PHYSICS TODAY

October 2016 • volume 69, number 10

A publication of the American Institute of Physics

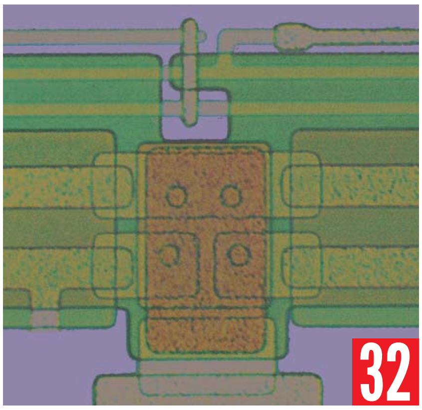
The search for MAGNETIC MONOPOLES

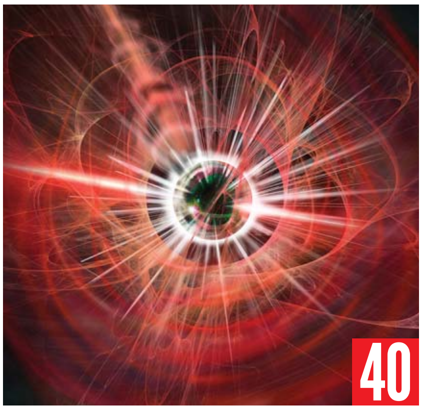
Clinton and Trump on science

Spinning up solid-state NMR

A mission to map dark energy

FIVE
BENCHTOP INSTRUMENTS
ONE
UNIFIED INTERFACE
VirtualBench is an all-in-one device that combines a mixed-signal oscilloscope, a function generator, a digital multimeter, a programmable DC power supply, and digital I/O into one instrument. Simple, convenient, and compact, VirtualBench is an impressive value that opens up new possibilities for how engineers can interact with benchtop instruments.
See how at ni.com/virtualbench
NATIONAL INSTRUMENTS
VirtualBench





PHYSICS TODAY

October 2016 | volume 69 number 10

FEATURES

ON THE COVER: As schoolchildren, we learn that all magnets have two poles—north and south. But nothing in the laws of physics rules out the possibility of monopoles, magnetic counterparts to electric charges. On **page 40**, Arttu Rajantie describes ongoing efforts to detect magnetic monopoles in the debris of high-energy particle collisions, and he explains why hopes of eventually finding the hypothetical particles aren't as far-fetched as they may seem. (Image courtesy of Heikka Valja/MoEDAL collaboration.)

Recently on PHYSICS TODAY ONLINE

www.physicstoday.org

AIP ESVA, PT COLLECTION

▶ Singularities

John Trump, the late uncle of Republican presidential candidate Donald Trump, was a prominent physicist and engineer. William Thomas recounts how Trump made his mark on high-voltage generators, World War II radars, and cancer therapy.

ESO/M. KORNMESSER

▶ Points of View

Astronomer Mikko Tuomi explains how a relatively simple error in archival telescope data led him and his team to the discovery of a small, probably rocky planet orbiting Proxima Centauri, the star nearest to the Sun.

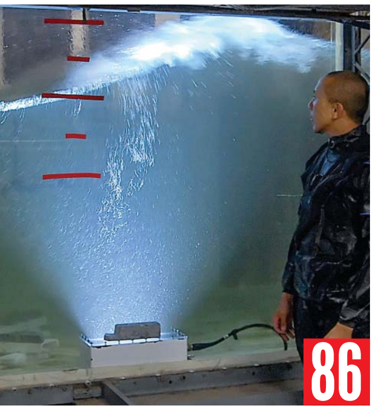
▶ Bookends

An article in the July issue argued that physicists should study history. Melinda Baldwin, Physics Today's new Books editor, recommends five must-read books for those interested in expanding their knowledge of the history of physics.

Physics Today (ISSN 0031-9228, coden PHTOAD) volume 69, number 10. Published monthly by the American Institute of Physics, 1305 Walt Whitman Rd, Suite 300, Melville, NY 11747-4300. Periodicals postage paid at Huntington Station, NY, and at additional mailing offices. POSTMASTER: Send address changes to Physics Today, American Institute of Physics, 1305 Walt Whitman Rd, Suite 300, Melville, NY 11747-4300. Views expressed in Physics Today and on its website are those of the authors and not necessarily those of AIP or any of its member societies.

PHYSICS TODAY

www.physicstoday.org



DEPARTMENTS

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

Publisher
Randolph A. Nanna ptpub@aip.org
+1 301-209-3102

Editor-in-chief
Charles Day cday@aip.org

Managing editor
Richard J. Fitzgerald rjf@aip.org

Editor emeritus
Stephen G. Benka

Art and production
Rita Wehrenberg, production manager
Donna Padian, art director
Unique Carter
Kenneth Pagliuca

Editors
Melinda Baldwin mbaldwin@aip.org
Steven K. Blau skb@aip.org
Sung Chang sc@aip.org
Toni Feder tf@aip.org
Martha M. Hanna mmh@aip.org
David Kramer dk@aip.org
Jermey N. A. Matthews
Johanna L. Miller jlm@aip.org
Gayle G. Parraway ggp@aip.org
Ashley G. Smart ags@aip.org
R. Mark Wilson rmw@aip.org

Online
Paul K. Guinnessy, director pkg@aip.org
Andrew Grant, editor agrant@aip.org
Angela Dombroski atd@aip.org
Greg Stasiewicz gls@aip.org

Assistant editor
Cynthia B. Cummings

Editorial assistant
Tonya Gary

Contributing editor
Andreas Mandelis

Marketing manager
Christina Unger Ramos cunger@aip.org

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

PhysicsToday **@physicstoday**

FROM THE EDITOR

Froth on the daydream

Charles Day

PHYSICS TODAY is not the only publication I contribute to. I also write a column for *Computing in Science & Engineering*, a bimonthly magazine published jointly by the American Institute of Physics and the IEEE Computer Society. Called the Last Word, the column appears on the magazine's final page, where it provides, like an after-dinner mint, a light, mind-tingling ending to the hearty editorial fare in the rest of the magazine. At least, that's my goal.

Although I wrote computer code in my former life as an astronomer, I was never truly a computational scientist. In fact, I found programming frustrating because the language I used, Fortran, was so fussy. Writers and editors can choose among several synonyms. "Huge" might seem apt at first, but further reflection could favor "vast," "immense," "enormous," or "colossal." Programmers, however, must hew to a limited vocabulary and a rigid syntax.

My Last Word columns are perforce not about computational science. Rather, they explore the ways in which computers and information technology influence and crop up in everyday life and popular culture. Since 2006, when I took over the column from its founder, Francis Sullivan of the Institute for Defense Analyses, I've covered such topics as computer-generated poetry, the future of online advertising, infotainment systems in cars, and the manifestation of computers in *James Bond* movies.

Sometimes I'm asked how I find subjects to write about. The answer has two parts. The first is to always be on the lookout for ideas; the second is to be curious. That said, there are rich seams of inspiration that I habitually revisit. One of them is the Physics and Society section of the arXiv eprint repository.

When I last looked in the section, I found a paper intriguingly titled "Influence of selfish and polite behaviours on a pedestrian evacuation through a narrow exit: A quantitative characterisation."[1] In the paper's introduction, authors Alexandre Nicolas, Sebastián Bouzat, and Marcelo Kuperman explain that previous research had looked at whether a crowd of polite people evacuates faster through a single exit than a crowd of pushy people does. Nicolas and his coauthors examined crowds that contained an adjustable mix of the polite and the pushy.

They used two empirical approaches. First, they observed 80 human volunteers as they tried to exit through an adjustable opening. Some of the volunteers were told to behave politely (stepping aside, avoiding touching). Others were told to be pushy (rushing ahead, not avoiding touching). Having derived a simple expression for evacuation speed, the authors tested it using their second method: simulating people with magnetic disks whose repulsion could be preset.

The paper begins by describing a scene in the French novel *Froth on the Daydream* (1947) by Boris Vian (1920–59). I had never heard of Vian, so I looked him up on Wikipedia. There, I found his occupations listed impressively as "writer, poet, musician, singer, translator, critic, actor, inventor, and engineer." *Froth on the Daydream* is a literary novel with a surreal plot. Among its cast of characters is a thinly disguised Jean-Paul Sartre, who, in real life, had an affair with Vian's wife. The book did not sell well—unlike his bizarre parody of a crime novel, *I Spit on Your Graves* (1946), which was among the most popular of the year. Vian wrote it in 15 days.

Nicolas, Bouzat, and Kuperman are affiliated with the Centro Atómico in Bariloche, Argentina. As with Vian, I had never heard of the city, so I again turned to Wikipedia. Bariloche, I discovered, is a city of 113 000 people situated by a large lake in the foothills of the Andes. Its modern development sprang from the establishment of a small shop by German immigrant Carlos Wiederhold. More German-speaking immigrants joined him. Today, much of the city's architecture looks Austrian, German, or Swiss.

As you might have guessed by now, my digressions into French literature and Argentine geography are here to make a point: that following one's curiosity can be rewarding or at least stimulating. Now I know about an interesting author and a surprising city.

Scientists are also rewarded by following their curiosity. Nuclear chemist Sherwood Rowland embarked on a study of atmospheric chlorofluorocarbons, a field distant from his own, following a chance conversation on an Austrian train.[2] He and his postdoc Mario Molina were awarded a share of the 1995 Nobel Prize in Chemistry for their work on the ozone hole.

References

1. See http://arxiv.org/abs/1608.04863.
2. See www.nobelprize.org/nobel_prizes/chemistry/laureates/1995/rowland-bio.html. PT

READERS' FORUM

Commentary

Reporting on global warming: A study in headlines

The extent to which recent heat waves can be shown to be caused by global warming depends in part on how one frames the question.

As humans continue to increase the concentrations of atmospheric greenhouse gases, heat waves are becoming more frequent.[1] Here in Durham, North Carolina, where I live, March 2012 was one of the warmest months over the past several decades, relative to the average temperature for each month. Let's imagine that three scientists looked into this heat wave, assessed the contribution from global warming, and reported their findings in news stories using three different headlines.

▶ **Headline A:** Recent heat wave was due 71% to natural variability and 29% to global warming.

▶ **Headline B:** Global warming increased the odds of the recent heat wave by only 0.25%.

▶ **Headline C:** Global warming has made heat waves like the recent one occur 22 times as often as they would have otherwise.

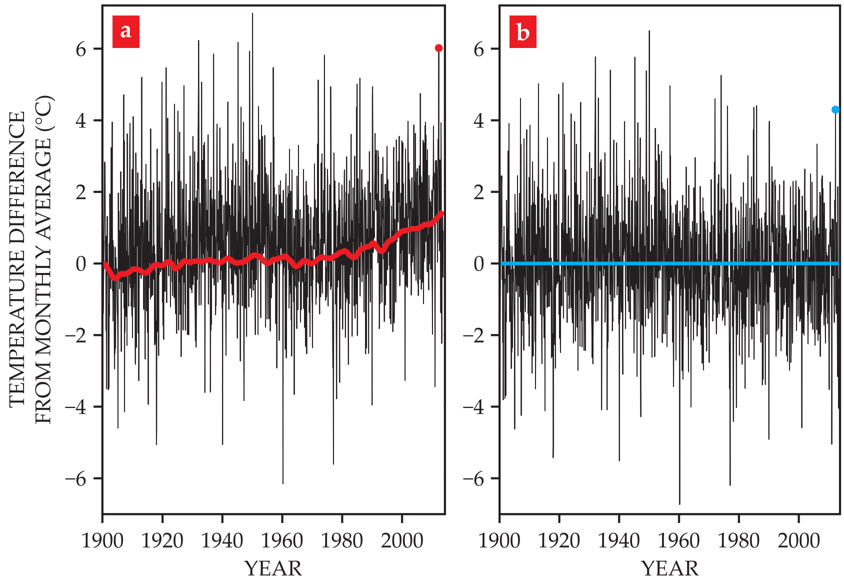


FIGURE 1. MONTHLY TEMPERATURE ANOMALIES in Durham, North Carolina, with and without global warming, 1900–2013. The black data in the panels show the anomalies. **(a)** The red curve gives the contribution due to global warming, as estimated by climate models. **(b)** When the global warming contribution is subtracted out, the remaining anomalies show the effects of natural climate variability. The horizontal blue line corresponds to zero anomaly. In March 2012, the +6 °C total anomaly shown in panel a (red dot) received the +4.25 °C natural contribution displayed in panel b (blue dot) and a +1.75 °C contribution from global warming.

A reader might think the three scientists fundamentally disagree on global warming's role in the heat wave. But the headlines could all be technically correct. The different *sounding* conclusions can all be drawn from looking at the same data from slightly different directions.

For headline A, the scientist needs to calculate global warming's contribution to the magnitude of the heat wave. Of the three, it is probably the most straightforward way to summarize the data. The left panel of figure 1 shows the monthly temperature anomaly[2]—the difference between the observed mean temperature for each month and the long-term average for that month of the year—for Durham from 1900 to 2013. The red line in the left panel is an estimate of long-term global warming in Durham, calculated from the average results of 27 independent simulations of physics-based numerical climate models.[3]

What would the temperature in Durham have looked like if there had been no global warming? We can calculate that by subtracting the estimate of global warming (red line) from each month's temperature anomaly (black). The result is shown in the right panel of figure 1. March 2012 would still have been a hot month even without global warming, but it would not have been as hot.

