mechanics in the 1920s. (For more on the field's origins, see the April 2025 *PT* article “Demythologizing quantum history.”)

The previous year, Kuhn had published what would prove to be his most famous work, *The Structure of Scientific Revolutions*, in which he posited that scientific fields occasionally undergo revolutions in thought, which he termed paradigm shifts. Seeking to establish an empirical basis for his theory of scientific development,¹ Kuhn had agreed in 1961 to lead the massive NSF-funded project called Sources for History of Quantum Physics, which sought to interview all the major players active in quantum physics from 1913 to 1938 who were still living at the time, with a heavy emphasis on those who participated in the quantum revolution of the 1920s. Oppenheimer was one of about 95 individuals whom Kuhn and two of his then-graduate students, John Heilbron and Paul Forman, spoke with between 1962 and 1964.

Those interviews were transcribed and assembled along with a considerable amount of contemporary correspondence, lecture notes, and miscellaneous materials into a microfilmed collection. Known as the Archive for the History of Quantum Physics (AHQP), it was made available at several international institutions to “bona fide scholars and students working under their supervision.” (One of the institutions was the Niels Bohr Library & Archives at the American Institute of Physics, which publishes *Physics Today*.) Anyone interested in looking at Oppenheimer’s interview faced an additional restriction: They had to seek per-



▲ A page of the original typescript of Oppenheimer's interview with Kuhn in November 1963. (Image from the AIP Niels Bohr Library & Archives.)

mission from his family, a task that for many years involved physically mailing a request to Oppenheimer's son, Peter, at a post office box in New Mexico.

Open access

As of April 2026, Oppenheimer's family and the Niels Bohr Library & Archives (NBLA) have made the Kuhn interview transcript available to the public for non-profit and educational use. (They have also made public two other interview transcripts held by NBLA: one from 1960, about the Manhattan Project and the Trinity nuclear test, and one from 1966, about Enrico Fermi. For more on those interviews, see the two sidebars.) Because the family had allowed scholars to look at the Kuhn transcript, it was often a crucial source for authors writing about Oppenheimer's early years. Kai Bird and Martin Sherwin's 2005 biography, *American Prometheus: The Triumph and Tragedy of J. Robert Oppenheimer*, which served as the basis for Christopher Nolan's 2023 biopic, *Oppenheimer*, made countless references to the interview in the early portion of the book. But the 1963 transcript remains an intriguing source worthy of examination:

J. Robert Oppenheimer, I. I. Rabi, Harold Mott-Smith, and Wolfgang Pauli (from left) sailing on Lake Zurich in Switzerland in 1929. (Photo from the AIP Emilio Segrè Visual Archives, Fermi Film Collection.)



It is one of the few examples of Oppenheimer reflecting at length about his early life.

New to all but what was almost certainly a small number of researchers, though, are the audio recordings of Kuhn's interview with Oppenheimer. They are now available on NBLA's website thanks to the efforts of the Philadelphia-based American Philosophical Society, one of the two sponsors of the Sources project and the primary repository for the audio materials from the AHQP. Made on a suitcase-sized tape recorder that was state of the art at the time, the recordings were originally preserved on two 7-inch reel-to-reel tapes at NBLA. They were then remastered onto 10-inch reels for preservation in 2003, when the American Philosophical Society took possession of them.

Unfortunately, the first of the original tape reels seems to have been damaged before it was transferred. At two points that coincide with the beginnings of each side of that reel, the recording is extremely distorted—to the point where it's only barely possible to make out what's being said—for approximately 13½ minutes, at which point the sound suddenly snaps into focus. That's not unexpected, because the medium wasn't intended to last forever, and the beginning part of a tape, which is more exposed on the reel in storage, tends to degrade more quickly than the end. (The digitized audio that NBLA has made available was copied from the preservation

reels onto cassette tape by the American Philosophical Society, which is currently applying for a grant to restore the original interview reels.)

But most of the roughly four-hour interview remains listenable, and the audio recordings bring Oppenheimer to life in a way a transcript never could. All the inflections of voice and interruptions are audible, as is Oppenheimer's peculiar manner of speaking. You would be hard-pressed to find anyone today who talks like he did. One can detect a trace of the mid-Atlantic accent—an affected manner of speaking that was briefly popular with the US elite (and golden-age Hollywood actors, such as Cary Grant and Katharine Hepburn) in the early to mid 20th century—in the highly enunciated way in which Oppenheimer finishes words that end in a consonant, especially the letter *t*. It's probable that he learned to speak like that at the Ethical Culture School in New York City, which he attended from the age of seven until he graduated high school in 1921.

Just as striking is the exceptionally slow speed at which Oppenheimer speaks in conversation. Concomitant with that are the extended pauses he takes in conversation, when he is presumably forming a thought. Several empty seconds could easily go by on the tape—he certainly wasn't afraid of the proverbial awkward silence. The accent, slow manner of speaking, and long pauses add gravitas to Oppenheimer's speech: He comes off as a rational, careful, and deliberate thinker—all



▲ Oppenheimer on Caltech's campus in 1930. (Photo from the Caltech Images Collection.)

qualities that in popular culture are associated with a genius.

One final aspect of the interview is also made immediately apparent by the audio: the thick cloud of cigarette smoke that must have been omnipresent. Both Oppenheimer and Kuhn have the gravelly, leathery, sandpaper-like voices of lifelong smokers, and the interview is interrupted on many occasions when Oppenheimer breaks out into massive coughing fits. Both were notorious for their chain-smoking, and both died of tobacco-related cancers.

Spoken and unspoken

Human memory is fallible: One's memory of an event may differ from reality, and one's recollections of the past may change over time. It's for that reason that historians often place more weight on contemporary sources than retrospective interviews. That said, it's interesting to note that many of the stories commonly told about Oppenheimer's early years went unsaid in

his interview with Kuhn. Surviving letters to and from Oppenheimer during those years and later interviews with contemporaries have revealed that he was unhappy and struggled during his time in the UK at the University of Cambridge for the 1925–26 academic year.

But in the interview, he alludes to his unhappiness there only obliquely. He mentions his struggles with the experimental physics he was studying, at one point lamenting the “miseries of evaporating beryllium onto collodion,” and refers to the “troubles of the winter,” which might be a suggestion of his depression.² The only portion where his feelings really come out is toward the end of that discussion, when he reflects on that year: “I had very great misgivings about myself on all fronts. . . . I felt completely relieved of the responsibility to go back into a laboratory. I hadn't been good, I hadn't done anybody any good, and I hadn't had any fun whatever.” Perhaps it's unsurprising that the famous physicist wouldn't have wanted to admit to his past struggles in an interview he knew would help shape the historical record.

The silver lining of his time at Cambridge, as he tells Kuhn, was that there were “many more visitors,” including Paul Dirac, than at Harvard University. Indeed, another main through line of the interview is a window into the pre–World War II era, a time when the US was a provincial outpost of physics and the main centers of activity in the field were in Europe. Oppenheimer was one of the last US physicists who felt it necessary to go to the Old World for doctoral studies to be where the action was happening. As such, knowledge of European languages—particularly French and German—was critical to becoming a top-tier physicist. Oppenheimer mastered both tongues by the time he finished college and quickly began reading cutting-edge scientific literature in those languages. He was, as Kuhn notes at one point, forced to, for “it would have been hard to get much quantum mechanics from old-fashioned or even new-fashioned English texts.”

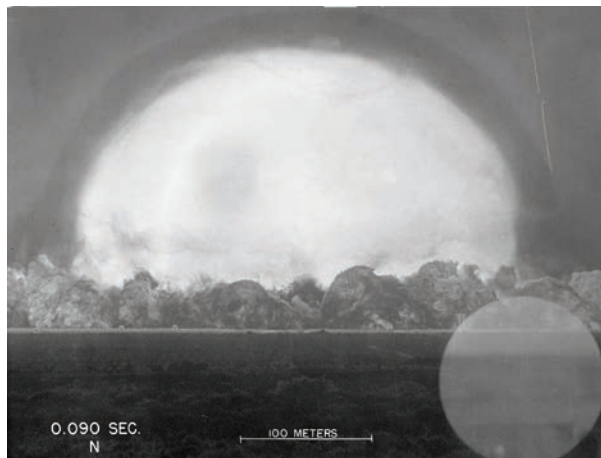
After his disappointing year in Cambridge, Oppenheimer went to the University of Göttingen in Germany to continue his graduate studies under theorist Max Born. There, he got to know a who's who of 20th-century physicists, including Werner Heisenberg, Pascual Jordan, John von Neumann, Gregor Wentzel, and Eugene Wigner. The interview brings

Oppenheimer's recollections of the Trinity test

The first of the other two interviews held by the Niels Bohr Library & Archives (NBLA) is the transcript of a February 1960 interview of Oppenheimer by journalist Robert Cahn, who was conducting research for an article he was writing for *The Saturday Evening Post* on the 15th anniversary of the Trinity nuclear test. The article, "Behind the first A-bomb," appeared in the 16 July 1960 issue of the magazine. Although Oppenheimer was directly quoted only once in it, the interview clearly provided the groundwork for Cahn's depiction of the test. (Interestingly, he was quoted far more extensively in an adapted version of the article that appeared in July 1995 in *The Christian Science Monitor* on the 50th anniversary of the test.⁴)

A copy of Cahn's interview transcript was donated to NBLA in the late 1990s by physicist Albert Allen Bartlett, a professor of physics at the University of Colorado Boulder and a veteran of the Manhattan Project. It's unclear how Bartlett got the transcript, but Cahn moved to Boulder late in life, so perhaps their paths crossed then. The transcript is somewhat mysterious: Cahn's questions to Oppenheimer are transcribed only in an abbreviated manner, presumably to save time, and the transcript appears to have been annotated by both Cahn and Bartlett. The audio of the interview seems to be lost.

The interview focuses on the Manhattan Project and the events leading up to the Trinity test on 16 July 1945. Of



▲ The fireball from the Trinity nuclear test, 90 milliseconds after detonation. (Image reproduced from the National Security Archive.)

particular interest may be Oppenheimer's extended recollections of the "I am become Death, the destroyer of worlds" quote from the Bhagavad Gita that, as he had said on several occasions, came to him when he saw the fireball.⁵ The first documented appearance of the story is in a 1948 profile of Oppenheimer in *Time* magazine, and scattered mentions of it can be found in publications from the early to mid 1950s.⁶ But it was launched to new fame by Robert Jungk's 1958 book *Brighter than a Thousand Suns: A Personal History of the Atomic Scientists*, one of the first popular histories of the atomic age, whose title directly references the Hindu text. (The book originally appeared in German in 1956.)