The result presented in headline A was thus calculated as follows: If the total anomaly with global warming in March 2012 was +6 °C and the contribution from natural variability was +4.25 °C, then global warming contributed +1.75 °C, or 29% of the anomaly, and the natural variability contribution was 71%.

Headline A quantifies how much global warming contributed to the magnitude of the heat wave, but let's now consider how much global warming contributed to the likelihood that the heat wave would occur in the first place.

Headlines B and C require the scientists to calculate global warming's influence on the change in the heat wave's likelihood. The conclusions of headlines B and C sound very different from one another, but arriving at those numbers requires similar calculations. Climate scientists often assume that in the absence of global warming, temperature anomalies follow some kind of probability distribution. There is precedent for thinking of surface-temperature anomalies as being normally distributed,[4] as is illustrated in figure 2. However, the quantitative results of this article, though not the qualitative point, are sensitive to the type of distribution assumed.[5]

Once a probability distribution is assumed, the next step is to notice how global warming has shifted the distribution over time. The top panel of figure 2 shows how the +1.75 °C change in the

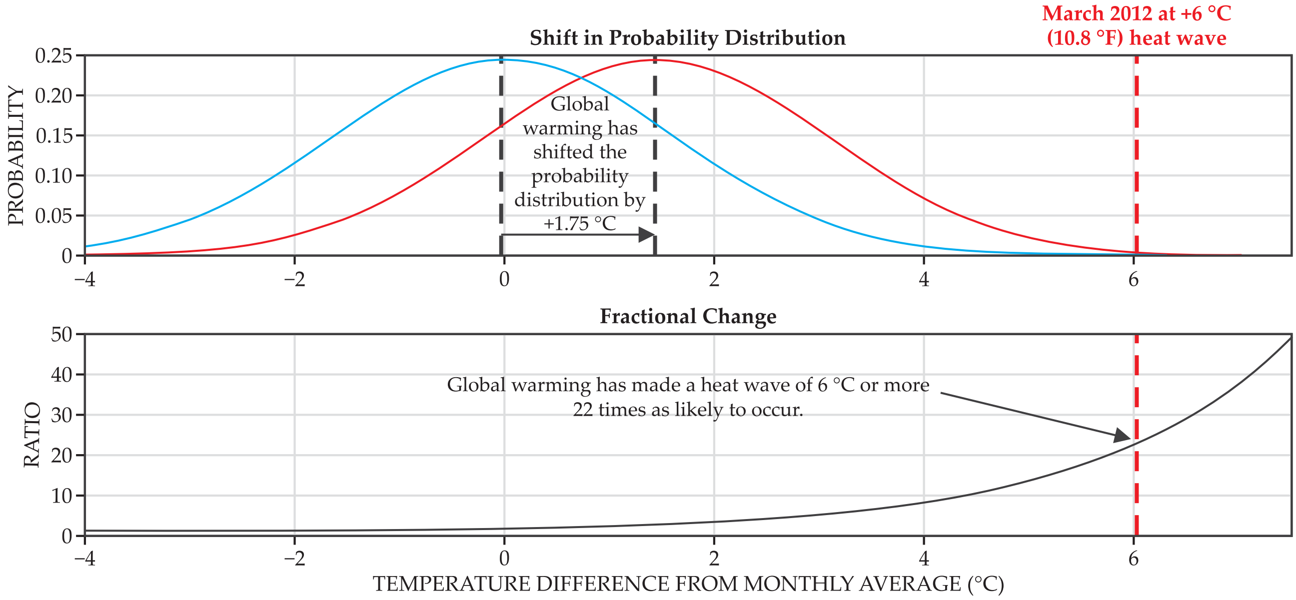


FIGURE 2. NORMAL DISTRIBUTION OF MONTHLY TEMPERATURE ANOMALIES in Durham, North Carolina, without global warming (blue) and with global warming (red). The shift due to global warming produces a small change in the absolute probability of a large temperature anomaly (top) but a big relative change (bottom).

baseline temperature from global warming has affected the probability of all temperature anomalies. So the result used in headline B was obtained as follows: Without global warming, an anomaly of +6 °C or warmer was very unlikely; its chance of occurring in any given month was about 0.0117%. Even considering that global warming shifted the mean of the distribution by +1.75 °C, an anomaly of +6 °C or greater was still very unlikely; its chance of occurring in any given month was about 0.26%. So global warming increased the chance of the March 2012 heat wave by approximately 0.25%.

The difference in probability with and without global warming may not seem big; however, the small shift in absolute probability translates into a big change in the return time (the time it takes on average to see a heat wave of a specified magnitude). A probability of 0.0117% for a +6 °C anomaly indicates that *without* global warming such an anomaly would be expected to occur once in 8550 months. However, a probability of 0.26% for a +6 °C anomaly indicates that *with* global warming the expectation is once in 380 months. Now the thought behind headline C becomes obvious: Global warming caused a heat wave of this magnitude or warmer to occur 22 times more often than would be the case without global warming.

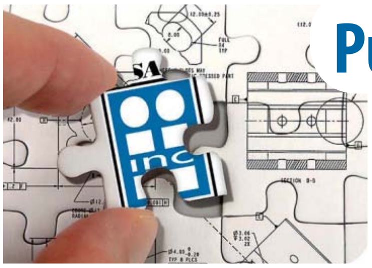
All three headlines are technically justifiable; they are simply different ways to present the data. Headline A says what proportion of the +6 °C anomaly is due to global warming. Headline B shows how much global warming changed the absolute probability of a heat wave of +6 °C or warmer. And headline C addresses how much global warming changed the expected frequency of a heat wave of +6 °C or warmer.

In my judgment, only headline B is fundamentally misleading. Since extremes have small probabilities by definition, a large relative change in the probability of an extreme will always seem small when expressed in terms of the absolute change in probability. Headlines A and C, on the other hand, quantify different pieces of information that can both be valuable when considering global warming's role in a heat wave. One of the lessons here is that writers with agendas have a great deal of latitude to craft headlines advancing the particular narrative they favor.

References

1. N. L. Bindoff et al., in *Climate Change 2013: The Physical Science Basis—Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker et al., eds., Cambridge U. Press (2013), chap. 10.
2. R. Rohde et al., *Geoinform. Geostat.: Overview* **1**, 1 (2013).
3. K. E. Taylor, R. J. Stouffer, G. A. Meehl, *Bull. Am. Meteorol. Soc.* **93**, 485 (2012).
4. J. Hansen, M. Sato, R. Ruedy, *Proc. Natl. Acad. Sci. USA* **109**, E2415 (2012).
5. F. E. L. Otto et al., *Geophys. Res. Lett.* **39**, L04702 (2012).

Patrick T. Brown
(*patrick.brown@duke.edu*)
Duke University
Durham, North Carolina



LETTERS

Perfection from a simpler time

The feature article "A perfect proposal" by Daniel Kleppner and Paul Horowitz (PHYSICS TODAY, January 2016, page 48) is enough to make a scientist cry. An entire field of science proposed in 800 words with a six-line equipment budget.

I suspect that proposal would not fare well today. It included no salary or fringe-benefits budget, no tuition budget, and no indirect cost recovery. No environmental impact statement was prepared, even though the antenna surely changed the aesthetics of the lab building, and it wasn't vetted by a grounds committee.

No bibliography was offered, no curriculum vitae were attached, and no figures were enclosed. The submission did not contain a "broader impacts" statement; since the impact was obvious to author and reviewer, why waste words?

The proposal included no mention of outreach or demographics. It gave deference to individual competitors rather than assembling a multi-investigator, cross-disciplinary team or demeaning the work of others. And the submitter had a reasonable expectation of a two-month review cycle and a high probability of funding.

Perhaps that's the point of the article: Much that attracted prior generations to science is now unfundable! If we came up with a proposal to fix what is so obviously broken with the grant and funding system, to whom would we send it?

Alexander Scheeline
(scheelin@illinois.edu)
University of Illinois at Urbana-Champaign

Thoughts on Einstein and general relativity

Recently I read that scientists have compared the vibrational frequency of a chemical bond of methane in a distant galaxy with that of methane here on Earth, and they now know that in the past 7 billion years, a particular nuclear force has remained unchanged to within at least 1 part in 10 billion. That experimental result failed to ease my mind regarding the world's stability, but it does illustrate the deep understanding we now have of our universe. Einstein's theory—surely one of humanity's grandest intellectual achievements—did open up new vistas that revealed the origin and evolution of our universe.

Just over 100 years ago, Albert Einstein published his general theory of relativity—10 years after his *annus mirabilis* when he, arguably, laid the foundations of quantum physics. In its broadest terms, the theory established the intimate connection between space, time, and matter. That inseparable relationship had no practical consequences under normal conditions, and Newton's well-established laws of motion needed to be modified only under very extreme ones—say, at speeds approaching the speed of light. So Einstein was astonished by the enormous fuss four years later, when an astronomical observation—the deflection of light by the Sun's gravity—confirmed his theory.

Einstein maintained that unlike Copernicus's theory, which demoted our planet from its central role in the solar system, his theory did not affect anyone's philosophy or worldview. Indeed, in 1915, when his eight-page paper "On the general theory of relativity" appeared in the *Proceedings of the Royal Prussian Academy of Sciences*, few people paid attention to it, and among physicists, there were more than a few skeptics.

Surprisingly for that time, Einstein presented his new theory to the general public even before it was quite finished, first in a newspaper article and soon after that in a popular lecture in Berlin's Treptow Observatory in June 1915. In fact, he gave nonspecialist lectures on relativity on many other occasions and also wrote a hugely successful book about it. Explaining your work to lay audiences is an excellent way to clarify your own ideas, but Einstein also saw it as a scientist's responsibility to society.[1]

That paper was one of seven articles he published in 1915. Another was entitled "My opinion on the war," in which he defended his pacifist position even as nationalistic fervor swept Germany. That Einstein was able to complete his theory under the prevailing circumstances is evidence of his extraordinary power of concentration.

World War I was in its second year, Berlin was experiencing a severe food shortage, and Einstein's personal life was in a shambles. His marriage to Mileva Marić had broken up the year before, and she had returned to Zürich with their two sons. Since then Einstein had been engaged in a bitter exchange of letters with her, even while he anxiously tried to retain a close relationship with his sons, who were 5 and 11 at the time. He had moved to an apartment not far from that of his cousin and good friend Elsa Löwenthal. A divorce agreement with Mileva became official in February 1919, and he married Elsa in June.

In November of that year, at a well-publicized meeting of the Royal Society in London, Arthur Eddington announced that his astronomical expeditions had measured the deflection of starlight by the Sun's gravitational field and that the result confirmed the general theory of relativity. Einstein became a worldwide celebrity overnight, and his life was changed irrevocably.

Reference

1. J. Eisinger, *Einstein at Home*, Prometheus Books (2016); *Einstein on the Road*, Prometheus Books (2011).

Josef Eisinger
(eisi@alum.mit.edu)
New York City

Harassment in our community: An open letter

Dear senior astrophysicists, physicists, and planetary scientists, including observatory directors, project leaders, program administrators, and department chairs:

In recent months a litany of harassment cases in our community have come to light. In all of those cases, senior members of the community were documented to have caused extensive and direct harm to some of our most vulnerable members. Troublingly, the public cases are only a small fraction of those that currently afflict our community; for every case of harassment publicly revealed, many, many more go uninvestigated or even unreported. For example, although we know there are many instances of racial harassment and harassment of people with disabilities in our community, those problems remain largely undiscussed and hidden. The entire situation is unacceptable.

Many members of the community are discussing the situation and striving to find ways to change it, but change will not occur without the vital involvement of those in positions of power and influence. Thus we call on you, our senior members, to enact the reforms necessary to put an end to the ongoing harassment of disabled people; members of the lesbian, gay, bisexual, and transgender community; people of color; women; and other underrepresented minorities.

Harassment has too often been met with inadequate and problematic responses from those in power. The vast majority of institutions have remained eerily quiet on the subject, and many senior scientists and community leaders have shown great reluctance to engage with any real, meaningful change. When action has been taken at all, it has largely been only after bad press made it clear that the harassment could no longer be ignored. Before outside pressure is applied, administrators frequently show little willingness to hold harassers, especially those in senior positions, responsible for the harm they have done. When an investigation does occur and finds someone guilty of violating an institution's policies, the punitive measures taken often are too meager to encourage reform or to redress the harm that has been done to the victims and to the broader community. Instead we have seen the harassers afforded various means of protection.

Senior members have, in words and actions, treated the harassers as victims without acknowledging the destructive effects of their behavior, and they have simultaneously dismissed as troublemakers the victims and allies who report abuse. When abuse is called out, responses often include special pleading that the abuse was committed by "only" a small number of scientists, a problematic response that derails discussion about reform and excuses most of the community from our common responsibility to enact change. This culture and type of discussion hampers action and enables abuse.

The status quo is intolerable and represents a failure of leadership.

It is vitally important that senior members of the community demonstrate strong leadership on this issue. It is not the sole responsibility of victims or junior members of the community to solve the problem, but time and again it has fallen on just those people to do the labor of supporting and fighting for the health, safety, and well-being of the vulnerable. True reform requires buy-in and support from members of the community at all levels, and most critically at the senior level.