By 1960, the story was widely known enough that Cahn specifically asks him about it. Oppenheimer's response is especially noteworthy because it appears to be the longest surviving version of the tale that he gave in his own words:

[Cahn:] (Passage which came to mind from Bhagavad-Gita?)

[Oppenheimer:] (Krishna?D)] Vishnu was trying to convince Argina [*sic*, Arjuna] who started out as a pacifist that a man must do his duty and that his soul is good, it is affected by whether he does his duty but not by whether he does harm. Real harm cannot be done by man. And this goes on for 30 chapters. And at one point he assumes his most awful form and says to Argina "I am become death the destroyer of worlds." And this is the line that came to mind. And when he is all through with that, he then goes back and says, "Now I have resumed my normal fore-armed [*sic*, four-armed] form." And I remember it always because I read it with a student at Berkeley who said to me the first time, "I suppose that's how a young man feels when he is behind the wheel of a powerful car."

This came to my mind (the line from Bhagavad-Gita) when I saw the light of the bomb. I was turned away from it, at the left of the door, looking out toward Mockingbird Gap. It was much brighter than sunlight, it had a golden quality. The first evidence that I had that something had happened was that the whole desert lighted up in the most brilliant golden light, and that's all.⁷

the vibrancy of that community to life. "In the sense that had not been true in Cambridge and certainly not at Harvard," Oppenheimer says to Kuhn, "I was part of a little community of people who had some common interests and tastes and many common in-

terests in physics. I remember this more than I do lectures or seminars. . . . Gradually, I guess, they gave me some sense and, perhaps more gradually, some taste in physics, something that I probably would not have ever gotten to if I'd been locked up in a room."

Oppenheimer on Fermi

On 1 November 1966, four months before he died of throat cancer, Oppenheimer was interviewed on camera by Charles Weiner, the first director of the American Institute of Physics's Center for the History of Physics, as part of a documentary being made about Enrico Fermi. Made under the auspices of Harvard Project Physics, which aimed to reform high school physics curricula by introducing the discipline's history into classroom instruction, the 46-minute documentary, titled *The World of Enrico Fermi*, came out in 1970 and has long been available on sites such as the Internet Archive.

But as is the case with most documentaries, the vast majority of Oppenheimer's 36-minute interview did not make it into the final cut. Along with other materials involved with the making of the documentary, the raw footage was deposited at the Niels Bohr Library & Archives, and it is now also available to the public online, along with the full transcript of the interview. Although many of Weiner's questions are clearly aimed to elicit responses



▲ J. Robert Oppenheimer being interviewed about Enrico Fermi. (Image from the AIP Niels Bohr Library & Archives, Harvard Project Physics Collection.)

that would be of interest to high schoolers, it's still noteworthy to hear Oppenheimer's thoughts on one of his fellow physicists. Of note are his lengthy reflections on Fermi's role in the establishment of what one would now term Big Science:

I would say that the next thing which made a very big difference to the profession of physics was that he was the first to use adequate analytic quantitative techniques of measurement in the high energy physics domain. And this—when he first had an operating accelerator, he didn't begin, as some colleagues have been known to do, by letting the beam hit various things and reporting, would [*sic*, with] wonder, what all happened, but he began by studying the nature of the various beams he could produce, and really got a controllable source of mesons, positive and negative. Then he didn't scatter the mesons on brass and sealing wax, but on hydrogen, which was a great help from the point of view of theoretical understanding. . . .

The first thing he discovered was that [*sic*, a] large scattering, in the state of larger isotopic spin common to like and unlike nucleons, and quite marked, which was very soon recognized by theorists as related to one means of approximately describing meson–nucleon interactions—the so-called strong coupling theory, which was started before the war, at least before this country was in the war. And this really gave a new point, a new lead and a new vigor to the theoretical description of strong interactions, and also set an example, a paradigm of what to do with accelerators. . . .

So, although it could have happened in other ways, in fact Fermi was the first person to found modern high energy physical techniques in the laboratory.⁸

In the portion of the interview about Göttingen, too, much goes unsaid. In particular, Oppenheimer seems unwilling to talk about—or unaware of—his reputation as a disruptive student in the classroom. Born related in his autobiography that Oppenheimer would interrupt speakers—including Born!—take the chalk, and begin instructing the class at the blackboard as to how things should be done. A group of students that included Maria Goeppert Mayer got fed up with Oppenheimer's antics and insisted that Born rein in the young prodigy or they would boycott the class. Born managed to finesse the situation by leav-

ing their written list of grievances visible when Oppenheimer stopped by to discuss his thesis.³

But one can detect a bit of that arrogance when Kuhn asks Oppenheimer about the most famous product of his time in Göttingen: a paper coauthored with Born that presented what is now known as the Born–Oppenheimer approximation, which assumes that the wavefunctions of nuclei and electrons in molecules can be determined separately. As Oppenheimer tells Kuhn, he came up with the initial idea and wrote up a four- or five-page draft, which he sent to Born over a holiday break. But Born was “completely horrified” by the brevity of the paper

Oppenheimer had drafted and “said that he would write it up properly.” As Oppenheimer continues:

He produced this thing which must be thirty pages long but which has nothing else in it except a few theorems which are fairly obvious, the mean of the average or the average of the mean are sometimes equal, and so on. I didn’t like it, but it was obviously not possible for me to protest to a senior author. . . . That’s the origin of the dull opus. I think I probably had nothing to do with the writing of the long paper; I may have changed a few things, put in a sentence or taken out a sentence, but certainly very minor, and it was certainly not something that was comfortable between us. It was obviously a rather deep difference of taste which was not something you could argue about.

It’s a funny way to describe the paper that remains Oppenheimer’s most cited work.

Learning how to teach

After spending time during the 1928–29 academic year in Leiden, the Netherlands, with Paul Ehrenfest and in Zurich, Switzerland, with Wolfgang Pauli, Oppenheimer returned to the US permanently in 1929 and took a job at the University of California, Berkeley, that also allowed him to teach at Caltech. In that dual role, Oppenheimer became a crucial apostle of the quantum gospel in the US—and thus a key figure in the country’s development as a global physics center. His reflections on that time teaching in California in the 1930s forms one of the other main threads of the interview—and include some of its most introspective moments.

As he tells Kuhn toward the end of the interview, he went from “a person who had been learning and also explaining in European centers . . . to someone who couldn’t much any longer learn from masters but could learn from the literature and from what he did himself; one who had a lot of explaining to do because there was no one else.” Indeed, because quantum theory was so advanced at the time, his course was typically taken by second-year graduate students; today, quantum mechanics is a standard part of the second-year undergraduate curriculum. As he recalls: “I found myself entirely in Berkeley and almost entirely at Caltech as the only one who understood what [quantum mechanics] was all about. . . . I didn’t start to make a school; I didn’t start to look for students. I started really as a propagator of the theory which I loved, about which I continued to learn more, and which was not well understood but which was very rich.”

But, Oppenheimer admits, he was initially “a very

difficult lecturer.” Over time, though, as he built stimulating connections with experimentalists on both campuses and the quality of the graduate students began to improve, so, too, did his teaching. His feeling of responsibility toward both his colleagues and the students helped make physics in California flourish. As he tells Kuhn: “I wasn’t an apprentice any longer. . . . I was interested in spreading this part of physics and was really rather widely interested in physics as a whole. . . .

“In a certain sense I had not grown up but had grown up a little.”

Thanks to Alex Wellerstein and Will Thomas for valuable comments that helped shape this piece and to Allison Buser, Elizabeth Wood, and Karina Cooper at the Niels Bohr Library & Archives for tirelessly answering my many questions about the Oppenheimer interviews and their provenance.

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For audio and video clips from the Oppenheimer interviews, visit <https://doi.org/10.1063/pt.30750840bf>.

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FROM THE ARCHIVES
October 1967





The Princeton period

Abraham Pais

Editor's note: This article, on J. Robert Oppenheimer's tenure as director of the Institute for Advanced Study, appeared in a special issue on Oppenheimer that was published shortly after his death.

An aerial view of the Institute for Advanced Study in Princeton, New Jersey, in an undated photo. (Photo from Princeton University, courtesy of AIP Emilio Segrè Visual Archives; design by Masie Chong with artwork adapted from iStock.com artist darkbird77.)

In September 1946 the American Physical Society met in midtown Manhattan. In the minutes of this meeting we read that it “was confined to papers on three topics: cosmic-ray phenomena, theories of elementary particles and the design and operation of accelerators of nuclear particles and electrons. Disparate as these three subjects may appear to be, the trend of physics is rapidly uniting them.”¹

Of that meeting, I have two vivid memories. The first one, being introduced to Robert Oppenheimer by Henrik A. Kramers and discussing with him the problem of radiation reaction on the scattering of an electron in an external field, a subject in which Oppenheimer and Bethe were actively interested at the time;² the second one, meeting Isidor I. Rabi for the first time, who at once fired the question: “Do you think the polarization of the vacuum can be measured?” I remember my amazement at a country where experimentalists would know, let alone bother, about vacuum polarization. For this was my first week in the United States. Thus I write as one of those who, because of age, geography or other reasons, did not meet Oppenheimer until after the war. That first week was a preview of things to come.

In January 1947 Oppenheimer gave the Richtmyer lecture at the New York American Physical Society meeting, entitled “Creation and Destruction of Mesons.”³ In this lecture he reported on the first results obtained with the 184-inch Berkeley cyclotron. He then went on to discuss the soft component of the cosmic rays that originates within a few radiation lengths from the top of the atmosphere and suggested that this component derives from the decay of neutral mesons. This pioneering remark on the role of π^0 mesons he made again in a subsequent paper⁴ on multiple-meson production.

After the talk he invited me for a drink in a Broadway bar where he told me that he had been offered the directorship of the Institute for Advanced Study in Princeton. He accepted this post in April and thus became the institute’s third director and the first to hold this position concurrently with a professorship there.

That spring, I saw Oppenheimer for the first time in full action. Early in 1947 it was suggested from various sides that a number of small panel conferences be held in the various branches of science. Their purpose should be to

review recent developments and discuss possible avenues of progress. Under the auspices of the National Academy of Sciences, and with the support of the Rockefeller Foundation, the first such conference in physics took place on 2–4 June 1947, on Shelter Island, New York. For this meeting Oppenheimer wrote the outline of topics for discussion entitled “The Foundations of Quantum Mechanics.” As was to happen so often in the following years, Oppenheimer showed himself to be the threefold master: by stressing the important problems, by directing the discussion and by summarizing the findings.

Mesons and cosmic rays

In his outline he discussed the copiousness of meson production in cosmic radiation in terms of meson theories then current and concluded that “no reasonable formulation along this line will satisfactorily account for⁵ the smallness of the subsequent interaction of mesons with nuclear matter.” In the discussion of this point, Robert E. Marshak got up to propose that there should be two kinds of mesons.⁶ It was, one may recall, in September of that year that Cecil F. Powell reported the discovery of π - μ decay at a Copenhagen conference.

The Shelter Island conferences witnessed the opening of a new chapter in quantum electrodynamics. Two of the men who played a leading role in this development were associated with Oppenheimer in the Berkeley days.

One of them, Willis Lamb (Berkeley PhD, 1938, with Oppenheimer) gave an account of the early results of the Lamb–Retherford experiment⁷ that indicated an upward shift of about 1000 MHz for the $2^2S_{1/2}$ state of hydrogen as compared with the prediction for a single particle in a Coulomb field. Rabi reported⁸ on a deviation in the hyperfine structure of hydrogen and deuterium that was soon to be attributed quantitatively by Julian Schwinger (research associate at Berkeley from 1940 to 1941) to an anomaly of the magnetic moment of the electron.

Immediately Oppenheimer emphasized that here one might have to work with self-energy effects. Small wonder. As Serber wrote, already in 1930 he had been concerned⁹ with atomic level displacements due to radiative effects. In 1934, Dirac¹⁰ and independently Wendell H. Furry and Oppenheimer¹¹ had noted “that the

charge of the electron defined in the usual way is not the true charge” (charge renormalization) and that there should be deviations from Coulomb’s law, a point taken up further by Edwin A. Uehling and by Serber. Here was also the answer to Rabi’s question of a few months ago: Whatever one was measuring, it was not exclusively the “Uehling terms” because these by themselves give an effect that is much too small and of the wrong sign. As is known, the electromagnetic nature of the Lamb shift became evident soon after the conference took place.¹²

At the institute

In the late summer of 1947 Oppenheimer and his family moved to Princeton, and a new era began at the Institute for Advanced Study.

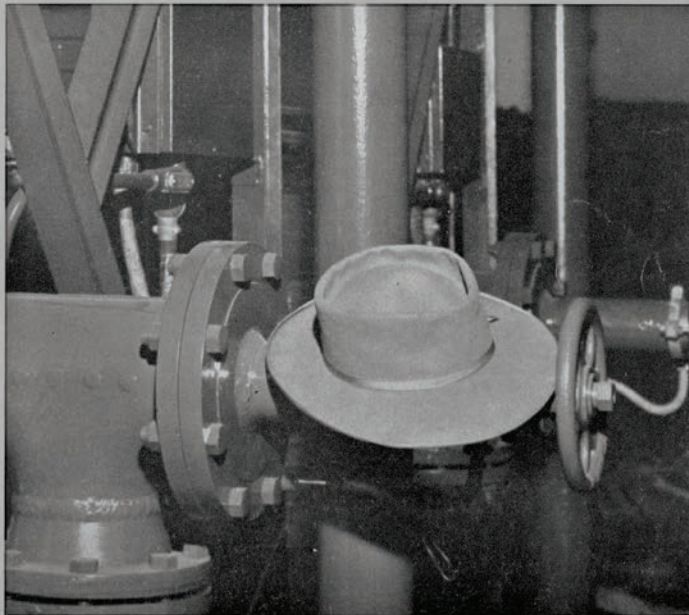
Physics had been represented at the institute since its inception—the first two professors appointed in 1933 were Oswald Veblen and Albert Einstein. Bohr and Dirac had been frequent visitors, and Pauli spent the war years there. In addition, a score of other physicists had worked at the institute at one time or another. But upon Oppenheimer’s arrival a function and quality of the institute developed which, for reasons to be profoundly respected, had not been there before. It became a center for physics.

Once again Oppenheimer’s outstanding talent for assembling the right people and stimulating them to great effort was the decisive factor. Regular periods of residence for eminent physicists have continued to play an important role in the life of the institute. But from the very start Oppenheimer brought to physics at the institute a new emphasis on youth. In fact, on his arrival in Princeton, five



▲ Postwar conversations in 1946 with (top) Gregory Breit of Yale University and (bottom) Victor Weisskopf of MIT.

PHYSICS *today*



TRENDS IN AMERICAN SCIENCE by Vannevar Bush See Page 5

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▲ Ubiquitous symbol. The cover of *Physics Today* (volume 1, number 1) shows the 184-inch Berkeley cyclotron with Oppie's familiar porkpie tossed on it.

research associates from Berkeley came with him as the first temporary physics members in the new style. The first physics paper to come out of the institute after he took over is an application of mass renormalization by one of these associates.¹³ It deals with the same aforementioned problem that Oppenheimer had worked on himself in collaboration with Bethe. This is characteristic for the continuity as well as for the transition in Oppenheimer's activities. For from then on, his principal activity was not so much his own research. Rather it was to be, in the original meaning, a director of physics.

A director, rather than a teacher in the conventional sense, for there is no such teaching at the institute. To be sure, we had our seminars. They were lively—sometimes very lively. And Oppenheimer's sharp insights played a major part in making them so. Yet Oppenheimer's main contribution to the work and the style of the institute was not merely the conducting of a seminar. His influence was far more important, more subtle perhaps but no less enspiriting. He could convey to young men a sense of extraordinary relevance of the physics of their day and give them a sense of their participation in a great adventure, as for example in the Richtmyer lecture: "There are rich days ahead for physics; we may hope, I think, to be living in one of the heroic ages of physical science, whereas, in the past, a vast new field of experience has taught us its new lessons and its new order."¹⁴ He could define and thereby enhance their dedication, by words such as these: "People who practice science, who try to learn, believe that knowledge is good. They have a sense of guilt when they do not try to acquire it. This keeps them busy. . . . It seems

hard to live any other way than thinking that it was better to know something than not to know it; and that the more you know the better, provided you know it honestly.”¹⁵

To an unusual degree, Oppenheimer possessed the ability to instill such attitudes in the young physicists around him, to urge them not to let up. He could be critical, sharply critical at times, of their efforts. But there was no greater satisfaction for him than to see such efforts bear fruit and then to tell others of the good work that someone had done.

Quantum electrodynamics

Oppenheimer again gave much drive to the two sequels to the Shelter Island conference. There was the Pocono Manor Inn conference (30 March to 1 April 1948) at which Schwinger gave an 8-hour marathon talk, and Richard P. Feynman’s contribution was not yet fully appreciated. At the very time of this conference Sin-itiro Tomonaga sat down in Tokyo and wrote to Oppenheimer (letter dated 2 April). In this important letter, Tomonaga gave an account of the independent progress that had been made by him and other Japanese physicists toward a “self consistent subtraction method,” or as we now say, the renormalization method. The Old Stone on the Hudson meeting (11–14 April 1949) also had experimental and theoretical refinements of electrodynamics as a main theme, and at that time Feynman’s diagrams were understood. This was the third and last of the precursors of the Rochester conferences.

Meanwhile, in the years of which I now speak, the late forties and early fifties, Oppenheimer had become known widely as a principal representative figure of the natural sciences. Thus when in 1948 the American Institute of Physics inaugurated a new journal, *Physics Today*, the dialogue between theory and experiment was symbolized on the cover of its first issue by a picture of a porkpie sombrero tossed on a cyclotron. When in 1950 the *Scientific American* devoted an issue¹⁶ to summarize that incredibly full half-century in science, 1900–50, it was fitting that Oppenheimer should write its general introduction.

Poet and physicist

In this introduction, Oppenheimer for once talks about himself, something he did only rarely. All

those whose lives have been enriched for having known his warmth and his friendship, as has mine, had to know Robert’s uncommonly strong protective sense of privacy that was sometimes mistaken for an inner aloofness. In any event, in the introduction just mentioned, he tells how, twenty years earlier, Dirac had taken him “to task with characteristic gentleness. I understand [Dirac had said] that you are writing poetry as well as working at physics. I do not see how you can do both. In science we say something that no one knew before in a way that everybody can understand. Whereas in poetry ...”

Oppenheimer’s physics papers were the real stuff; no poetry there. Yet, as is familiar to all who knew him and as can also clearly be seen in his more reflective writings, it is an integral part of the Oppenheimer style that he had more than a touch of the poet. He was a master of the language.

For many of us it was a joy to hear him discuss or paraphrase a subject, especially if the subject was somewhat familiar, for Oppenheimer’s discourse was not for beginners. But to some his style was alien. It is too simple to say that Oppenheimer polarized his surroundings, but it is true that the reactions that he evoked were never bland.

I must now briefly but sharply interrupt the main line of this account to mention events that have affected all of us, though certainly not all of us equally.

Security

On Sunday, 11 April 1954, a major newspaper ran an article whose title read in part: “Next target: the leading physicists.” It was the first intimation to the world at large of a coming ordeal that had long been expected and that would be in the public domain the very next day. I shall now relate something of the impact of these tense months on life at the institute.

The institute as such has never been asked to accept nor has it ever sought a classified contract.¹⁷ Clearly, therefore, the tumult of those days did not affect the nature of the work done there. It will be equally clear that these happenings dampened the spirit at the institute even more than it did at many other centers. On 14 April chairman Herbert Maass of the board of Trustees announced that Oppenheimer would continue as director. Yet there was reason for



▲ Day of rest. Oppie relaxes with his sister-in-law, Mrs Frank Oppenheimer, and Dorothy McKibbin, one of Project Y's first employees.

uncertainty about this, because the directorship of the institute is an appointment that needs a formal vote of renewal each year. Fortunately this concern turned out to be unfounded.