The situation as it stands has had a disastrous effect on the community and on the production of scientific knowledge. Many talented scientists, scholars, and promising students have already left the field due to experiences with harassment. With them go all their hard work and creative insights that could have contributed to scientific progress. If our

PHYSICS TODAY Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page PHYSICS TODAY

current climate of harassment remains unchanged, we stand to lose a great deal, both personally and professionally, in our field. It is imperative that you, the leaders of our community, change the climate to one where all are truly welcomed and given an equal chance to flourish.

We call on senior leaders in astrophysics, physics, and planetary science to do the following:

- Do all you can to protect the victims of harassment.
- Do your due diligence to research and understand the problems regarding harassment and their solutions.
- Instead of just working to do the minimum required by law, work to create the best possible environment for all.
- Call out behavior that promotes harassment, even if it is not illegal. Intervene to protect vulnerable members of the community.
- Make sure your antiharassment policies are concisely worded with clear definitions, reporting procedures, and consequences.
- Take your own antiharassment policies seriously and enact the disciplinary actions that are a part of them.
- Remove harassers from positions of power or venues where they can continue to harass, and do not allow them to be passed between positions or institutions.
- Stop collaborating with harassers and their enablers.
- Stop appointing harassers and enablers to positions of power.

We have the potential to build a better, healthier, and ultimately more productive community, but to do that we need senior leaders to commit to enforcing standards of acceptable behavior that support the equitable treatment of all people in our community.

A version of this letter has been signed, as of this writing, by 393 scientists from around the world. For a full list of signatures, see https://sites.google.com/site/openlettertoseniorscience.

CONTACT PHYSICS TODAY

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

Coauthor credit

The letter above my signature in the August issue of PHYSICS TODAY (page 12) was coauthored by David H. Sharp. I apologize for the submission oversight.

Terry Goldman
University of New Mexico, Albuquerque

Corrections

August 2016, page 40—Meghnad Saha boarded at the Eden Hindu Hostel in Calcutta.

August 2016, page 44—The Saha Institute of Nuclear Physics was formally inaugurated by Irène Joliot-Curie. PT

SEARCH & DISCOVERY

Sterile neutrinos give IceCube and other experiments the cold shoulder

Recent null results heighten the tension between the bulk of neutrino experiments and the few that hint at the putative particle's existence.

FIGURE 1. THE ICECUBE LABORATORY sits under the serene glow of the aurora australis at the South Pole. Kilometers below the Antarctic ice, 5160 photodetectors watch for Cherenkov light from charged particles that are produced when atmospheric neutrinos collide with nuclei in the bedrock or ice. (Photo by Ian Rees, IceCube/NSF.)

Under kilometers of ice at the South Pole, the IceCube Neutrino Observatory's 5160 optical detectors keep watch for neutrinos that have traveled through Earth from the opposite side of the globe. (See the article by Francis Halzen and Spencer R. Klein, PHYSICS TODAY, May 2008, page 29.) The observatory was built primarily to serve as a telescope to study neutrinos from astrophysical sources. However, it also detects neutrinos born in the aftermath of cosmic-ray protons crashing into nuclei in the upper atmosphere. About once every six minutes, one of those atmospheric neutrinos finds its way to IceCube's monitoring zone, collides with a nucleus in the ice or bedrock, and produces a charged particle that can be detected from the Cherenkov light it gives off. Figure 1 shows the IceCube Laboratory, which houses the computers that collect and process raw data.

The standard model of particle physics posits the existence of three flavors of neutrinos. Among IceCube's many scientific quarries are signs that some of the atmospheric neutrinos, during their transit through Earth, transform into sterile neutrinos—hypothetical particles that interact with other matter only via gravity. A recent analysis of 20 145 high-energy atmospheric neutrino events from 2011–12 has yielded no such sign.[1]

Meanwhile, researchers from MINOS (Main Injector Neutrino Oscillation Search) and the Daya Bay Reactor Neutrino Experiment recently joined forces. MINOS is an accelerator-neutrino experiment at Fermilab; Daya Bay is a reactor-based experiment in South China. When the joint collaboration analyzed data from the two experiments, along with data from a third source, the Bugey-3 reactor-neutrino experiment in France, the researchers, too, found no evidence for sterile neutrinos.[2]

Although the results don't rule out sterile neutrinos, they do place stringent limits on how a possible sterile neutrino might mix with the three well-established ones. In so doing, they heighten the tension between a handful of experiments that have tantalizingly hinted at an unseen sterile neutrino and those that are perfectly compatible with the usual three flavors: electron, muon, and tau.

The sterile hypothesis

Neutrino flavors, which are eigenstates of the weak interaction, are quantum mechanical superpositions of mass eigenstates. Because the mass eigenstates have different masses, each one propagates differently. Thus a neutrino born as one superposition, after propagating some distance, can evolve into a different superposition. The flavor- and mass-eigenstate bases are related by the unitary transformation $|\nu_i\rangle = \sum_\alpha U_{\alpha i}|\nu_\alpha\rangle$, where $U_{\alpha i}$ is the amplitude for mass state i to be in flavor state α. The matrix elements $U_{\alpha i}$ are conventionally expressed in terms of so-called mixing angles. Oscillations between flavor states are then characterized by the mixing angles and by the differences Δm^2 between the squared masses of the mass eigenstates.

Neutrino-oscillation experiments come in two varieties: those that track the

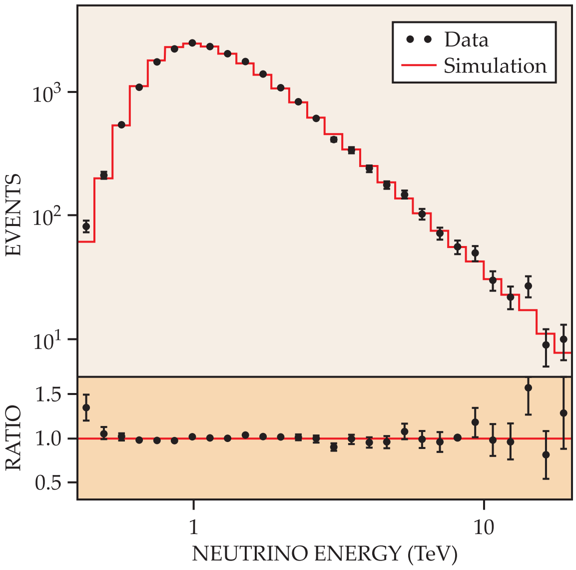


FIGURE 2. ICECUBE ENERGY SPECTRUM. The number of observed atmospheric muon neutrinos compared with a Monte Carlo simulation that assumes no sterile neutrinos. The lower panel shows the ratio of observed to simulated events. If oscillations into sterile neutrinos with a mass of 1 eV were present, a dip in the spectrum would appear at a neutrino energy of 3 TeV. (Adapted from ref. 1.)

disappearance of a particular neutrino flavor while in transit and those that detect the appearance of a neutrino flavor that wasn't present at the source. In the 1990s the appearance-type LSND (Liquid Scintillator Neutrino Detector) experiment at Los Alamos National Laboratory set out to look for electron antineutrinos ($\bar{\nu}_e$) 30 m downstream from where a proton beam slammed into a beamstop to produce muon antineutrinos ($\bar{\nu}_\mu$). (See PHYSICS TODAY, August 1995, page 20.)

In 1995 the LSND team reported finding excess numbers of $\bar{\nu}_e$ in their $\bar{\nu}_\mu$ beam. The result, which implied a $\Delta m^2 \approx 1\ \text{eV}^2$, has come to be known as the LSND anomaly because the standard three-neutrino model can't reconcile such a large Δm^2 with those deduced from atmospheric- and solar-neutrino experiments, which are an order of magnitude smaller. One attractive way out of that predicament is to augment the model with a sterile neutrino with a mass of roughly 1 eV.

Light sterile neutrinos of the kind implied by LSND were unanticipated. In its simplest form, the leading theoretical treatment of sterile neutrino flavors, called the seesaw model, invokes three TeV-mass-range sterile neutrinos—one partnered with each known neutrino—whose decay properties can account for the matter–antimatter imbalance in the universe. Another idea proposes a keV-mass sterile neutrino as a dark-matter candidate. "There's not a whole bunch of theoretical models that scream that these light sterile neutrinos need to exist," explains Fermilab theorist Boris Kayser. Thus, he says, searches for light sterile neutrinos have been driven largely by experimental hints.

Those hints emerged from the LSND experiment, but they didn't stop there. MiniBooNE, an accelerator experiment at Fermilab, first discounted the LSND results, but then reopened the account when additional measurements showed that the ν_μ to ν_e oscillation might be different from the $\bar{\nu}_\mu$ to $\bar{\nu}_e$ oscillation. (See PHYSICS TODAY, October 2010, page 14.)

Recent improvements in models of $\bar{\nu}_e$ production inside nuclear reactors prompted reevaluations of reactor experiments from the 1990s. Those improved models predicted a 6% greater $\bar{\nu}_e$ flux than the old experiments saw (see PHYSICS TODAY, May 2016, page 16). That reactor antineutrino anomaly could be explained by an eV-mass sterile neutrino.

Also in the 1990s, Gallex (short for Gallium Experiment) at Italy's Gran Sasso National Laboratory and SAGE (Soviet-American Gallium Experiment) at the Baksan Neutrino Observatory in Russia used radioactive chromium-51 (and later argon-37 at SAGE) as a ν_e source to test the performance of their radiochemical solar-neutrino detectors. The two experiments detected 15–20% fewer neutrinos than expected. Called the gallium anomaly, the results are again explainable with an eV-mass sterile neutrino.

Lamppost in the desert

IceCube's principal investigator, Francis Halzen (University of Wisconsin–Madison), says that the space of mass-squared differences and mixing angles that could support a putative sterile neu-

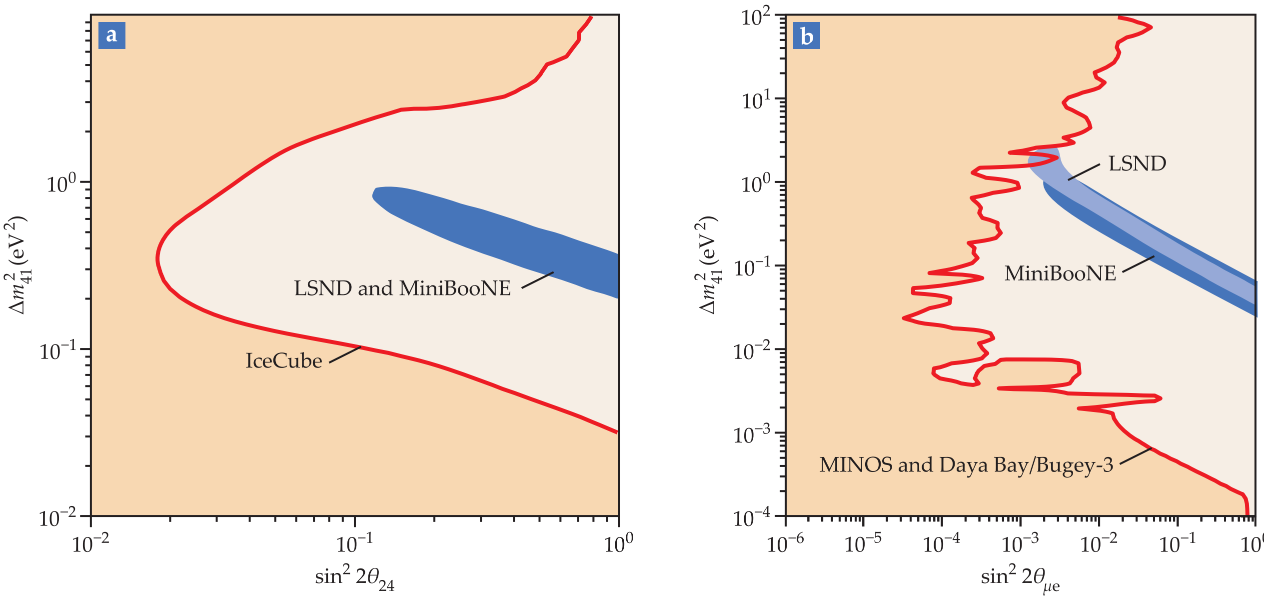


FIGURE 3. THE SIMPLEST EXTENSION of the standard three-neutrino picture adds one sterile flavor state and thus a fourth mass eigenstate. **(a)** Based on that extension, an analysis of atmospheric muon neutrino observations by the IceCube Neutrino Observatory excludes the unshaded region of parameter space to the right of the red line at a 90% confidence level. That exclusion is in conflict with the allowed region for sterile neutrinos from a combined fit of LSND (Liquid Scintillator Neutrino Detector) and MiniBooNE experiments (dark blue). (Adapted from ref. 1.) **(b)** A combined evaluation of the MINOS (Main Injector Neutrino Oscillation Search) accelerator experiment and the Daya Bay and Bugey-3 reactor experiments appears to exclude separately fitted LSND (light blue) and MiniBooNE (dark blue) allowed regions. Similar to panel a, the region to the right of the red line is excluded at a 90% confidence level. The composite parameter $\theta_{\mu e}$ characterizes the oscillation between muon and electron flavor states that involves the fourth mass eigenstate. (Adapted from ref. 2.)

trino is like an infinite desert at night. "Twenty years ago," he says, "the LSND experiment put a lamppost in this desert of parameters."

As fortune would have it, IceCube is well suited to test the LSND anomaly. At neutrino energies of 320 GeV–20 TeV, the range that the IceCube researchers analyzed for their sterile search, interactions with matter can resonantly enhance neutrino oscillation. "And it turns out that if you throw in a sterile neutrino, everything changes," says Halzen.

The IceCube collaboration considered the simplest possible model, one with the three known neutrinos and one sterile neutrino of eV-range mass. For such a model, IceCube's detectors should see ν_μ events disappear at a 3 TeV resonant energy. Figure 2 shows the ν_μ energy spectrum detected by IceCube. Says Halzen, "This resonance is there or it's not. And it's not."

As shown in figure 3a, the results appear to rule out the region of parameter space consistent with the LSND and MiniBooNE observations. An independent analysis of publicly available IceCube data by Jiajun Liao and Danny Marfatia, both at the University of Hawaii, at Manoa, drew similar exclusions.[3] However, Liao and Marfatia caution that if nonstandard neutrino–matter interactions are sufficiently large, the limits might be evaded. Halzen concedes that more complex models could circumvent the IceCube limits, but he isn't impressed. If ways around the limits can be conceived, Halzen says, it just means "now it's the Wild West."

More no news

The MINOS experiment tracked neutrino disappearance by comparing the ν_μ flux at a detector 1 km downstream from the source with the flux at a second detector 734 km away. Oscillations into sterile neutrinos, depending on the sterile mass, would show up either as a deviation from the expected energy spectrum or as a reduction in total ν_μ flux observed at the two detectors.

Daya Bay monitors electron antineutrinos that originate from six nuclear reactors at the eponymous reactor complex in China's Guangdong province. The reactor cores are located 300 m to 2 km from the experiment's eight liquid-scintillator detectors. The presence of sterile neutrinos would distort the $\bar{\nu}_e$ energy spectrum. But given the detector–source distances, Daya Bay is mostly sensitive to Δm^2 less than 0.1 eV^2. Bugey-3 was a reactor experiment carried out in the 1990s that used two liquid-scintillator detectors to measure the $\bar{\nu}_e$ flux from two reactors in a power plant in eastern France. Because Bugey-3 had detectors closer to the reactors, it was more sensitive to Δm^2 in the eV^2 range.

Like IceCube's analysis, the one by the MINOS–Daya Bay team also considered one sterile flavor and one additional mass eigenstate. And again, the results appear to exclude the portion of parameter space allowed by LSND and MiniBooNE, as shown in figure 3b.

Missing but not gone

Now that IceCube and MINOS–Daya Bay appear to have removed what Halzen calls the LSND lamppost, what's to be done? As MIT's Janet Conrad, a member of the IceCube collaboration, points out, "Disappearance experiments also have anomalies." Including the gallium and reactor antineutrino anomalies and the new IceCube results in global fits of existing oscillation data tends to shift allowed regions to greater Δm^2. "That illustrates how important it is to consider all of the data," she says. "Sterile neutrinos are slippery little beasts."

The quest continues. Several planned experiments—the Precision Oscillation and Spectrum Experiment at Oak Ridge National Laboratory, the Detector of Anti-Neutrino based on Solid Scintillator project at the Kalinin Nuclear Power Plant in Russia, and the Stereo experiment at the Institut Laue–Langevin in France—aim to suss out the reactor antineutrino anomaly. At Fermilab, the Short-Baseline Neutrino Program to search for sterile neutrinos will have a complement of three detectors—Imaging Cosmic and Rare Underground Signals detector, MicroBooNE, and the Short-Baseline Near Detector—to monitor an accelerator neutrino source (see PHYSICS TODAY, July 2015, page 23). MicroBooNE began collecting data last October as a standalone experiment. "There's a big global effort to do future experiments," says Kayser. "This is an experimental question. And we really need experiments to settle the issue."

Sung Chang

References

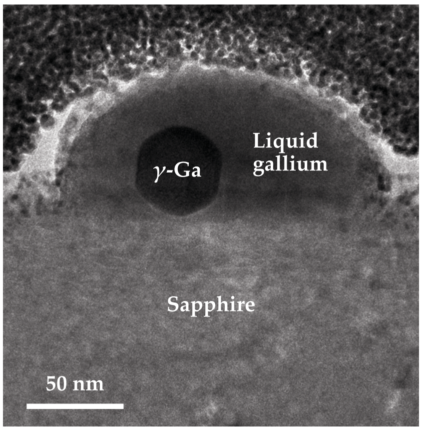
1. M. G. Aartsen et al. (IceCube collaboration), *Phys. Rev. Lett.* **117**, 071801 (2016).
2. P. Adamson et al. (Daya Bay, MINOS collaborations), *Phys. Rev. Lett.* (in press).
3. J. Liao, D. Marfatia, *Phys. Rev. Lett.* **117**, 071802 (2016).

A droplet that won't freeze harbors a crystal that won't melt

The gallium nanodroplet's anomalous phase behavior is a new twist on the maxim "small is different."

To the casual observer, the tiny crystal of gallium visible in the adjacent figure might seem remarkable primarily for its scale, just 40 nm—roughly 100 atoms—in diameter. But for the University of Western Australia's Alexandra Suvorova, who took the transmission electron microscope (TEM) image, the bigger surprise was that the speck of frozen Ga was there at all. According to the metal's phase diagram, the observed crystalline structure—a hexagonally packed arrangement known as the γ phase—occurs only at temperatures below 236 K, far cooler than the ambient temperature at which the image was taken.

Moreover, the diminutive lump of solid is enveloped in a shell of molten Ga, which seems to fly in the face of conventional rules of thermodynamics. Those rules stipulate that at a fixed pressure, a pure substance's liquid and solid phases can coexist at precisely one temperature, the melting point. For Ga at atmospheric pressure, that temperature is around 303 K, several kelvin hotter than Suvorova's droplet. Even when the droplet is chilled below 200 K or heated to 800 K, it retains its two-phase character. The finding,[1] newly reported by a team led by Maria Losurdo (CNR-NANOTEC, Bari, Italy) and April Brown (Duke University), has theorists scratching their heads.



A BURIED GEM. At the core of the molten gallium nanodroplet shown here, the metal adopts a crystalline form known as the γ phase. The liquid and solid phases coexist over a temperature range of more than 600 K. Interactions between the droplet and the underlying sapphire substrate are thought to cause the anomalous behavior. (Adapted from ref. 1.)

Nicola Gaston, a physicist at the University of Auckland, has been studying metal nanoparticles for more than a decade and says she's never seen anything quite like it. Experiments have generated indirect evidence of coexistence, she says, "but they've never produced anything so clear as this."

Gaston adds that the earlier experiments tended to suggest solid–liquid coexistence in small temperature windows of "maybe 5 K or 10 K." Those observations fit with the predictions of numerical models that account for finite-size effects that become significant at nanometer length scales.[2] But the models can't explain the 600 K coexistence range observed for the Ga nanodroplets.

Losurdo and her colleagues suspect that the unusual behavior is related to the droplet's interactions with the underlying sapphire support. Because sapphire's crystalline lattice nearly matches that of γ-Ga in size and shape, the partial crystallization of Ga at the sapphire surface would relieve interfacial stress and reduce the droplet's energy—even at temperatures ordinarily too high for the solid to exist. At the droplet's outer surface, the high energetic cost of forming a gas–solid interface would prevent the liquid shell from completely freezing.

When collaborating theorist Kurt Hingerl (Johannes Kepler University Linz) modified standard energy-balance equations to include those surface effects, he got results consistent with the group's working hypothesis. Follow-up experiments provided yet more supporting evidence: Solid cores failed to materialize in Ga droplets deposited on amorphous glass instead of sapphire. Still, Hingerl acknowledges, the team's theoretical model remains incomplete. It doesn't explain, for instance, why only a small fraction of the Ga along the sapphire boundary crystallizes, despite energy balances that indicate an overwhelming preference for the solid–solid interface.

As Gaston sees it, however, the TEM images alone are reason enough for excitement. Interfaces buried in the interiors of metal nanoparticles are both notoriously difficult and important to study. Understanding how they form and evolve is crucial to deploying the particles in phase-change memories, nanoplasmonics, and other applications. (For more on metal nanoparticles, see PHYSICS TODAY, June 2007, page 26.) Losurdo and her colleagues aren't the first group to use TEM to tackle that problem, but they were able to achieve exceptional resolution—high enough, for example, to confirm theoretical predictions that Ga's solid–liquid interfaces are not atomically abrupt but roughly four atoms thick.

"The quality of the experimental images is fantastic," comments Gaston. "Soon we'll be able to combine these kinds of experiments with theory to start sketching out phase diagrams at the nanoscale."

Ashley G. Smart

References

1. M. Losurdo et al., *Nat. Mater.* **15**, 995 (2016).
2. A. Aguado, M. F. Jarrold, *Annu. Rev. Phys. Chem.* **62**, 151 (2011).

Solid-state NMR resolves protein structures—no deuteration required

Spinning the samples at extraordinarily high frequency is key to untangling the biomolecules' complicated spectra.

A murder-mystery villain, if she were resourceful and patient enough, could bring about her victim's demise by replacing all his drinking water with heavy, or deuterated, water. That's because D_2O, although superficially similar to H_2O, behaves differently enough in enzymatic reactions that in large quantities it's detrimental to living tissues. Rats die within a week when given nothing but D_2O to drink.

Escherichia coli bacteria, on the other hand, can survive in D_2O. That's fortunate for protein researchers, who genetically engineer the bacteria to manufacture deuterated proteins to use in nuclear magnetic resonance spectroscopy: Replacing most of a protein's abundant magnetic hydrogen-1 atoms with deuterium, which is invisible to NMR tuned to ^{1}H, helps to simplify the spectrum. To ensure uniform isotopic substitution, researchers first use bacteria to create entirely deuterated proteins, then back-substitute some

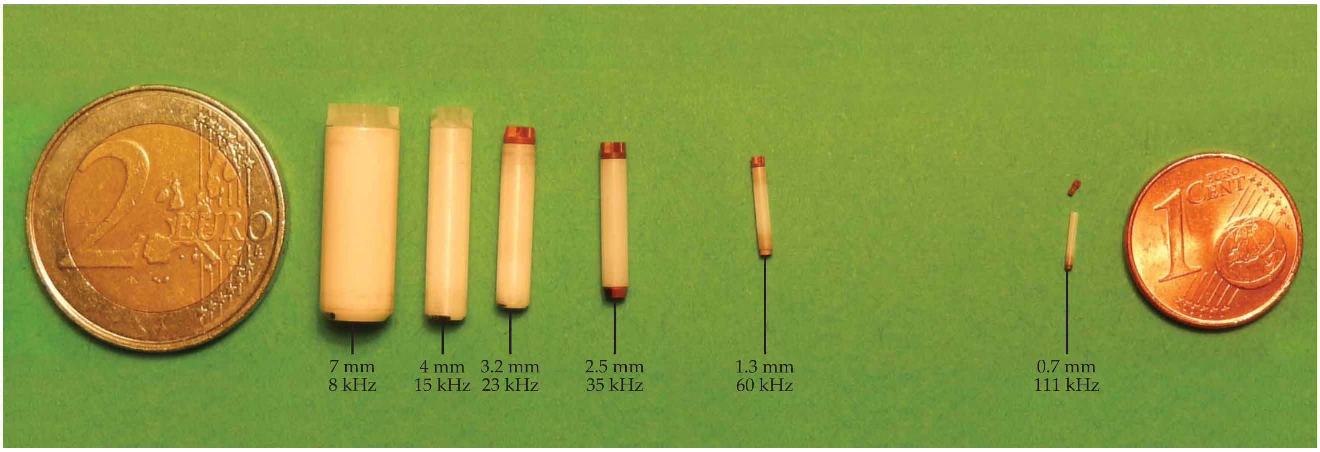


FIGURE 1. IN MAGIC-ANGLE SPINNING NMR, a sample is loaded into a cylindrical rotor that is spun rapidly to mimic the effects of molecules tumbling in a fluid. As shown here, the maximum spinning frequency depends on the rotor diameter. The smallest rotor, 0.7 mm in diameter, was recently debuted. (Courtesy of Guido Pintacuda.)

of the D atoms with ^{1}H at predetermined chemical locations.

Although D_2O doesn't kill the bacteria, it slows their metabolism, and they produce protein only in minute amounts. Furthermore, the back-protonation step isn't easy. As a result, partially deuterated samples are difficult and expensive to make—and for many proteins, not even possible.

Now Guido Pintacuda and colleagues at the European Center for High-Field NMR in Lyon, France, have used ^{1}H NMR to find the structures of two nondeuterated proteins, including a virus coat protein whose structure was previously unknown.[1] To narrow and separate the spectral peaks, the researchers were aided by some of the most advanced equipment in the world, including an NMR spectrometer with a magnetic field of more than 23 T. More importantly, they took a decades-old technique called magic-angle spinning (MAS) and boosted its effectiveness by rotating their samples at speeds of more than 100 kHz. Such high spinning frequencies became possible only a few years ago.

Magnetic dynamics

NMR is widely used to elucidate the structures of molecules both large and small. When placed in a magnetic field, a molecule's magnetic nuclei precess at a field-dependent frequency. But the local field felt by each nucleus isn't exactly equal to the applied field: It's slightly modified, for example, by the swirling cloud of electrons surrounding the nucleus and by proximity to other magnetic nuclei. The spectrum of those deviations, called chemical shifts and measured in parts per million, provides information about the specific environment of each nucleus and thus about the molecule's structure.