Before the final decision, the council of the American Physical Society issued a statement on 13 June through its president Hans A. Bethe, in which they stressed that the turn of events might “prevent the development of the best thought.” *[Editor’s note: See page 44 for more on APS’s preparation of a statement.]* After the final ruling had been made, a



formal statement was issued by all twenty-six permanent members and professors emeriti at the institute, of which I quote the following part:

“Dr Oppenheimer has performed for this country services of another kind, more indirect and less conspicuous but nevertheless, we believe, of great significance. For seven years now he has with inspired devotion directed the work at the Institute for Advanced Study, for which he has proved himself singularly well suited by the unique combination of his personality, his broad scientific interests and his acute scholarship. We are proud to give public expression at this time to our loyal appreciation of the many benefits that we all derive from our association with him in this capacity.”*

While I speak as one of the many who think at this moment of a man treated with gross injustice, as one of the many who deeply respect the stand of Harry Smyth, even so this is not the evening to relive our own anguish. Let us rather remember that in spite of other serious responsibilities that had to be part of his destiny, Oppenheimer’s foremost devotion was always to physics. As he put it himself sometime later: “we have, all of us to preserve our competence in our own professions, to preserve what we know intimately, to preserve our mastery. This is, in fact, our only anchor in honesty.”¹⁸ Thus it was a comfort to him that physics flourished at the institute in these years. Of this I shall now continue to tell.

In some old notes from the Pocono Conference I found these comments. By Oppenheimer: “Now it doesn’t mat-

ter that things are infinite.” By Rabi: “What the hell should I measure now?” They reflect the sense of optimism of the late forties, especially the expectation that with the new theoretical tools other than electromagnetic interactions would soon give sensible results.

Subnuclear research

The mood and the scene changed drastically in the fifties. It was soon clear that hydrodynamics would not yield as readily to the degree that electrodynamics had. At the same time a whole new world of particles and interactions began to unfold. I do not recall any mention, at Pocono or Old Stone, of the original cosmic-ray findings of George D. Rochester and Clifford C. Butler. But it was not long before vast efforts began to penetrate the subnuclear world, by experimentalists with newly available accelerators and by theorists who attempted to find new rules if not laws to cope with the extended vista of strong, electromagnetic and weak interactions.

And so we witness in the fifties two main theoretical approach marches. First, the development of a much needed new phenomenology. Secondly, a reconsideration of the foundations of field theory and a search for new methods to cope with situations in which, if not field theory, then at least-power series expansions appear to fail.

It is in this period that theoretical particle physics became largely separate from theoretical nuclear physics. The pioneering developments in this new field are most closely associated with work done at the institute in the Oppenheimer era. Other subjects such

* This statement was signed by: James W. Alexander, Julian H. Bigelow, Harold F. Cherniss, Freeman J. Dyson, Albert Einstein, Kurt Gödel, Hetty Goldman, Herman H. Goldstine, Ernst Kantorowicz, E. A. Lowe, Benjamin D. Meritt, Deane Montgomery, Marston Morse, Abraham Pais, Erwin Panofsky, George Placzek, Atle Selberg, Walter W. Stewart, Homer A. Thompson, Oswald Veblen, John von Neumann, Kurt Weitzmann, Hermann Weyl, Hassler Whitney, E. L. Woodward, Chen Ning Yang.

as astrophysics and statistical mechanics were also successfully pursued. In those years the institute became a leading center at which aspiring theorists sought to spend time. Its list of alumni is most impressive. One can find them now all over this country as well as abroad. All of us who were part of these active and generally harmonious years will forever be deeply grateful to Robert Oppenheimer.

In the early sixties, there was a large scattering of the physics staff at the institute. Once again Oppenheimer directed the formation of a new team and, by and by, the continuity of the operation will be evident. It was also in this period that the institute's beautiful new library was opened. When you visit it, you should remember that this is Robert's building. It took some doing to get it done.

In the postwar period Oppenheimer's own writings focused more and more on the fact that the relations between the modern sciences and the general culture of our time are not as intimate and fruitful today as they could be. What precisely was his concern in this matter? Was it the problem of "mass culture"? Of course he recognized the importance of popularization, yet "That is not now my problem," he said.¹⁸ What really preoccupied him was that the span of things the intelligent man can cope with is dangerously narrowing; that the relationships between common sense and specialized knowledge are in greater difficulty now than ever, because the rate of increase of that which is known is now greater than ever. Even to the scientist it is often difficult to appreciate the essentials of a neighboring discipline, not completely foreign but not quite his own, "even in physics we do not entirely succeed in spite of a passion for unity which is quite strong."

Was it then his intent to explain isotopic spin to philosophers? No harm in trying, he thought, but "as for particle physics, what we are sure of today may not yet be ready to make its contribution to the common culture."¹⁹

To the intellectual community

Briefly, then, what Oppenheimer had in mind was this. First, he addressed himself to what is loosely called the intellectual community. He wished to foster a common understanding primarily within this community. Second, as an ex-

ample of what in his opinion could profitably be shared, he mentions the lesson of quantum theory which we call complementarity. He wished and in fact tried to explain this lesson to the biologist, the statesman and the artist because he believed that what to the physicist is a technique represents at the same time a general way of thinking that could be liberating to all. Third, he saw a twofold duty for our educational system. In the face of increasing demands on education we should continue to stress that the cultural life of science lies almost entirely in the intimate view of the professional. At the same time, "no man should escape our universities without . . . some sense of the fact that not through his fault, but in the nature of things, he is going to be an ignorant man, and so is everyone else."²⁰

Of the great effort needed to achieve these aims he said the following: "I think that, with the growing wealth of the world, and the possibility that it will not all be used to make new committees, there may indeed be genuine leisure, and that a high commitment on this leisure is that we reknit the discourse and the understanding between the members of our community.

"As a start, we must learn again, without contempt and with great patience, to talk to one another; and we must hear."¹⁸

Oppenheimer himself talked and wrote with authority on these subjects, an authority which derived from the only primary source acceptable to us: the personal participation of the professional in his craft, whatever the craft may be. Thus it was in keeping with Oppenheimer's style that, as he devoted himself to these general themes, it was never at the expense of his own hardboiled interests in the progress of physics. He kept fully abreast of all new developments in his field which he loved so deeply.

In early 1966 it became clear that Oppenheimer was most seriously ill. Even then he did not lose his inexhaustible curiosity for physics but kept talking shop, in pain but lucidly, till the end.

Freeman J. Dyson has told me of Oppenheimer's last visit to the institute. He came to participate in a discussion on the selection of the young physicists who will be members of the institute in the coming academic year. He knew he would not be there to greet them.

Robert Oppenheimer died on 18 February 1967.

Any single one of the following contributions would have marked Oppenheimer out as a pre-eminent scientist: his own research work in physics; his influence as a teacher; his leadership at Los Alamos; the growth of the Institute for Advanced Study to a leading center of theoretical physics under his directorship; and his efforts to promote a more common understanding of science. When all is combined, we honor Oppenheimer as a great leader of science in our time. When all is interwoven with the dramatic events that centered around him, we remember Oppenheimer as one of the most remarkable personalities of this century. In the years to come the physicist will speak of him. So will the historian and the psychologist, the playwright and the poet. But it would take the singular combination of talents of this extraordinary man himself to characterize his life in brief. Perhaps Robert has done just that. I shall conclude by reading a few lines which he wrote fourteen years ago.

“The wealth and variety of physics itself, the greater wealth of the natural sciences taken as a whole, the more familiar, yet still strange and far wider wealth of the life of the human spirit, enriched by complementary, not at once compatible ways, irreducible one to the other, have a greater harmony. They are the elements of man’s sorrow and his splendour, his frailty and his power, his death and his passing, and his undying deeds.”²¹

PT

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Abraham Pais (1918–2000) joined the Institute for Advanced Study in Princeton in 1946 and was professor there from 1950 to 1963. This article is an edited version of a speech given at the Oppenheimer memorial session of the APS meeting held in Washington, DC, on 24 April 1967.

Planning reactions to the Oppenheimer security-clearance review

Allison Buser

Cognizant of their role within the scientific community, scientific societies had to weigh how to respond to the actions by the Atomic Energy Commission.

After spearheading the design of the first nuclear weapons at the Los Alamos Laboratory during World War II, J. Robert Oppenheimer became a key adviser to the US government on nuclear policy in the immediate postwar period. As Cold War tensions heightened during the late 1940s and early 1950s, Oppenheimer's emphatic opposition to the development of the hydrogen bomb and desire for international mediation of atomic research brought him into conflict with many government and military figures. His opponents in the government began challenging his loyalty to the US, pointing to his associations with Communists and Communist organizations in the late 1930s and early 1940s.

In response to being informed in December 1953 that the Atomic Energy Commission was suspending his security clearance, pending the resolution of 24 allegations leveled against him, Oppenheimer requested a formal hearing before an AEC Personnel Security Board. So in 1954, the AEC assembled a three-person board to hear the case and recommend whether to strip Oppenheimer of his security clearance.

Aware of the outcome's implications for the future relationship between scientists and the US government, the physics community closely monitored the hearing. With one member dissenting, the board recommended on 27 May 1954 that Oppenheimer's security clearance be revoked; in a 4 to 1 vote, that decision was upheld by the AEC on 29 June. The decision provoked widespread outcry from the scientific community, who saw it as diminishing the value and influence of scientific expertise in public policy. (For *PT*'s coverage of the hearing, see "The Oppenheimer case" in the July 1954 issue. For more about the outcome, see "Decision" in the August 1954 issue.)

Draft statements from the American Physical Society

In preparation for the AEC decision, the council of the American Physical Society drafted two different statements to be signed by APS president Hans Bethe: version A, to be issued if the charges were dismissed, and version B, to be issued if Oppenheimer's clearance was to be revoked. APS's official statement, issued on 12 June in response to the board's vote to revoke, included much of version B. (Scans courtesy of the AIP Niels Bohr Library & Archives, J. H. Van Vleck papers, 1853-1981.)

Oppenheimer

The following is the draft of a statement to be issued by the Council of the American Physical Society if and when the Loyalty Review Board or the AEC publish their decision. It is written for the case of a favorable decision; in case of an unfavorable decision, version B is to be substituted for the first two paragraphs.

The Drafting Committee consisted of Professor E. Bright Wilson, Jr. and Professor Norman Ramsey, both of Harvard. They state that they are not very satisfied with their own efforts and would like to see a statement with more public appeal. I personally believe that the statement in its present form is satisfactory. Version B is supplied by myself.