For a small, simple molecule, a one-dimensional spectrum of chemical shifts may contain enough information to determine the structure. But for larger molecules, researchers typically require multidimensional spectra: Applying specially designed sequences of RF pulses, they probe spin excitations that coherently hop from one atom to another, with each chemical shift recorded on a separate, orthogonal axis. Such a spectrum offers invaluable clues about which of a molecule's atoms—or which of a protein's amino acids—are spatially close enough to transfer a spin excitation between them.

But that's not all. The pulse sequences for multidimensional NMR spectra can be tailored to probe and follow changes in the molecule on time scales of picoseconds to milliseconds—not just changes in spin states, but also movements of atoms. That capability gives NMR one of its biggest advantages over other techniques for investigating protein structures. X-ray crystallography and cryo-electron microscopy, for example, can resolve structures with exquisite resolution. (For more on cryo-EM, see PHYSICS TODAY, August 2016, page 13.) But both techniques are limited to molecules in static environments—immobilized in a crystal or frozen in a sheet of ice. NMR can probe not just a protein's structure but also the dynamic processes that are central to its biological function.

Conventional solution-phase NMR relies on molecules' rapid random tumbling to average out anisotropic dipolar couplings between nuclei. But that averaging doesn't work for solids and solid-like samples, such as viscous, sticky agglomerates of bulky biomolecules. In those cases, each spectral line is broadened into a thicket of unresolved lines arising from molecules with different orientations. Fortunately, researchers can recover the benefits of rapid tumbling by spinning the sample about an axis oriented at a particular "magic" angle, 54.7°, with respect to the field. At that angle, nuclear couplings fall to zero. (See the article by Clare Grey and Robert Tycko, PHYSICS TODAY, September 2009, page 44.)

The higher the spinning frequency, the more effective MAS is at narrowing and resolving spectral lines, but frequency is limited by the size of the cylindrical rotor that houses the sample. Spinning a too-large rotor too quickly can destroy the sample through frictional heating, destabilize the gas-lubricated rotation, or even disintegrate the rotor itself. Figure 1 shows some examples of rotors and their maximum spinning speeds. The smallest one, at 0.7 mm in diameter, was designed for the new experiments by Pintacuda's collaborators at Bruker Biospin in Germany.

The march to higher MAS frequencies has been a decades-long technical challenge. Building and operating a smaller rotor requires miniaturizing everything from the cooling system to the seals that hold the container closed. It also entails inserting a gooey protein sample into a container the size of a mechanical pencil lead. A further challenge: Shrinking the sample itself, all else being equal, lowers the measurement sensitivity.

Isotope exchange

Although the spin precession of any magnetic isotope can be the basis for an NMR spectrum, solution-phase experiments are most often tuned to detect ^{1}H. Its large gyromagnetic ratio leads to strong signals, and its high natural abundance means that samples can be prepared without any special isotopic labeling. But in solid-state NMR, dipole–dipole coupling between ^{1}H nuclei is a major source of anisotropic line broadening that MAS at modest frequencies can't adequately reverse.

As a result, nearly all solid-state NMR experiments were, until recently, based on isotopes other than ^{1}H; for proteins and other biomolecules, that usually meant carbon-13 and nitrogen-15. Because of the low natural abundances of those isotopes, samples had to be isotopically enriched. The process is similar to deuteration: Insert the gene for the protein into bacteria that are fed with isotopically enriched nutrients. Fortunately, bacterial metabolism isn't slowed by ^{13}C and ^{15}N the way it is by D_2O.

Both ^{13}C and ^{15}N have low gyromagnetic ratios. To obtain reasonable signals from those nuclei, researchers needed relatively large samples, which limited MAS frequencies. For example, in 2002 when Hartmut Oschkinat and colleagues obtained the first complete structure of a protein[2] from ^{13}C and ^{15}N MAS NMR, they used several protein samples of 6–10 mg each, packed into 4-mm-diameter rotors spun at just 8–13 kHz. Although faster spinning is possible with a rotor that size, the need for many-milligram samples was thought to place an effective cap on the frequencies that would ever be feasible.

Around the same time, several groups were experimenting with ^{1}H NMR on heavily deuterated samples; in 2007 Chad Rienstra and colleagues used the method to resolve the structure of GB1, a model protein often used to test solid-state NMR techniques.[3] The switch from ^{13}C and ^{15}N to ^{1}H boosted the signal by almost an order of magnitude and motivated the development of smaller rotors and higher MAS frequencies. Much of the progress was spearheaded by Ago Samoson, of the Tallinn University of Technology in Estonia, and his colleagues, who crossed the 100 kHz threshold with a protein sample in 2012.

In 2014 Samoson collaborated with Matthias Ernst, Beat Meier (both at ETH Zürich), and Anja Böckmann (at the University of Lyon) to resolve a protein structure with 100-kHz MAS NMR from two samples of just 0.5 mg mass, each placed in a 0.8 mm rotor.[4] Pintacuda's new work, in comparison, used a single 0.5 mg sample of each protein.

The expense of growing bacteria in D_2O is less daunting when all that's needed is a milligram of protein, but the challenge of back-protonation remains a limitation. Each of a protein's amino acids contains one H site—the so-called amide H, bound to the N atom that puts the "amino" in "amino acid"—that's more easily displaced than the rest. When a deuterated protein comes in contact with H_2O, amide D atoms readily change places with H atoms in the water, while the rest of the protein's D atoms remain in place.

But that process can swap *all* the amide D atoms only if the protein is not yet folded, or if it's prone to quick, stochastic folding and unfolding. For proteins that fold tightly and remain folded, the only amide D atoms that are exchanged are the ones near the surface of the folded structure. Large parts of the protein remain invisible to the NMR study. And the class of tightly folded proteins includes many of particular medical interest, including membrane proteins (which are often the targets of drugs) and virus capsids. Misfolded proteins known as amyloid fibrils, which are associated with Alzheimer's and Parkinson's diseases (see the article by Tuomas Knowles, Michele Vendruscolo, and Christopher Dobson, PHYSICS TODAY, March 2015, page 36), are also best addressed by solid-state NMR in fully protonated form.

Virus frontiers

Pintacuda and colleagues' initial plan was for a proof-of-principle study of the fully protonated form of GB1, the model protein used by Rienstra and colleagues. But on the strength of those results, the researchers decided also to look at the virus protein AP205CP (short for *Acinetobacter* phage 205 coat protein), whose structure had yet to be resolved by any technique. The protein is a dimer consisting of two copies of a sequence of 130 amino acids; 90 copies of the dimer, in turn, make up the virus capsid. And it's an illustrative example of how back-protonation doesn't always work.

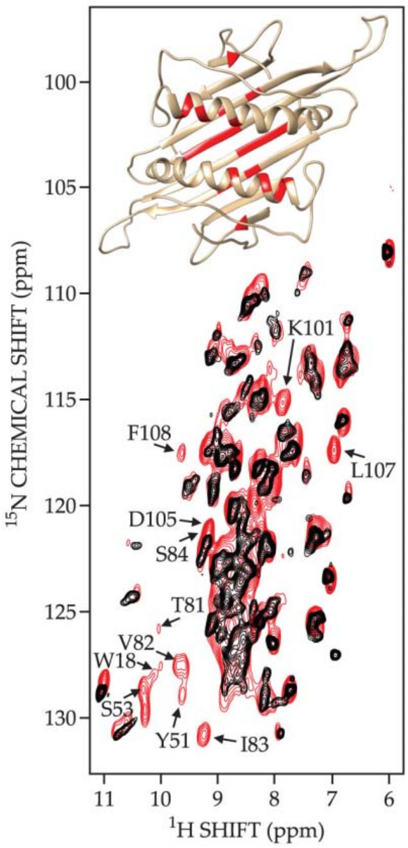


FIGURE 2. TWO-DIMENSIONAL NMR SPECTRA of the virus coat protein AP205CP, partially deuterated (black) and fully protonated (red). The labeled amino-acid spectral peaks in the fully protonated spectrum are missing from the partially deuterated one; for example, "V82" indicates the 82nd amino acid in the protein, which is valine. The missing amino acids' positions are shaded in red in the structural diagram at the top. (Adapted from ref. 1.)

Figure 2 shows two versions of a 2D spectrum of AP205CP's amide H atoms and their associated N atoms. The spectrum of a deuterated, back-protonated sample is shown in black. The spectrum of the fully protonated sample, shown in red, has several peaks that the black spectrum lacks; those additional peaks correspond to amide sites on the deuterated protein that couldn't be exchanged.

Also shown is the NMR protein structure, with the locations of the unexchangeable amides shaded in red.

Pintacuda and colleagues didn't need to deuterate their sample, but they did use ^{13}C and ^{15}N labeling to get information about the positions of C and N atoms. So their method is still limited to proteins that can be grown in laboratory cell cultures—they can't, for example, harvest a protein sample directly from a human patient. Pintacuda speculates that it could one day be possible to find a solid-state NMR structure of a protein using no isotopic labeling at all, merely the naturally present magnetic nuclei. "But resolving the proton resonances would be much harder," he says, "because we wouldn't have the information from nearby carbons and nitrogens."

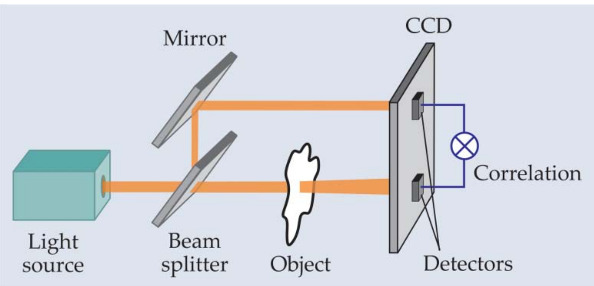
Although GB1 and AP205CP are both

PHYSICS UPDATE

These items, with supplementary material, first appeared at www.physicstoday.org.

X-RAY GHOST IMAGING

In its basic form, ghost imaging is a technique that indirectly produces a likeness of an object by combining the information from two light detectors—one that views the object and one that doesn't. By splitting a speckled laser beam so that two beams strike spatially separated locations on a CCD camera screen and by placing an object in one of the beams, as shown here, researchers can calculate the intensity correlations between the two signals as the beams are scanned in synchrony and construct the object's ghost image. Demonstrated in 2002 using visible light, the technique holds promise for remote atmospheric sensing because of its insensitivity to turbulence. Two research groups have now extended ghost imaging to the hard x-ray regime. Daniele Pelliccia (RMIT University in Australia) and his colleagues passed an x-ray beam produced by the European Synchrotron source through a diffracting silicon crystal grating oriented to transmit part of the undiffracted beam at a slight angle from the diffracted beam. An ultrafast camera placed 20 cm downstream of the beamsplitter detected both signals—one of which was partially blocked by the imaging target, a copper wire.



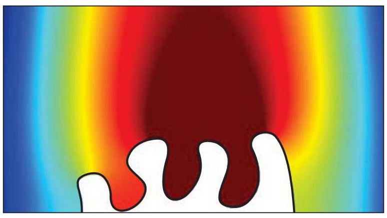
Because the system worked with individual synchrotron pulses, retrieving the wire's ghost image took more than just calculating intensity correlations; the group also had to filter out low-frequency artifacts associated with mechanical vibrations induced by the synchrotron pulse rate. By contrast, Hong Yu (Chinese Academy of Sciences) and colleagues periodically moved their test object—a gold film with five slits—into and out of a synchrotron's x-ray beam to create their intensity-correlated signals—no beamsplitter or frequency filtering required. Turbulence is not a problem for x-ray imaging, but radiation exposure is. Pelliccia and colleagues speculate that one could pass a weak beam through fragile tissue but use its intensity correlations with a stronger beam that never touches the tissue to produce a low-noise microscopy image. (D. Pelliccia et al., *Phys. Rev. Lett.*, in press; H. Yu et al., *Phys. Rev. Lett.*, in press.) —RMW

HIGH-VELOCITY CLOUD BLOWS MILKY WAY BUBBLE

Spread through the disk of the Milky Way are about 20 vast bubbles of million-degree plasma wrapped in warm shells of neutral atomic hydrogen. Blowing up a so-called supershell to its typical size of 1000 light-years requires an energy, 10^{45} J, equivalent to at least 30 supernovas. Given that massive short-lived stars cluster in groups of a few dozen, it's indeed possible that supershells are inflated by supernovas. But evidence for an alternative formation scenario has been uncovered recently by Geumsook Park of Seoul National University in Korea and her collaborators. The team used a seven-band receiver at the Arecibo radio telescope in Puerto Rico to resolve the spatial and velocity structure of a supershell known as GS040. At the very center of GS040 they found a high-velocity cloud (HVC). Such clouds contain a million or so solar masses of warm gas and fly through space at speeds 50 km/s higher than is typical for stars and other galactic components. According to previous calculations, when an HVC slams into the galactic disk, it launches a supersonic expansion of hot plasma that is energetic enough to form a supershell. That appears to be what led to the formation of GS040, which, given the shell's current size, took place 5 million years ago. Where did the HVC come from, and how did it acquire its high speed? Park and her colleagues speculate that the HVC is either a fragment of a nearby galaxy that was tidally disrupted by ours or a leftover part of the intergalactic medium from which our galaxy and its neighbors formed. (G. Park et al., *Astrophys. J. Lett.* **827**, L27, 2016.) —CD

PLASMA DISCHARGE FOR FOOD STERILIZATION

Nonequilibrium plasmas, generated at atmospheric pressure through electric discharge, are in wide commercial use, especially for cleaning surfaces and improving surface adhesion. By producing a range of reactive chemical species, both charged and neutral, they can also inactivate or kill bacteria and other pathogens. When bacteria colonize the surface of fresh fruits and leafy vegetables, they encase themselves in a protective layer known as a biofilm. Plasmas' ability to breach biofilms has caught the attention of the food industry. Yet for plasmas to be deployed as food decontamination tools, their ability to do the job must be understood, controllable, and reproducible. In one step toward that goal, Dawei (David) Liu, Xinpei Lu, and colleagues at China's Huazhong University of Science and Technology and at Shanghai Jiao Tong University have now used a two-dimensional discharge model to analyze the interactions between the plasma and a biofilm on the surface of an apple. In the simulations, which spanned a region 3 mm wide by 5 mm high, the apple served as a floating electrode, and a series of



small proteins, high-frequency MAS NMR can potentially be used on much larger molecules. The main challenge is measurement sensitivity: The larger the protein, the fewer copies of it there are in a 0.5 mg sample, and the weaker the resulting signals. Doubling the size of the molecule under study would require an experiment four times as long. But each of Pintacuda and colleagues' structures was found with less than two weeks of data collection. There is plenty of room to expand.

Johanna Miller

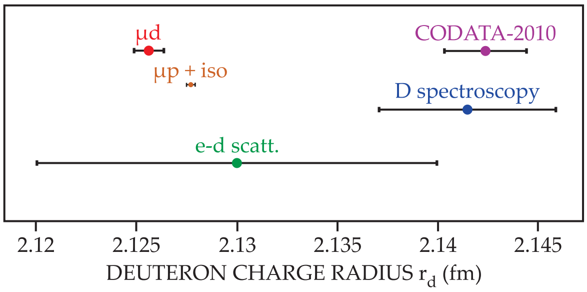
References

1. L. B. Andreas et al., *Proc. Natl. Acad. Sci. USA* **113**, 9187 (2016).
2. F. Castellani et al., *Nature* **420**, 98 (2002).
3. D. H. Zhou, *Angew. Chem. Int. Ed.* **46**, 8380 (2007).
4. V. Agarwal et al., *Angew. Chem. Int. Ed.* **53**, 12253 (2014).

nanosecond pulses of −25 kV applied to a full-width electrode 4 mm above it triggered narrow plasma filaments known as streamers. To calculate the details of the streamers' propagation and interactions with the 400-µm-wide, 100-µm-thick biofilm, shown here in white, the researchers self-consistently accounted for 115 reactions involving 18 different chemical species, photoionization, and biofilm structure and conductivity. They found that localized ionization occurs above the biofilm, and the plasma spreads into the biofilm recesses. Although the biofilm's irregular shape may shield some nooks from reactive chemical species, diffusion between the plasma pulses evens out the distribution to a level that could satisfy decontamination thresholds. (H. Cheng et al., *Phys. Plasmas* **23**, 073517, 2016.) —RJF

DEUTERON JOINS PROTON AS SMALLER THAN EXPECTED

According to the international Committee on Data for Science and Technology (CODATA), the charge radius of the proton is 0.8768(69) fm. Few researchers would give that number much thought if not for measurements in 2010 and 2013 that yielded a radius 4% smaller than and 7.2 standard deviations distant from the CODATA value. Randolf Pohl of the Max Planck Institute of Quantum Optics in Garching, Germany, and colleagues obtained the curiously low radius after analyzing the energy-level shifts of muons orbiting hydrogen nuclei. With a mass 207 times that of the electron, a muon has a tighter orbital that more closely overlaps the nuclear charge distribution, which makes the negatively charged particle a useful tool for probing nuclear dimensions. The discrepancy between the results of muon-based and other experimental investigations has come to be known as the proton radius puzzle.



Now Pohl and his colleagues have used the same technique to measure the radius of the deuteron, a nucleus of one proton and one neutron. The researchers shot a beam of muons at a target of D_2 gas. Lasers excited some of the atoms whose electrons were replaced by muons and probed the muons' energy-level transitions. By combining the measurements with theory, the researchers came up with a deuteron charge radius of 2.12562(78) fm. That's 7.5 σ smaller than the CODATA value (see graph; the new result is in red). In addition, both the proton and deuteron sizes are in tension with the values obtained by applying the same technique to atoms with electrons rather than muons.

The new study reinforces the notion that something is amiss in our understanding of particle or atomic physics. The most tantalizing possibility is that the standard model is wrong—perhaps muons interact with other particles differently than electrons do, for example. Pohl considers that explanation unlikely. His group and others are conducting experiments to precisely measure the Rydberg constant, which, if favorably reevaluated, could resolve the discrepancy. (R. Pohl et al., *Science* **353**, 669, 2016.) —AG

UNRAVELING THE JET-LAG ASYMMETRY

Jet lag, the sluggishness we feel after landing in a new time zone, has a directional bias: Studies suggest it takes longer to recover from eastward travel than from westward travel. A new model developed by Michelle Girvan, Edward Ott, Thomas Antonsen, and colleagues at the University of Maryland, College Park, may explain why. The team used tools of nonlinear dynamics to model a region of the brain known as the suprachiasmatic nucleus (SCN), a network of roughly 20 000 time-keeping neurons devoted to maintaining the body's circadian rhythm. Jet lag happens when those neurons fall out of sync with the local cycle of night and day. Modeling the dynamics of the SCN, however, is a tall order. Although the neurons all take cues from the same source—the retina—they don't all respond in the same way. Nor do they share the same natural oscillation periods; absent visual cues, the periods of the average person's SCN neurons would be distributed around an average value slightly longer than a day—about 24.5 hours. In 2008 Ott and Antonsen devised a way to represent such heterogeneous networks of oscillators in terms of just a few key variables. Now they've applied that approach to the SCN. Their model predicts that the slight deviation of the neurons' natural periods from 24 hours can lead to large recovery-time asymmetries. The worst-case scenario turns out to be an eastward trip across nine time zones: An Angeleno arriving in Paris would require six more days to recover than would a Parisian landing in Los Angeles. (Z. Lu et al., *Chaos* **26**, 094811, 2016.) —AGS PT

ISSUES & EVENTS

Clinton and Trump: Where do they stand on science?

The candidates' positions on climate change and energy policy differ starkly. Comparing their views on other issues is harder.

As in past elections, it's an understatement to say that science and technology (S&T) haven't been much of an issue in this presidential campaign. Apart from climate change and its close kin energy policy, S&T issues have barely been mentioned on the campaign trail by either Democratic nominee Hillary Clinton or Republican nominee Donald Trump. If Trump has positions on science policy matters, he has kept them to himself. Clinton, on the other hand, has published a considerable amount in position papers available on her campaign website.

Neither campaign responded to multiple requests from PHYSICS TODAY for input to this article or to make their S&T advisers available for interviews. Clinton did provide answers to a list of 20 S&T questions posed by ScienceDebate.org, a coalition of 56 scientific societies, universities, and other nonprofits; Trump provided more general, terse responses to the questions.

"I watch the nightly news, and if [Trump's] even mentioned science, I must admit I'm not in the room when it's happened," says Princeton University physicist William Happer. "I think science for him and his team is sort of a sideshow."

David Goldston, a former staff director of the House Science, Space, and Technology Committee who now oversees the Natural Resources Defense Council Action Fund, agrees: "Where he's going on science is a total mystery. It's not clear who he talks to. We know he's not a reader. We know he's taken the most extreme nonscientific position on climate change possible, and that's kind of it."

Even identifying which members of Trump's nascent transition team will handle science, space, and technology issues has proven difficult. Bob Walker, a lobbyist and former Republican chairman of the House Science Committee, says he has heard nothing to indicate

HILLARY FOR IOWA/CC-BY-2.0

GAGE SKIDMORE

that a member of Trump's small campaign staff is "doing any serious work on the science, space, and technology agenda." He says that Clinton, conversely, has a couple hundred staffers, some with S&T backgrounds, already working on transition.

Neal Lane, a former science adviser to President Bill Clinton, notes that Trump personally "has said very negative things about his respect for scientific evidence, as with vaccines and climate change, where he repeats views that are not based on science. There's nothing positive I've seen about the Trump campaign's views on science. But they haven't said very much."

The Clinton campaign has not been particularly visible when it comes to science policy. "It may be important to them when they need to govern, but it's not particularly important in terms of winning the election," says Albert Teich of the George Washington University's Elliott School of International Affairs.

Regardless of who controls the White House and Congress next January, it's likely that basic research, with the possible exceptions of climate change and social sciences, will continue to enjoy bipartisan support. "I'm not really worried we'd move away from an understanding that the federal government needs to be in basic research," says Walker.

Lane is also guardedly optimistic. "Good things about science are said by both parties in Congress and by presidents," he says. "But bigger issues related to ideological battles over federal spending are holding down the budgets." Basic research, particularly at the National Institutes of Health, has been underfunded for the past decade, he says, but not because of opposition from either party. "Nobody seems to be against the physical sciences or the biomedical sciences."

The outcome of the presidential election could well affect science budgets, says Goldston, since funding for R&D depends on the amount of discretionary spending available. "If you look at Trump's fiscal plan, while he hasn't said much specific about science or much else, you've got an overall spending approach and tax proposal that would severely limit the amount of investment the government could put into anything, including science." In contrast, Goldston notes, Clinton hasn't advocated policies that would reduce the federal budget, either by curtailing spending or cutting taxes.

Rodney Nichols, a consultant and former president of the New York Academy of Sciences, says the next administration must grow federal R&D budgets to keep the US competitive with China and other emerging economies. Regarding S&T, he says, "The US shouldn't expect to be number one in every area, but it should look to be number two so it can understand what is going on in every important field. It's very likely that over the next decade, we're going to be lucky to be number two in all the important fields," he warns.

Walker says he's concerned about Trump's silence on science policy issues "because some of the revolutionary changes that are taking place in technology are having a major impact on the culture and the economy."

Happer, a former director of energy research at the Department of Energy in the George H. W. Bush administration, notes that Democrats have favored federal support for applied research, whereas the GOP generally believes it should be left to the private sector. Walker agrees, saying he worries that Clinton may try to "stack the technology agenda with applied science that favors a certain political agenda."

At least two well-known S&T publications, *Scientific American* and *Wired,* have come out strongly against Trump. Both have traditionally steered clear of political endorsements. Republicans William Ruckelshaus and William Reilly, former administrators of the Environmental Protection Agency, back Clinton. In a joint statement released in August, they said Trump "has shown a profound ignorance of science and of the public health issues embodied in our environmental laws," whereas Clinton "is committed to reasonable, science-based policy."

An open letter signed by the leaders of 145 technology companies warns that Trump "would be a disaster for innovation."

The following is a summary of the candidates' known views on major S&T issues as derived from speeches, interviews, tweets, and other publicly available sources.

Climate change

On no scientific issue could the candidates' stated positions be further apart than climate change. Rush Holt, executive officer at the American Association for the Advancement of Science, believes Trump's attitude on climate change "is pretty telling in that he immediately dismisses it as a political statement without seeming to have any interest in getting to the bottom of the issue."

In a much-quoted 2012 tweet, Trump famously derided climate change as a hoax perpetrated by China to make US manufacturing noncompetitive. He later dismissed the comment as a joke, but his statements and tweets in the years since have consistently downplayed climate change as a major concern. On 30 December 2015 Trump told a rally in Hilton Head, South Carolina, "Obama's talking about all of this with the global warming and . . . a lot of it's a hoax. It's a hoax. I mean, it's a money-making industry, OK? It's a hoax, a lot of it."

And in August he told the *Miami Herald,* "I'm not a big believer in manmade climate change . . . [temperature] goes up, it goes down, and I think it's very much like this over the years. We'll see what happens." He added, "Many years ago, I believe it was in the 1920s, they talked about the phenomena of global cooling." Other Trump statements on the subject are confusing. After telling interviewers at the *Washington Post* in March of concerns in the 1920s that Earth was cooling, he noted that "our biggest form of climate change we should worry about is nuclear weapons."

Trump was more tempered in his responses to ScienceDebate.org, saying, "There is still much that needs to be investigated in the field of 'climate change.'" He went on to suggest that the nation's limited resources be used for accessing clean water, eliminating diseases, increasing food production, and developing energy sources that "alleviate the need for dependence on fossil fuels."

Incongruously, in December 2009 Trump and three of his children were among dozens who signed an open letter in the *New York Times* that urged President Obama, at a UN climate conference in Copenhagen, "to ensure meaningful and effective measures to control climate change." It also exhorted Congress to pass meaningful legislation. The letter continued, "If we fail to act now, it is scientifically irrefutable that there will be catastrophic and irreversible consequences for humanity and our planet."

Trump has said he would cancel the UN climate agreement reached in Paris last December and halt US payments to "UN global warming programs." He would rescind the Obama administration's Climate Action Plan, which imposes limits on carbon dioxide emissions from new and existing power plants, tightens energy efficiency standards, and encourages actions to adapt to and mitigate the effects of climate change. He has promised to revitalize the US coal industry.

During a May rally with West Virginia coal miners, Trump lamented the elimination of ozone-depleting propellants from hairspray. "I said, Wait a minute, so if I take hairspray and if I spray it in my apartment, which is all sealed, you're telling me that affects the ozone layer?" he said. "I say no way folks, no way."