VERSION "A"

The Council of the American Physical Society welcomes the decision of the Loyalty Review Board in affirming its belief in the loyalty of Dr. J. Robert Oppenheimer. Many members of the American Physical Society have known and worked with Dr. Oppenheimer for many years and share with the Review Board its confidence in the loyalty and integrity of Dr. Oppenheimer.

However, two features of the original charges against Dr. Oppenheimer have caused much concern to the Council, which believes that repeated use of charges with similar characteristics would be harmful to the best interests of the United States.

The Council is disturbed that practically all of the charges against Dr. Oppenheimer concern past associations which occurred more than twelve years ago. These associations have been well known to government authorities and have been repeatedly reviewed and restudied by the wartime Manhattan District of the U.S. Army and by its successor, the Atomic Energy Commission. Because of the changing nature of the threat against our country, security criteria must of course be continuously revised; however, for precisely the same reason, past actions of an individual under an entirely different international situation must not be judged to have the same implications as similar actions at present.

The chief new charge against Dr. Oppenheimer arose from the advice he gave on request concerning the H bomb. This question was a very difficult technical and policy matter on which opinions widely differed, with many men of assured loyalty sharing Dr. Oppenheimer's views. Disloyalty charges based on policy disagreements appear to be customary in Russia, but we regard them as not only morally reprehensible but also very harmful to our national welfare. If a man whose advice is

Page -2-

sought must fear that his loyalty and integrity may be challenged because his reasoned recommendations later become politically unpopular, he may be tempted to give advice that is politically safe rather than technically valid. In our country, a wise decision is most easily reached by the free conflict of opposing opinion.

VERSION "B"

The Council of the American Physical Society is deeply perturbed by the decision of the AEC (or Loyalty Review Board, as the case may be) in withdrawing the clearance of Dr. J. Robert Oppenheimer. Many members of the American Physical Society have known and worked with Dr. Oppenheimer for many years and as a consequence of this association have great confidence in the loyalty and integrity of Dr. Oppenheimer.

From the very beginning, two features of the original charges against Dr. Oppenheimer have caused much concern to the Council, which believes that repeated use of charges with similar characteristics would be harmful to the best interests of the United States.

Hans A. Bethe

A glimpse into AIP's deliberations

In this letter, Robert R. Davis, the editor of *Physics Today*, updates a member of the governing board of the American Institute of Physics, publisher of the magazine, about developments in the Oppenheimer hearings and about discussions within AIP regarding how—and if—to respond. At the time, the AIP federation comprised the Acoustical Society of America, APS, American Association of Physics Teachers, Optical Society of America (now Optica), and Society of Rheology.

Recounting actions and perspectives of people both inside and outside the organization—AEC commissioners Lewis Strauss (chair), who vigorously opposed Oppenheimer, Eugene Zuckert, and Henry Smyth; review board chair Gordon Gray; Joint Committee on Atomic Energy chair W. Sterling Cole; Oppenheimer lawyer Lloyd Garrison; radio broadcaster Fulton Lewis Jr; and AIP governing board members Frederick Seitz (chair), Karl Darrow, Hugh Knowles, Harry Olson, George Pegram, and Mark Zemansky and secretary Wallace Waterfall—the letter captures much of the concern and political turbulence surrounding the hearing. (Scans courtesy of the AIP Niels Bohr Library & Archives.)

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June 24, 1954

Dear Harry:

Mary Ann just called to say that your letter to Wallace had arrived, and she quoted the section concerning the Wednesday meeting and the AEC's release of testimony. Wallace is now at the ASA meeting and will no doubt be deeply involved at least for the rest of the week, so I'll tell you a little of the many things I've been learning.

The full testimony (992 pp) was distributed by the AEC to the press for release on June 16, but the story was broken a day earlier by Fulton Lewis Jr. Oppenheimer and his counsel are reported to have opposed the release but were obviously in no position to stop it, so Garrison countered by releasing the text of his brief to the Commission, which he had filed on June 7. The newspapers have said that the real reason for the release was that Zuckert had taken a copy of the transcript off to study it and then lost it. Although it turned up in a railroad lost & found department a short time later, it was considered possible a reporter might have had access to it, and the decision was then made to release the full transcript, minus classified information amounting to about 5%. (I've just checked and find the lost document was a 100-page summary of the transcript, which included, however, certain classified passages).

Democrats on the Joint Committee also opposed releasing the testimony, but it was released anyway - reports are that Smyth voted against release with everyone else voting for. The AEC, in making it public, found a simpler excuse: "The Commission protects the privacy of the individuals concerned in such proceedings if they so desire. In this instance, privacy was maintained for the hearings before the Board. However, Dr. Oppenheimer's attorneys, as was their privilege, have issued texts of some documents. In the present circumstances, release of the transcript, within the limits of security, will in the opinion of the Commission best serve the public interest." In the released transcript, however, one finds Gray saying to each witness as he is sworn: "...we treat these proceedings as a confidential matter between the Commission and its officials and Dr. Oppenheimer and his representatives and witnesses. The Commission will initiate no releases with respect to this proceeding. We are expressing the hope that each witness will take the same attitude--and they all did.

With respect to our Wednesday meeting here: I, personally, felt that in the light of the new release and Knowles's intransigence that it might be best to follow Seitz' early impulse and wait for a decision by the AEC. I also felt that since the APS forms the bulk of the AIP, much of the pressing need for an immediate statement had been relieved by the release of the APS statement. I'm convinced, by the way, that no matter what the decision, there will be ample reason for a statement later on, and there may be some advantage in being in the position of not having said anything publicly if it should turn out later that a stronger and more specific statement (in full knowledge of the facts) may seem essential. If a statement had already been made on the basis of less information that fact might easily become an argument against saying anything further. Knowles said he would of course consider the desirability of saying something at a later date, and the matter was left there. Mark Zemansky is coming this week to borrow my set of the transcript and will be ready to propose something definite when the decision is announced or shortly thereafter.

Knowles' point of view is probably known by you, but I was personally unprepared for what he said, in spite of being forewarned. His argument was almost entirely hypothetical, being based on the thesis that one never knows whether an innocent looking person is really as innocent as he looks and therefore the slightest suspicion or evidence of political nonconformity must be accepted as reason enough for getting the person out of a sensitive job. All he knew of the Oppenheimer case was what he learned from the majority report, which he accepted as gospel. With respect to the draft statement, he objected to taking majority statements "out of context" (in at least one case, I'll admit, quite rightly!), but I was compelled to point out that the majority report itself was a most vivid example of a biased position built upon statements taken out of context. (This becomes very apparent, by the way, if one reads the full record in comparison with the majority report.) Knowles' only ultimatum (my word) was that any statement released by the Institute should be prefaced by some complimentary words about the fair treatment and earnest impartiality of the board in its conduct of the hearing. This was warmly seconded by KKD and Pegram. My own reactions have been less sanguine, but I appreciate certain reasons for thinking that such a remark might in order, however debatable it is. Knowles, I'm dead certain, would much prefer that no public statement be made, but it is possible that the case may deteriorate to such a level that even he will change some of his views.

Cole[#], for example, has indicated to newsmen that he will press for a full inquiry by the Joint Committee if the Commission grants clearance, and that one subject will be the way the Commissioners vote. This is supposed to have irritated Zuckert, whose position has never been made public. If it irritates him enough, Cole may get his chance. The result would be a complete catastrophe in many ways, not the least of which would be the complete wrecking of government-scientific relations. This is stated as a fact and I believe it is, although I know that the situation could be tempered by prompt Administration action. The feeling of alarm (and real anger, I think) that has spread among the nuclear physicists seems more authentic, and therefore more serious, than in any other situation I can recall. Now that the testimony is out, furthermore, the intramural fight may[#] cause some second-order explosions violent enough to touch off a public battle of serious proportions. The suspicions that personal vindictiveness may have played a part are quite well borne out by the transcript and it seems inevitable that everyone within earshot having the slightest stake in the matter will take sides - and I suspect the alignment (within physics, at least) will be extremely lopsided.

In view of this line of conjecture, which I feel in my bones to be probable, the societies and the Institute may well be in the middle of a very tough fight. It will be important to maintain a solid position on the society level, but I'm afraid the APS will be too deeply involved (and perhaps even split to some extent) to be able to remain above the situation. It is my hope, however, that this is not a likelihood, but only a possible area of danger. In any case, it is perfectly apparent that the AIP will be in an awkward position unless it sticks to the large issue - which, as I see it, has to do with the absolute need for good relations between the government and physicists. This seems to be lost sight of on the part of the Commission (or at least Stauss) and is rapidly being disregarded by individual physicists.

The foregoing is about as good as I can do in the way of describing my current feelings. It's offered partly because you may not have heard some of the facts here mentioned, and partly so that you're clear (I hope) as to my views in the matter. I'm admittedly biased, but I'm trying to be logical and as objective as possible.

Enclosed are some clippings you may have missed and page proof for July as it relates to the case. I hope it seems about right since it's too late to change anything.

Best regards,

R. R. Davis

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 **AIP**

Does nuclear stockpile stewardship's science diminish global security?

The answer is relevant to the physics community, especially for scientists who are choosing their research paths.

By **Stewart Prager** and **Denisse Córdova Carrizales**

Under broad pressure for a global moratorium on nuclear weapons tests, the US in 1994 initiated a new nuclear weapons R&D initiative: the science-based Stockpile Stewardship Program (SSP). The purpose of the SSP is to ensure the “safety, security, and reliability” of the US nuclear arsenal without the need to detonate nuclear weapons.¹ Many policy analysts have argued that the program is sensible: “Safe” bombs will have a minimal likelihood of detonating from accidents, unauthorized actions, errors, and acts of nature; “secure” bombs won’t be accessed by unauthorized personnel; and “reliable” bombs will detonate with the desired explosive energy at the specified time and place.

Usually, discussions of the SSP’s merits end there, and the conclusion is that the program is unambiguously beneficial for global security. A full assessment of the program, however, involves several other factors.

That the SSP allows the US to obtain information comparable to that accrued by testing raises many questions. Does the SSP encourage a proliferative response from other nations? Does it reinforce US adherence to nuclear weapons as tools of geopolitics and warfare? Is certifying the technical reliability of the US nuclear arsenal through a program like the SSP essential? Would such reliability ever be seriously doubted by an adversary? Does the SSP spur the development of new, destabilizing nuclear weapons? Does the net effect of the SSP decrease the threat from nuclear weapons? In this article, we discuss the factors underlying those questions and conclude that the SSP contributes to a nuclear arms race.