For her part, Clinton's position papers say climate change "threatens our economy, our national security, and our children's health and futures." She embraces the current administration's approach of implementing climate policy through administrative measures rather than attempting to work with an unwilling Congress on enacting legislation.

Clinton has said that by 2025 she will reduce greenhouse gas emissions by 30%, relative to their 2005 level; that is more than the 26–28% reduction the Obama administration pledged in Paris. And Clinton says she will put the country on a path to an 80% cut in emissions by 2050, the amount that many climate scientists believe will be required to stabilize world temperatures at safe levels.

"I believe in science," Clinton said in accepting the Democratic nomination in July. "I believe that climate change is real and that we can save our planet while creating millions of good-paying clean energy jobs."

Energy

Clinton has ambitious plans to rapidly grow renewable energy over the next 10 years. "Let's build a cleaner, more resilient power grid with enough renewable energy to power every home in our country," she said in an 11 August speech outlining her economic policy. Residential usage is roughly one-third of total US electricity consumption, and renewables were about 13% of total US generation in 2015.

Within her first term, according to Clinton campaign materials, 500 million solar panels will have been installed in the US, the equivalent of rooftop solar installations on 25 million homes. That additional 140 GW of solar capacity would be an eightfold increase from current levels. The Solar Energy Industries Association estimates about 100 GW of new solar capacity will be on line by 2021.

Clinton described how over 10 years she would increase 10-fold the amount of wind, solar, and hydroelectric generation on public lands and waters. She would extend current subsidies to wind and solar generation and increase spending on R&D for energy storage, advanced nuclear technology, and carbon capture and storage. A proposed $60 billion, 10-year "clean energy challenge" would create a partnership with state and local governments to provide competitive grants and other incentives for accelerating clean-energy deployments. Clinton says she will cut by one-third both oil consumption and energy wasted in buildings.

Clinton told ScienceDebate.org that she will increase R&D on advanced nuclear power and work to ensure that existing nuclear plants are "appropriately valued" for the contribution they make toward the nation's zero-carbon-emission electricity supply.

Trump's announced energy policy focuses on achieving energy independence, saving the declining coal industry, and encouraging increased oil drilling, particularly on federal lands and on the outer continental shelf. He promises in a position paper to scrap unnecessary and outdated regulations, "revoke policies that impose unwarranted restrictions on new drilling technologies," and encourage a reapplication to build the Keystone XL pipeline, which Obama rejected.

Trump has voiced disdain for renewable energy and energy efficiency. In April 2012 he tweeted, "Not only are wind farms disgusting looking, but even worse they are bad for people's health." In October of that year, he tweeted, "Remember, new 'environmentally friendly' lightbulbs can cause cancer. Be careful—the idiots who came up with this stuff don't care."

In his ScienceDebate.org responses, however, Trump said energy independence required exploring "every possible energy source, including wind, solar, nuclear, and biofuels. We can make nuclear power safer, and its outputs are extraordinary given the investment we should make," he said.

R&D, NASA

Clinton laments in her campaign materials that federal spending on R&D as a share of GDP today is lower than before the 1957 launch of *Sputnik 1*. She says she will increase R&D budgets at NSF, DOE, and the Defense Advanced Research Projects Agency, "so that we can tackle big challenges—like ensuring America continues to lead the world in High Performance Computing, green energy, and machine learning."

"Advancing science and technology will be among my highest priorities as president," Clinton told ScienceDebate.org. "I am deeply concerned by the recent increase in partisan political efforts to interfere in science. I strongly support the free exchange of ideas and data, peer review, and public access to research results and other scientific information, all of which can help protect science-based policy decisions from undue influence from special interests."

Clinton, who has noted her desire as a girl to become an astronaut, told a questioner at a New Hampshire town-hall meeting in December that the space program "is a huge economic boon" that has produced commercial products and spin-off companies. She told ScienceDebate.org, "We must maintain our nation's leadership in space with a program that balances science, technology and exploration; protect our security and the future of the planet through international collaboration and Earth systems monitoring; expand our robotic presence in the solar system; and maximize the impact of our R&D and other space program investments by promoting stronger coordination across federal agencies, and cooperation with industry."

In her position statements, Clinton says that she will set aside a small portion of federal research budgets for commercialization efforts, enact reforms to reduce excessive patent litigation, and revise export controls. She would allow entrepreneurs temporary relief from student-loan repayments and would forgive up to $17 000 of student loans for innovators who start businesses in distressed communities.

In responses to ScienceDebate.org, Clinton says she will boost the NIH budget, which will include increasing research on Alzheimer's and other dementias to $2 billion annually and continuing Vice President Joe Biden's cancer "moonshot" initiative.

Trump told ScienceDebate.org that "the federal government should encourage innovation in the areas of space exploration and investment in research and development across the broad landscape of academia." Regardless of budget pressures, "we must make the commitment to invest in science, engineering, healthcare and other areas that will make the lives of Americans better, safer and more prosperous."

Speaking specifically of space exploration, Trump told the organization it will "bring millions of jobs and trillions of dollars in investment to this country." Observation from space and exploration "beyond our own space neighborhood" are priorities, he said, but they should be done with international partners.

Trump's few utterances concerning federal R&D programs have been confusing at best. At a New Hampshire rally in August 2015, he responded to a question about returning to the Moon by saying, "I think it's wonderful. I want to rebuild our infrastructure here on Earth first." In a 2012 tweet, he accused Obama of gutting NASA and making the country dependent on the Russians, a reference to the cancellation of the space shuttle program, which was terminated by President George W. Bush. More recently, on 3 August, in Daytona Beach, Florida, he declared, "Look what's happened with our whole history of space and leadership. Look what's going on folks. We're like a third-world nation."

In an October 2015 interview with conservative radio talk show host Michael Savage, Trump offered, "I hear so much about the NIH, and it's terrible."

David Kramer

White House science adviser talks space, climate change, and budgets

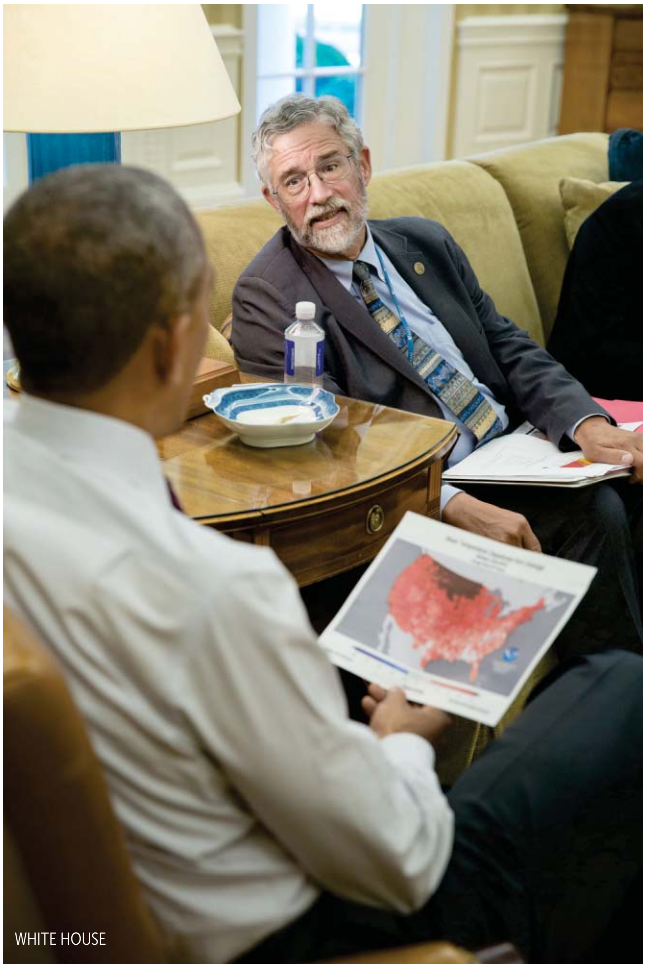
John Holdren recaps the Obama administration's science policy achievements and disappointments.

Longtime policy wonk John Holdren describes his nearly eight years as science adviser to President Obama as "the pinnacle" of his career and a "wonderful and exciting ride." As the administration nears its end, the former academic physicist says Obama's science and technology accomplishments far outweigh Holdren's few regrets.

Although the US must rely on Russia to transport Americans to the International Space Station and no humans have gone beyond low-Earth orbit since the Apollo era, Holdren says President Obama's space program is on track. "We're planning a wide variety of missions beyond low-Earth orbit. There will be some further announcements about that over the remainder of the term," he said in a 25 August interview with PHYSICS TODAY. Although Holdren didn't elaborate, a spokesman later said he wasn't talking about new crewed missions, but "additional public discussion of steps on our journey to Mars" and elsewhere in the solar system.

The scaling back of an earlier plan to send astronauts to explore a near-Earth asteroid shouldn't be seen as a setback, Holdren says; rather, the adjustment was necessitated by "a variety of physical and technical realities." The current plan is for a manned trip in the mid 2020s to a stable orbit near the Moon, where the astronauts will rendezvous with a chunk of an asteroid placed by a robotic spacecraft set to launch in 2021.

Holdren insists Obama made the right call in terminating the Bush administration's program to return to the lunar surface. A commission established by Obama in 2009 had determined that the Bush plan, known as Constellation, was "unexecutable," he notes. "It was years behind schedule; it was three- to fourfold over budget; it was sucking the oxygen out of every other NASA program. We had to fix it, and although it has been described as a cancellation, actually we reshaped it." Development continues on the components—the Aries heavy-lift rocket and the Orion crew vessel—both needed for traveling beyond low-Earth orbit.



NEARING THE END of his almost eight years in office, John Holdren has surpassed his predecessor, John Marburger, as the longest-serving science adviser to a US president.

Having astronauts operating near the Moon "has enormously important implications for all kinds of things," Holdren says, one of which is that a stable lunar orbit "is a much better jumping-off point for going to Mars" because of the energy required to escape the Moon's gravity. "We are on track with a trajectory that ultimately will get us to Mars in the 2030s," he says, noting that getting there sooner was never possible because the required technologies don't yet exist.

Holdren praises Obama's record on arms control and nonproliferation. For successes, he cites the 2011 New START agreement with Russia, which will reduce the number of deployed nuclear warheads to 1550 on each side by early 2018 (PHYSICS TODAY, May 2012, page 24), last year's deal to suspend Iran's nuclear program (PHYSICS TODAY, December 2015, page 26), and the removal of hundreds of weapons' worth of fissile materials from 30 countries (PHYSICS TODAY, May 2014, page 18). But he avoids a question about costly programs under way to modernize the nation's nuclear arsenal; he says he can't discuss future budget issues.

An optimist

Trained in plasma physics, Holdren was a professor of environmental policy and director of the science, technology, and public policy program at Harvard University before he became Obama's science adviser and the director of the Office of Science and Technology Policy (OSTP) in 2009. A self-described optimist, Holdren thinks the growing symptoms of a warming planet will lead the world to conclude that the costs of inaction on climate change are much greater than the costs of responding to it. The plummeting cost of renewable energy and corresponding rapid increase in its deployment should further reduce mitigation costs. Energy efficiency is also becoming cheaper and more widespread. Nuclear energy and carbon capture and storage could be significant in limiting temperature rise, he says.

Although Obama failed to get congressional approval for a carbon cap and trade system early in his administration, Holdren believes that a future president and Congress eventually will agree "in one way or another" to put a price on carbon. "Right now, we're doing it in effect through regulations of various kinds. That's not the most efficient way to do it."

Holdren is the longest-serving science adviser to a US president; his term surpasses that of his predecessor, John Marburger, by several months. Holdren has some advice for his successor. "Keep your priorities straight. Your first responsibility is to the president"—not the federal science and technology agencies, the scientific community, or the media.

The science adviser's second priority is to run OSTP, which has doubled in size to about 120 staff during the Obama years. That growth, Holdren says, occurred because the president "is more interested in science and technology and why it matters to every aspect of his agenda" than any other president, with one possible exception. "I like to say President Obama is the most science-savvy president since Thomas Jefferson, but there is a lot more science to be savvy about."

Holdren says his successor also should "stay close to the action; be at the table." He quotes an unnamed chief of staff to Obama admonishing the science adviser, "If you're not at the table, you're on the menu." It's one reason Holdren couldn't be "in all places at all times and all things to all people," he adds. Finally, the next adviser should partner with, cooperate with, and get to know colleagues throughout the agencies and in the White House, he says. "You will get a lot more done working together than you ever will fighting over territory."

Although the science adviser position, established after World War II, has been filled by physicists or, less frequently, chemists and engineers, Holdren says "it would be great" if a life scientist were to be chosen next. Precisely because he didn't want his science advice to come solely from physical scientists, Holdren says, Obama appointed two life scientists, Harold Varmus and Eric Lander, to cochair his President's Council of Advisors on Science and Technology.

Although Holdren denies looking forward to retirement, the 72-year-old insists he won't stay on under a new president. "My wife would divorce me; it would end a 50-year marriage." But when asked, he says his biggest regret is that Obama can't serve another term, then quickly adds that he also regrets being unable to obtain more funding for federal R&D.

Public support needed

For sustained, large budget increases, he says, the scientific community "will need to get better at telling concrete stories about how investments in research and development have improved the quality of our lives, strengthened our economy, created jobs, and opened new horizons in understanding the world around us and the universe around us. We just have tended to talk too much in abstract terms—how many dollars, what percentage of GDP, and so on."