We argue that the existence of the SSP and the technical advances that it yields could have destabilizing implications for the geopolitics of nuclear weapons. The SSP, therefore, violates the intent of the 1996 multilateral Comprehensive Nuclear-Test-Ban Treaty (CTBT),

the goal of which is to prevent “the proliferation of nuclear weapons in all its aspects.” A public consideration of both the merits and dangers of the SSP is needed. Discussions are particularly important in the physics community, given the large number of physicists who are employed by the SSP.

Today, the danger from nuclear weapons is growing as arms control treaties are abandoned, states with such weapons are engaged in conventional war, new risks emerge from cyberattacks, nuclear threats from leaders are issued more regularly, and the US and other states modernize their nuclear weapons systems. The massive modernization programs signal a commitment to nuclear weapons for much of the century. Assessing the role of the SSP in the deepening crisis is as critical now as similar discussions were at the beginning of the nuclear era when many physicists—including Niels Bohr, Albert Einstein, Enrico Fermi, James Franck, and Leo Szilard—considered the consequences and ethics of nuclear weapons research.

The core argument

Before 1997, about 2000 nuclear weapons tests were carried out aboveground, underground, and underwater; more than half of those were by the US.^{2,3} Nations that conducted testing largely did so to advance weapons science, ensure the reliability of existing weapons, and validate new designs.

After several decades of efforts to limit nuclear weapons testing, the United Nations General Assembly adopted the CTBT and opened it for signature in September 1996. Since then, it has been signed by 187 nations and ratified by 178 of them. The CTBT is derived from two earlier treaties: the Limited Test Ban Treaty of 1963, which prohibited testing everywhere except underground, and the Threshold Test Ban Treaty of



▲ The Minuteman III intercontinental ballistic missile (ICBM) was first designed in the 1960s to launch nuclear warheads. To modernize the US nuclear stockpile, including developing new warheads that could replace those in the existing 400 ICBMs, researchers conduct various physics experiments at the National Ignition Facility and elsewhere as part of the US Stockpile Stewardship Program. (Photo by Staff Sgt Alan R. Wycheck, North Dakota/National Archives photo no. 6461659.)

1974, which banned tests with yields that exceeded 150 kilotons. Those treaties were driven by public concern over the arms race and radioactive fallout from testing.

The US signed the CTBT in 1996 but never ratified it. The congressional vote to ratify in 1999 failed

because of partisan politics and concerns about whether the substitution of US testing by the SSP would be sufficient and how the absence of testing by other nations would be verified. Nonetheless, as a signatory, the US is obligated to not test any nuclear weapon,⁴ and

other nations have adhered to the ban. No tests have been conducted since 1996 except by India and Pakistan in 1998⁵ and North Korea as late as 2017.⁶

US policymakers have advanced an additional argument in support of the test ban: It freezes the technological lead that the US secured through past nuclear tests. The US previously conducted 1030 nuclear tests; Russia, 715; France, 210; the UK and China, 45 each; and the others, less than 10 each.² The enormous success of the ban has slowed the spread of nuclear weapons to new states and the further development of weapons in existing nuclear states.

The US agreement to the CTBT is facilitated by the SSP, which supplies information on nuclear weapons science and technology. The SSP supports a broad-based scientific program that's relevant to the primary and secondary components of nuclear warheads. Examples include the study of materials under extreme compression, subcritical nuclear tests of imploding materials, and inertial confinement fusion experiments to elucidate the physics of fusion burn and matter at high-energy densities.⁷ Experiments are complemented by computational modeling with supercomputers.¹ Indeed, the military value of supercomputers has led to export controls on their distribution.⁸

The SSP employs about 8100 scientists and 13 200 engineers.¹ Research and technology funding for the program has escalated from \$2 billion in 2019 to \$4.2 billion in the fiscal year 2026 federal budget request. Overall, expenditures on nuclear weapons have similarly surged.

Given the intent of the CTBT, however, the conclusion seems inescapable that the SSP violates the spirit of the treaty. The main purpose of the test ban is to slow the advance and spread of nuclear

weapons by limiting the knowledge that is gained through testing. The preamble of the CTBT states that “the cessation of all nuclear weapon test explosions and all other nuclear explosions, by constraining the development and qualitative improvement of nuclear weapons and ending the development of advanced new types of nuclear weapons, constitutes an effective measure of nuclear disarmament and non-proliferation in all its aspects.”

Yet the US gleans more knowledge of nuclear explosions through SSP science than through actual detonations. “We’ve progressed from observing high explosives being blown up to carefully studying their chemistry, morphology, crystallinity, and aging characteristics,” says Jon Maienschein, former director of the Energetic Materials Center at Lawrence Livermore National Laboratory (LLNL).⁹

The SSP is a test-ban work-around that affords the US the advantages of testing without actually testing. Russia, France, the UK, and China have programs similar to the

SSP. Other countries that neither test nor have a science-based stewardship program could create geopolitical instability as they seek to reduce the disparity. Indeed, India has not signed the CTBT on account of nuclear power imbalances. In a 20 June 1996 statement at the Conference on Disarmament, Arundhati Ghose, India’s UN ambassador and permanent representative, said that the country “cannot accept any restraints on its capability if other countries remain unwilling to accept the obligation to eliminate their nuclear weapons.”

Reliability, new designs, and the arms race

Before the SSP, nuclear tests were not essential for the certification of reliability of nuclear weapons. George Miller, former director of LLNL, states that “nuclear weapons were never certified by nuclear tests; nuclear tests were important, but frequently not even the most important part of the process because there were never enough nuclear tests over the full range of con-

ditions to provide certification.”¹⁰

Nonetheless, a critical goal of the SSP is to certify annually that nuclear warheads are technically reliable, a responsibility carried out by the three national security laboratories: LLNL, Los Alamos National Laboratory, and Sandia National Laboratories. Unclassified reports from the national security laboratories indicate that a typical technical metric for reliability is 90% confidence that the warhead yield will be within 10% of that specified. Historically, US nuclear subsystems have, with 100% success, performed at the specified yield; the National Academy of Sciences reports that the “reliability of existing systems is determined entirely by the ‘non-nuclear’ subsystems,” which includes the delivery system.¹¹

Technical metrics of reliability, although sensible for most technological systems, become meaningless when they’re applied to the unique case of nuclear weapons. Reliability for nuclear weapons ultimately refers to a measure of psychological deterrence of a potential adversary. It seems inconceivable that a hostile state would ever doubt that the thousands of US nuclear weapons are anything less than assuredly lethal and an ever-present threat to the existence of other nations. It seems similarly unlikely that the US would act in a conflict based on the assumption that the weapons of other states are unreliable.

At the inception of the SSP, the geopolitical landscape was one of negotiated nuclear arms reduction. As stated in the *Stockpile Stewardship Program Strategy* of 1994, “No new weapons are being designed.” The strategy, however, also called for “breakthroughs in unexplored areas of science and technology,” which, if needed in the future, could provide the knowledge base for new design ideas.¹²



▲ Inside the metal case shown here are weapons-grade plutonium samples. To better understand the effect that a hostile environment, such as a missile defense system, may have on US nuclear weapons, researchers at the National Ignition Facility exposed the plutonium to intense pulses of neutrons in 2025. The radiation was generated by the implosion and heating of nuclear fusion fuel by incident lasers. (Photo by Jason Laurea/LLNL.)

The lack of emphasis on new weapons designs was consistent with the reduction of the number of nuclear warheads in the US and Russia and persisted through the Nuclear Posture Review of 2002, which recognized the “reduced threat posed by the former Soviet Union,” and the one in 2010, which stated that the “most immediate and extreme danger is nuclear terrorism” and that the “other pressing threat is nuclear proliferation.”

In 2018, as nuclear competition among nation-states began to grow, so, too, did the emphasis of the SSP on new weapons designs. Indeed, the main purpose of US nuclear weapons tests before the CTBT was not to certify reliability but to develop new designs. The 2018 Nuclear Posture Review states that the “need for flexibility to tailor U.S. capabilities and strategies to meet future requirements and unanticipated developments runs contrary to a rigid continuing policy of ‘no new nuclear capabilities.’” Similarly, one aim of the 2025 Stockpile Stewardship and Management Plan is “to define the appropriate warheads to support anticipated future threats.”¹¹

Another nation may well fear new nuclear designs derived from the SSP and respond in an escalatory fashion. A 1994 JASON report, written by an independent group of scientists that advises the government on sensitive scientific and technological matters, expressed that concern. The report states that the SSP “may be perceived by other nations as part of an attempt by the U.S. to continue the development of ever more sophisticated nuclear weapons.”¹²

The development of new concepts or significant design changes could also lead to internal pressure for the US to resume nuclear testing to ensure their validity. Currently, the Trump administration and some members of Congress have called for the resumption of nuclear testing.

Nations without a current SSP and without nuclear weapons could use unclassified published research for weapons development, according to Robert Goldston and Alexander Glaser of the Program on Science and Global Security at Princeton University. They note that “success in ... the National Ignition Facility ... could lead to greatly increased R&D in inertial confinement fusion worldwide, along with increased proliferation risks.”¹³

Indeed, recent satellite observations reveal that China is constructing an inertial confinement fusion facility, which is viewed as a military asset, in Mianyang in Sichuan Province.¹⁴ The size of the experimental bay is about 50% larger than that of the National Ignition Facility (NIF), which might indicate a superior scientific capability. The project, which can have collateral benefit for the development of fusion energy,

has not been announced by the Chinese government and highlights the potential for the SSP to contribute to a nuclear arms race. France’s Laser Megajoule facility, which opened in 2014, has capabilities that are comparable to NIF.

The net effect

As stated in the annual Stockpile Stewardship and Management Plan, the program must be “capable of servicing the stockpile for 50 years or more.”¹⁵ Thus, the SSP advances the salience of nuclear weapons as geopolitical tools and thereby moves the world further from arms control and disarmament.

We consider three possible scenarios involving the SSP, nuclear testing in the US, and their effects on the stability of the nuclear world order. In the first, the US has an SSP but no testing. As we’ve discussed, this current scenario contributes to a nuclear arms race and the spread of SSPs in other nations. In the second, the US has no, or a reduced, SSP but returns to nuclear testing. That situation is likely worse than the first one because nuclear testing would strongly incentivize other nations to test. In the third scenario, the US maintains neither an SSP nor testing. We believe that scenario would be the most stabilizing approach and would dampen rather than stimulate an arms race.

A nuclear stewardship model of reduced activity, although it would sacrifice a small amount of reliability assurance, would continue to ensure stockpile safety and security while being consistent with the intent of the CTBT. We recognize that such an approach would face strong challenges from many of the people working in the nuclear weapons complex.

For physicists and the physics community, the SSP’s effect on global well-being is especially relevant, particularly for early-career physicists, and can influence whether one chooses to work on advancing nuclear weapons—a consideration with technical, policy, and ethical dimensions. Perhaps the most visible and exciting component of the SSP, at least from a physicist’s viewpoint, is NIF, a technological and scientific marvel at LLNL. NIF research advances progress toward the goal of carbon-free fusion energy and enhances understanding of matter under extreme conditions.

Many of the physicists and engineers who work at NIF may be motivated by those goals, but the primary purpose of the experiment and the reason for funding it is to enhance the understanding of the nuclear fusion process that occurs in a nuclear warhead.¹⁶ We urge each of our colleagues who work at NIF and on other aspects of the SSP to do their own self-assessment of the net effect of their creative work. A full discussion in the broader scientific community on the net

effect of the SSP has not been had, to our knowledge, and is overdue.

In the 20th century, many revered physicists struggled with similar issues. Some chose to build US national security labs. Others—such as Hans Bethe, a Nobel laureate and the former director of the theoretical division of the Manhattan Project—eventually opted out of nuclear-arms research. In 1995, he wrote in an open letter that “individual scientists” can influence the national debate on weapons development “by withholding their skills.”¹⁵ He called on “all scientists in all countries to cease and desist from work creating, developing, improving and manufacturing further nuclear weapons.” **PT**

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Tyler Drye tackles challenges to technical patents

By **Toni Feder**

Patent attorney; Sterne, Kessler, Goldstein & Fox

BS, physics, Clemson University, 2009
PhD, chemical physics, University of Maryland
in College Park, 2014
JD, George Mason University, 2022

What was your research focus?

Single-crystal growth and characterization of novel semiconductors and superconductors.

What were you looking for in a job?

I came to the realization that my PhD adviser spent most of his time writing grants and overseeing research. I liked being hands-on in the lab.

I thought I might want to be a researcher at a national lab, but I became aware of how the system

(Photo courtesy of Sternekessler.com.)



works: You have to tackle problems that get funding. The problems I wanted to work on may not always get funded, and the problems that get funding may not always be interesting. I started looking around to see what else I could do.

How did you end up in patents?

At a job fair, there was a booth from the US Patent and Trademark Office. They expressed interest in my background, and the idea of learning about new technologies and trying to understand things from an inventor's perspective appealed to me. I worked at the USPTO for a year and a half.

Where did you go from the USPTO?

In 2016, I moved to a law firm where the focus was on patent prosecution—from writing patents to getting them issued. After a few years, I went to law school. I was interested in working on different aspects of patents, including assertion of patent rights and challenges to patents. Three years ago, I joined Sterne, Kessler, Goldstein & Fox.

How do you spend your time?

The bulk of my time is spent reading and writing.

How do you use your physics?

Everything I do involves understanding the complex technologies that underlie patents. I take ideas in such fields as optics, materials chemistry, and medical devices and put them into language that examiners, judges, or laypeople can absorb.

What new skills have you needed?

Legal writing and research require a very high level of precision.

I've learned to handle disagreements with examiners and to understand and further clients' interests and goals. I've become a better listener. Those skills have made me a better person.

What do you like most?

It's rewarding when you get a good outcome for the client—money in damages, or permission to use technology. And I learn new things every day. **PT**

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Signals through salt: Building machines that use the language of biology

Physiological communication relies primarily on ions to carry signals. The emerging field of bioiontronics aims to build engineered devices that can do the same.

By **Yujia Zhang** and **Hagan Bayley**

Since life began on Earth, biology has spoken the language of ions. Often called electrolytes, salt-derived ions—such as calcium, potassium, and magnesium—are used in the human body to send signals that regulate processes like nerve signaling and the beating of the heart. Scientists are only just beginning to catch up and develop devices that use ions, rather than electrons, to carry information with charge. In 2007, researchers demonstrated an ion-ejection device built from polymers that controlled the ion signaling of neurons in a petri dish. From there, the nascent field of bioiontronics—communication with living matter through ions and molecules for the detection and modulation of biological activities—has expanded.

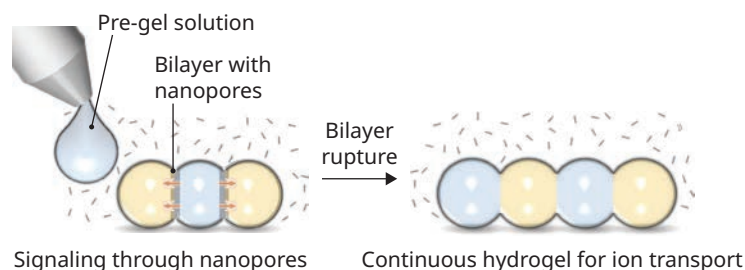
The prospect of seamlessly exchanging ionic signals with biological systems makes bioiontronic devices appealing for medical applications. You might envision, for example, using ion pumps and iontronic diodes to modulate brain activities through the one-way release of ions and neurotransmitters. Conversely, ionic signals transmitted from biological environments into bioiontronic devices could enable the detection of biological activities. Iontronic devices for targeted drug delivery are in preclinical stages of development, and certain recording devices, such as DNA sequencers, are already commercially available.

Unlike iontronic devices, conventional metal-based electrodes, such as those used to monitor brain activity or heartbeats, are commonly used for the stimulation and measurement of electrophysiological activities—action potentials from individual cells and local field potentials from groups of cells. Changes in electric fields are the composite result of assorted ion movements. Conventional electrodes, therefore, cannot be used to identify a specific ion species or read out the molecular information behind a given cellular activity. In that regard, bioiontronics offers more precise selection of ionic and molecular species and provides novel capabilities for the detection of disease markers, such as electrolyte imbalances, certain neurotransmitters, and protein biomarkers.

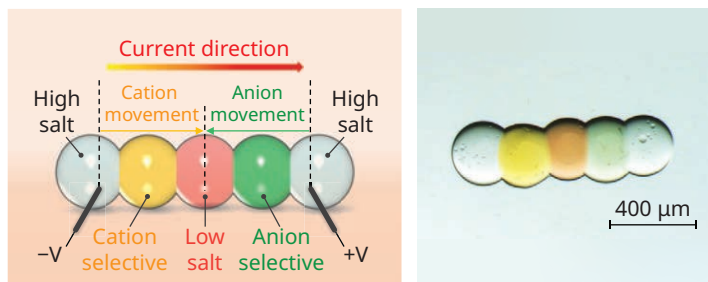
Recent advances in mechanisms, materials, device prototypes, and system designs have shown the potential of iontronic devices at biological interfaces. Below, we explore one category of devices: droplet-based devices, termed dropletronics.

Dropletronics

For minimally invasive applications in medicine, it is preferable for bioiontronic devices to be miniature, soft, and biocompatible and have the capability for both functionality and responsiveness, such as biode-



◀ **Figure 1.** To create dropletionic devices, hydrogel droplets are deposited into a surfactant-containing oil with a micropipette, and the droplets self-assemble through the formation of droplet interface bilayers. Protein nanopores (**left**) can be inserted into the bilayers to permit ionic and molecular conduction. Alternatively, photoinitiated rupture of the droplet interface bilayers can be used to form a continuous ion-conductive structure (**right**).



◀ **Figure 2.** A microscale droplet-based 125 mV power source is shown schematically (**left**) and in a bright-field image (**right**). Food dyes are used to distinguish droplets with different compositions. (Figure adapted from Y. Zhang et al., “A microscale soft ionic power source modulates neuronal network activity,” *Nature* **620**, 1001, 2023.)

gradability and remote-controlled activation. Droplettronics, which are fabricated from tiny hydrogel droplets, hold potential to meet those requirements.

To form droplettronic devices, such as the one shown in figure 1, picoliter to microliter hydrogel droplets are deposited in a surfactant-containing oil. The surfactants rapidly self-assemble on the droplets’ surfaces to form a monolayer coating. When two droplets are brought together, a metastable bilayer forms between them. Multiple droplets can be deposited to form linear, 2D, or 3D networks.

There are three key benefits of the surfactant-supported droplet assembly process. First, each droplet can contain different materials, including nanoparticles and various solutes. The droplets can therefore be used to build heterostructured, tailored devices, such as power sources, transistors, and logic gates like those used in conventional electronics.

Second, the droplet interface bilayers can incorporate nanopores or channels to allow communication between droplets. That ability has been used to investigate ion transport through membrane channels and to develop synthetic tissues. Third, external activation sources, such as temperature, light, or pressure changes, can be used to rupture the droplet interface bilayers and produce a continuous hydrogel structure without compromising the distinctness of each droplet. That hydrogel structure offers biocompatibility, strong mechanical stability, and, after bilayer rupture, high ionic conductivity.

Stand-alone droplettronic devices will require a battery to power them. With a design inspired by the electricity-producing cells in electric eels, teams (led by the authors of this article) at the University of Oxford and EPFL, the Swiss Federal Institute of Technology in Lausanne, produced a power source by depositing a five-droplet chain consisting of a low-salt droplet and two high-salt droplets separated by two charge-selective droplets, as shown in figure 2. The five droplets create a salt concentration gradient that allows cation movement in one direction and anion movement in the other, thereby producing an output ionic

current. The bilayers between the droplets enable the formation of a stable droplet network in which energy is not dissipated until a connection is made between droplets, either through nanopores or triggered rupture of the bilayers.

The design provides a soft ionic power source that is more than five orders of magnitude smaller by volume than previous hydrogel power sources. The device has been used as a biocompatible current source to modulate the electrical activities of neural tissues *in vitro* and in *ex vivo* mouse brain slices.

Other droplettronic power sources have been developed through the incorporation of various energizing materials, such as lithium-containing particles, used to form tiny lithium-ion batteries, and metabolic molecules, used for enzyme-enabled biobatteries. The inclusion of magnetic particles enables droplettronic devices to move under an external magnetic field in a way that allows them to be used as microrobots, including ones that are microscale mobile power sources. In research settings, those techniques have been used to power the movement of charged drug molecules and the defibrillation and pacing of *ex vivo* mouse hearts.

By configuring droplet combinations, the teams have developed diodes, transistors, various reconfigurable logic gates, and synthetic synapses with ionic memory effects. The various droplettronic components and their circuitry configurations represent a step forward in the development of integrated iontronic circuits with a wide range of potential applications. Already, researchers have fabricated a droplettronic device that can interface with living heart cells and record the ionic signals produced by their coordinated beating.

Outlook

Several challenges remain for developing droplettronic devices. For example, interfaces between droplets can currently undergo a one-time-only irreversible rupture that serves as an off-to-on switch for the droplettronic power source. A reversible process would be a

significant improvement for energy applications and other functionalities. In biological environments, the harnessing of endogenous energy resources, such as glucose or ATP (adenosine triphosphate), might provide a long-term energy solution for dropletic implants. Further, enhanced robustness under biological conditions demands advances in the selection of materials, device design, system integration, and encapsulation.

Dropletics are just one example of the variety and potential of bioiontronics. Other bioiontronic device platforms include solid-state nanofluidic chips and macroscopic polymer devices, to name but two. The future of the field lies in the fabrication of complete bioiontronic systems and the integration of those components with living tissues. Potential applications for bioiontronics include quantitative sensing, early disease detection, *in situ* drug synthesis, spatiotemporal control of drug delivery, and the motility and control of microrobots. Achieving that potential will require interdisciplinary knowledge, from fields including microtechnology, physics, chemical biology, electrochemistry, bioelectronics, and biomedical engineering.

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Additional resources

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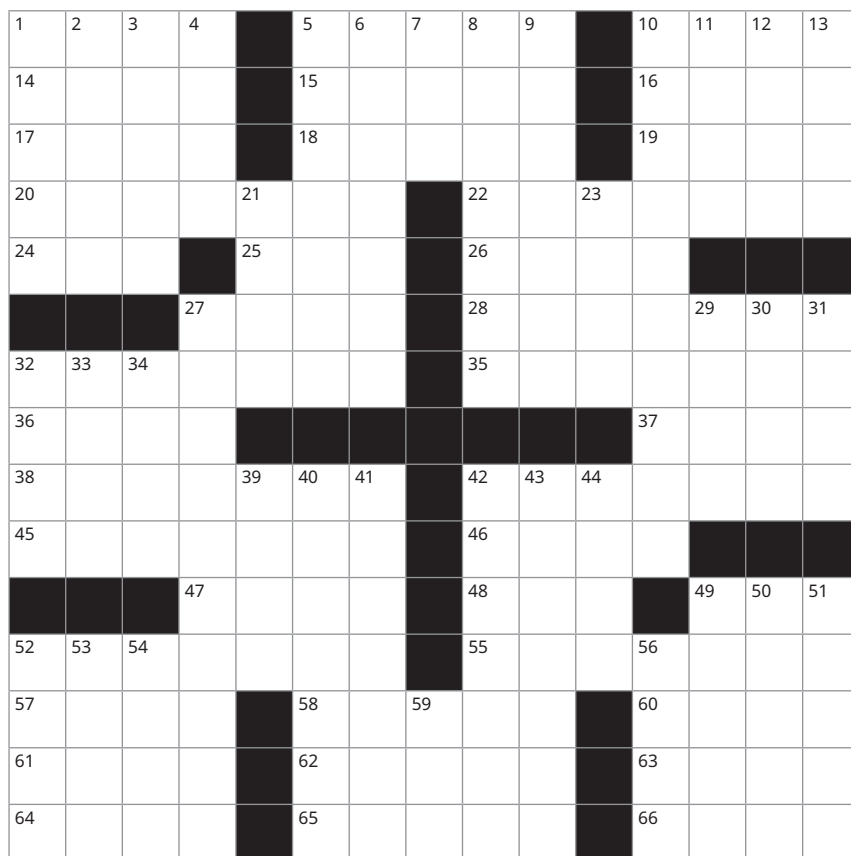
CROSSWORD

Signal boost

By Doug Mar

ACROSS

- 1 You might say this if you can't hear clearly
- 5 Swatting sounds
- 10 Mystical glow
- 14 A black one traps light
- 15 Breaking a bad one is good
- 16 Rugged rock
- 17 Speck
- 18 Host synonym, which sounds like maybe it should be squared
- 19 *Everything Everywhere All at ___* (Best Picture winner)
- 20 Like some underwear or Johnson–Nyquist noise
- 22 Perplexed
- 24 Musical sense
- 25 Made a fast stop?
- 26 Word of woe
- 27 Type of noise associated with small numbers of discrete particles
- 28 Lends a 24-Across?
- 32 Epimenides (of paradox fame) and others
- 35 Signal-to-noise ratio is often expressed using this unit
- 36 Gel starter?
- 37 Support staff?
- 38 Start to go out, or a type of noise that has a $1/f$ frequency spectrum
- 42 Used an atomizer
- 45 Opening in a mask
- 46 Taken by mouth
- 47 Competent
- 48 Length of time it takes Earth to rotate 0.25 deg.
- 49 Winery container
- 52 Meteor shower associated with comet Swift–Tuttle
- 55 Quantitative measure of disorder
- 57 Fat in a bird feeder
- 58 First episode in a TV series
- 60 Color of the noise in 38-Across
- 61 Jai ___ (Basque sport)
- 62 Something skipped across a pond
- 63 Utter delight



- 64 Softest mineral, with hardness equal to 1 on the Mohs' scale
- 65 Poly ending
- 66 Maria on the moon

DOWN

- 1 Color of noise that can mask unwanted sounds
- 2 Hullabaloo
- 3 Change
- 4 Pull apart
- 5 Illinois city that is home to a liberal arts college of the same name
- 6 Tiny settlements
- 7 As easy as ___
- 8 Dappled
- 9 Metal marble
- 10 Relating to sound
- 11 Containers often found in probability textbook problems
- 12 Track event
- 13 Elderly
- 21 Sanskrit term meaning "great," as in ___raja or ___rishi
- 23 Neither fem. nor neut.
- 27 Random and unpredictable, like noise

- 29 Online auction site whose first sale was a broken laser pointer
- 30 State bird of Hawaii
- 31 Dogs pull it
- 32 Coffeehouse
- 33 Count on
- 34 Great Lake whose shoreline includes three counties of the same name
- 39 Japanese city famous for beef and sake
- 40 Word found in the mailing address of *Physics Today*
- 41 Makes additional revisions
- 42 Unnamed person
- 43 Device that comes in laser and inkjet
- 44 Tirade
- 49 Sheer fabric
- 50 Sleeper's breathing problem
- 51 Rug rats
- 52 HS junior's exam
- 53 Software contract that most people don't read (abbr.)
- 54 What both roots are when the discriminant of a quadratic is positive
- 56 Dungeons & Dragons and others, for short
- 59 Fate



Fluid fingers through the sand

By Ryan Dahn

When fluids interact with granular materials such as sand, the resulting behavior is often complex. Erosion and deposition generate intricate patterns in rivers and oceans, for example, and fluid flow can weaken faults or trigger the formation of sinkholes. This image, submitted by Miles Morgan and Bjørnar Sandnes of Swansea University in the UK, shows water flowing downward through a dense granular bed that's confined between two plates. The fingerlike patterns created by the invading fluid are caused by the interplay between hydrodynamic, gravitational, and frictional forces as it flows through the chamber.

After submerging grains in a cell filled with water and allowing them to settle, Morgan, Sandnes, and their colleagues induced a rate-controlled flow using pumps at the top and bottom of the chamber: Water was injected at the top, and water—or some combination of water and grains—exited at the bottom. To help

visualize how the invading fluid mixed with the water already present in the chamber, the former was dyed blue and the top layer of the latter was dyed red. The behavior depended on the flow rate. At low flow rates, the fluid easily passed between the grains without causing them to move. At moderate flow rates, the grains moved in a predictable manner that was dominated by gravity. But at high flow rates, instabilities such as the viscous fingers seen here began to emerge. The researchers express hope that their work will lead to more-accurate rheological models of fluid flow in natural hazards, industrial processing, and geophysical flows. (M. L. Morgan et al., “Wormhole formation in fluid-driven granular flow,” *Commun. Phys.* **8**, 468, 2025; image courtesy of Miles Morgan and Bjørnar Sandnes.)

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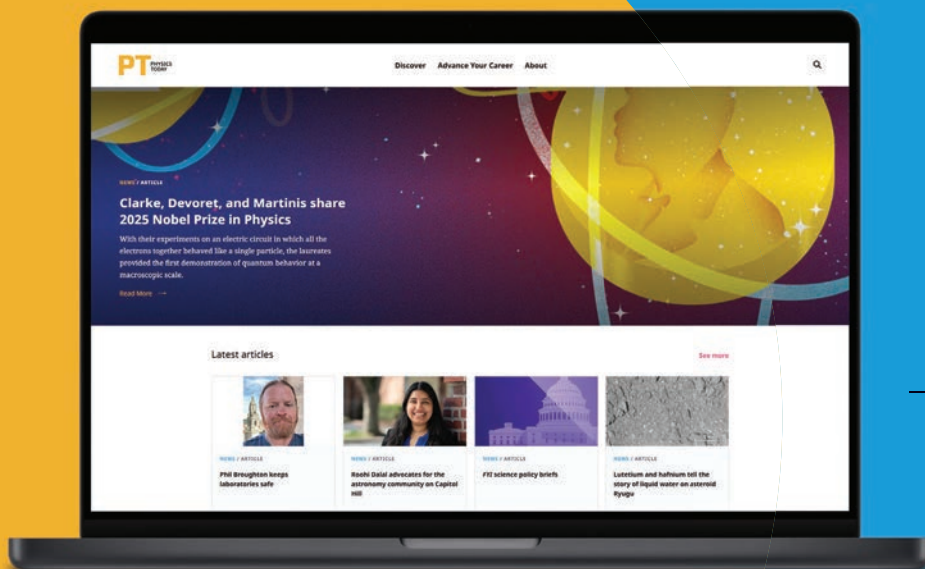
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