Obama's intent to double the budgets of NSF, NIST, and the Department of Energy's Office of Science over a 10-year period faltered in the face of budget constraints imposed to reduce deficits. Pointing to basic research investments that serendipitously resulted in inventions such as the laser, Holdren notes that "the folks that sit in Congress and read the titles of NSF research grants and say 'I don't see how this makes sense' are barking up the wrong tree. . . . We know from historical experience the portfolio of investments in basic research yields enormous results, and we have in place at NSF and at our other science-related agencies the sort of gold-standard peer-review process that ensures we are making the best possible bets."

Holdren says caps on discretionary spending justify Obama's decision to propose that Congress create a new mandatory account to fund $4.6 billion of R&D in fiscal year 2017 at a half-dozen science agencies, including NASA, NSF, and DOE. Some $1.9 billion of that would pay to establish a network of 45 NIST manufacturing technology centers. But Congress is unlikely to approve new mandatory programs because they cede lawmakers' control over the budget. Still, he says, "We believe that even if we don't get everything we want from Congress there is merit in putting out before the public and before Congress the things we believe the government needs to be doing and should be doing in R&D."

David Kramer

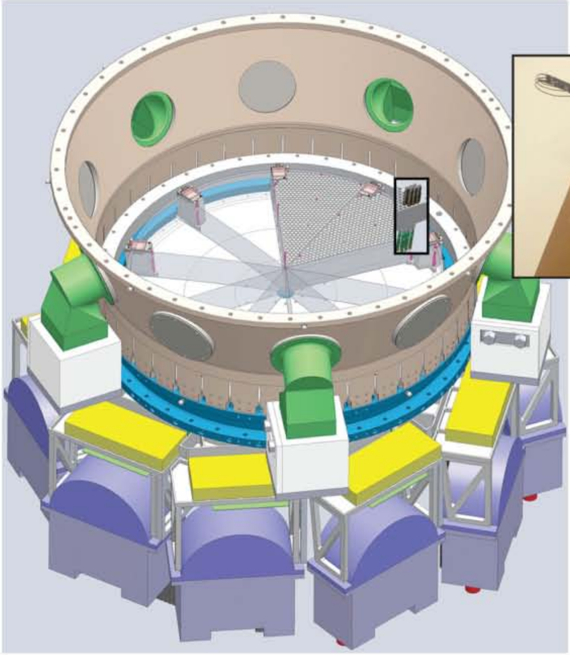
Extragalactic survey aims to shed light on dark energy

Robot-controlled optical fibers will help create 3D map of the cosmos.

It won't be the "billions and billions" that astrophysicist and science popularizer Carl Sagan famously referred to, but the 35 million galaxies that the Dark Energy Spectroscopic Instrument (DESI) will map in three dimensions will increase by more than an order of magnitude the number of galaxies with precisely known redshifts. DESI will lead the way among several next-generation projects to characterize dark energy; the data may also yield insights about dark matter, general relativity, neutrinos, galaxy formation, and more.

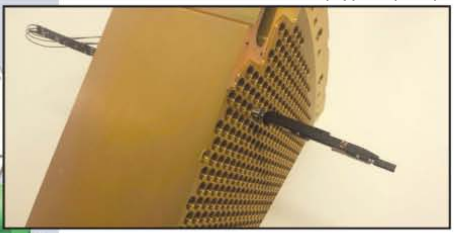
The DESI project will entail reincarnating a 45-year-old, 4 m telescope on Kitt Peak in Arizona. Until now, under the auspices of the NSF-funded National Optical Astronomy Observatory (NOAO), the Mayall telescope has been a workhorse used by the wider astronomy community. But in 2012 NSF, following a review of its budget and priorities, decided to cut purse strings to the telescope, although it retains ownership.

The DESI collaboration saw an opportunity, and next year it will begin reconfiguring the telescope for a roughly $115 million, five-year dedicated extragalactic redshift survey. The Department of Energy is footing the running costs of up to $8 million annually in addition to $56 million of the $75 million conversion. The remaining $19 million comes



R. LAFEVER AND J. MOUSTAKAS, DESI COLLABORATION

DESI COLLABORATION



ONE OF THE ROBOTIC POSITIONERS (above) with which the Dark Energy Spectroscopic Instrument will point optical fibers at preselected targets to measure redshifts. DESI will have 5000 such robots, divided among 10 wedges, like the one shown. The assembly will be located at the focal plane of a 4 m telescope (as in the schematic at left). The fibers can be reconfigured within a couple of minutes. Over five years DESI will map 35 million galaxies.

from international partners and private donors—the Gordon and Betty Moore and the Heising–Simons Foundations provided seed funding. Scientists at Lawrence Berkeley National Laboratory are leading construction on the new instrument. In addition to US institutions, the collaboration includes scientists from Australia, Brazil, Canada, China, Colombia, France, Mexico, South Korea, Spain, Switzerland, and the UK. The survey will begin measuring redshifts in January 2019.

Robotic power

DESI gets its muscle from the speed at which it can gather 3D galaxy positions. The instrument is a follow-on to others, notably BOSS (Baryon Oscillation Spectroscopic Survey, a Sloan Digital Sky Survey project). But it will collect many more spectra at a time than any previous instrument.

At the focal plane of the telescope will be an aluminum plate that is just shy of a meter across and made up of 10 wedge-shaped segments. Each segment has 500 hexagonally arranged circular holes 8.4 mm in diameter. Robotically controlled optical fibers can be positioned over the holes, and because of pivot arms they have 12-mm-diameter patrol areas that slightly overlap those of their neighbors. The 5000 fibers are independently moved around by tiny motors similar to those that make a cell phone vibrate. By contrast, notes David Sprayberry, an NOAO scientist who is overseeing the telescope's transition, the positioning of fibers on BOSS is done painstakingly by hand.

With DESI, the fibers will collect data for 20–30 minutes, and then the telescope will be repointed and the fibers positioned for a new set of targets; that automated process will take a minute or two. DESI's targets are being selected from three ongoing surveys: two based on Kitt Peak and the third in Chile.

The galaxy light will be bundled into 10 cables and run down the telescope to a spectrograph room. That, Sprayberry says, is the part that keeps him up at night. "The cables are long and stiff and the optics on the free end of them are delicate," he says. "We are still figuring out how to install the cables on the telescope without damaging them."

Looking for hints

Observational evidence indicates that the universe will expand forever and is made up of about 5% ordinary matter, 25% dark matter, and 70% dark energy. "But we know only about ordinary matter, not about the other 95% of the universe," says project member Ofer Lahav of University College London.

Dark energy was originally discovered through its apparent influence on the increase in acceleration of expansion that started 7 billion years ago. Going from discovering dark energy to finding out what it is requires more detailed data on the cosmic expansion. "It's not like the Higgs particle, that you know when you have it," says project scientist Brenna Flaugher of Fermilab. "With dark energy, we don't know what we have to measure to understand what it is. We are looking for hints."

That's where DESI comes in. By analyzing the galaxy map data in two distinct ways—through baryon acoustic oscillations (BAO) and redshift-space distortions—scientists hope to learn how dark energy behaves, if not exactly what it is.

In the hot plasma of the very early universe, oscillations resembling sound waves—the BAO—were produced by the opposing forces of gravity and gas pressure. Where local perturbations in density existed, matter coalesced and enhanced the BAO signal. The density waves propagated spherically until 400 000 years after the Big Bang, when the universe had cooled sufficiently for free electrons and protons to bind together into neutral hydrogen. Galaxies formed preferentially at the sites of the initial perturbations and where the propagation stopped; their separations constitute a physical length scale that has expanded with the universe.

A convenient way to characterize the distribution of galaxies is to calculate the distance between pairs of them. By computing vast numbers of pairwise distances, investigators can identify BAO signatures and then follow how those separations evolve over cosmological time scales.

The same DESI data can also be plumbed for distortions in redshift space. Gravity pulls galaxies into regions of higher mass, increasing the galaxies' velocities so that, along our line of sight, the redshifts of closer galaxies are stretched while the redshifts of more distant ones are squished. The redshift-space distortion can provide information about both the expansion rate of the universe and the growth of structure due to gravity.

Comparing the BAO and redshift-space distortion measurements with theoretical models could yield insights into whether the cosmological constant is in fact constant and into the physical phenomena ultimately responsible for the expansion of the universe. "The combination of methods is very powerful," says Lahav. "DESI will test current models of dark energy. And it will also test Einstein's theory of general relativity."

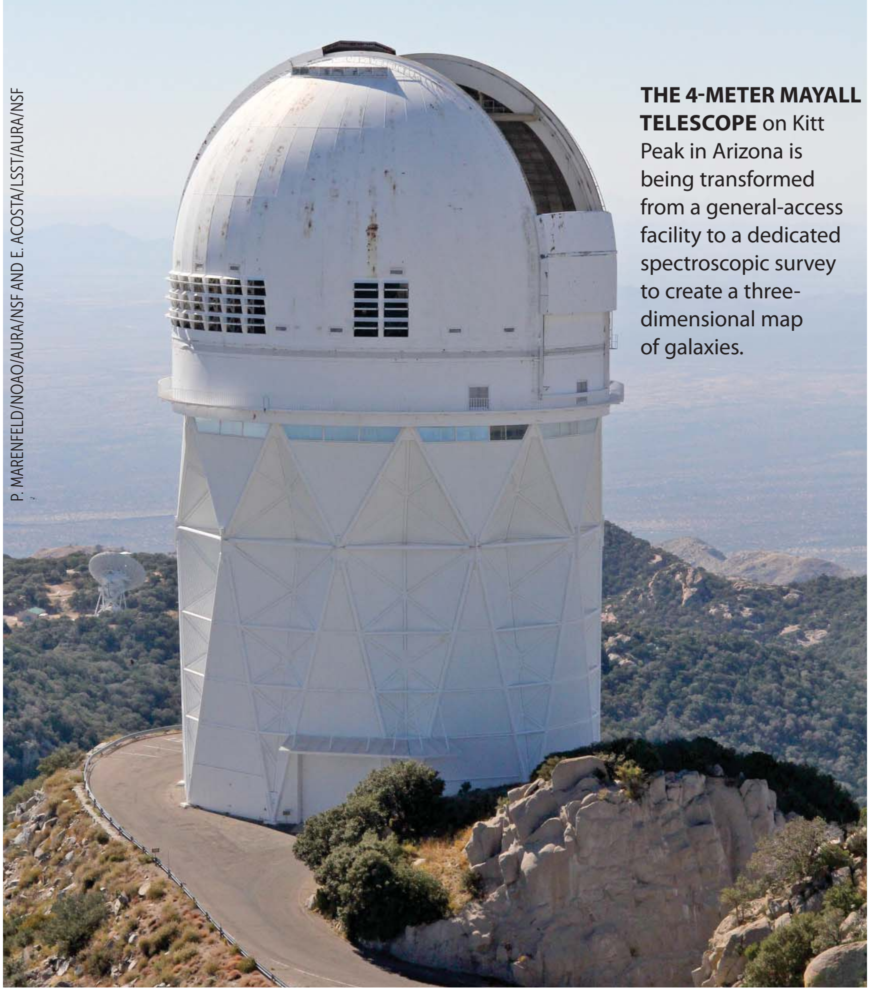
"A gold mine"

About 700 000 of DESI's targets will be bright, high-redshift quasars. They can be used as beacons to measure the absorption of hydrogen along the line of sight and map the distribution of hydrogen gas, thus providing another window onto cosmological structure and its evolution. The quasars' brightness makes them DESI's most distant tracers and allows cosmologists to measure the influence of dark energy back 12 billion years.

DESI's science will go beyond the primary goal of studying dark energy. The quasar spectra, for example, can also be used to probe the structure of intervening galaxies. And DESI's fibers could be trained on targets—transient objects, say, such as supernovae or gravitational-wave sources—identified by other telescopes.

When the night sky is too bright to take spectra of distant galaxies (out to redshift 1.6), DESI will survey closer galaxies (below redshift 0.6) and measure the redshifts of millions of stars in our galaxy. "Mapping out stars in the Milky Way gives you a way to figure out how clumpy the dark matter is," says DESI cospokesperson Risa Wechsler of Stanford University.

DESI will also be sensitive to neutrino mass. "Without massive neutrinos, the universe would be more blobby; with neutrinos, it is smoother," says Lahav.



P. MARENFELD/NOAO/AURA/NSF AND E. ACOSTA/LSST/AURA/NSF

THE 4-METER MAYALL TELESCOPE on Kitt Peak in Arizona is being transformed from a general-access facility to a dedicated spectroscopic survey to create a three-dimensional map of galaxies.

"One dream we have with DESI is to measure the mass of neutrinos" by looking at the clustering patterns of galaxies.

After a yet-to-be-determined proprietary period, the DESI data will be released to the wider astronomy community. Says project member Will Percival of the UK's University of Portsmouth, "Once you have such a survey, it's a gold mine of data for lots of science. A whole range of physics is encoded into the distribution of galaxies."

DESI is not the only new experiment to characterize dark energy's influence on the cosmos. The other main ground-based projects in the works are the prime focus spectrograph planned for Japan's Subaru Telescope in Hawaii, scheduled to begin science operations in mid-2019; a wide-field spectrograph on the William Herschel Telescope on La Palma in the Canary Islands, set to start up in June 2018; and studies with the Large Synoptic Survey Telescope in Chile, which is slated to start collecting data in 2022. Two space missions to be launched in the 2020s will also have strong dark-energy components: the European Space Agency's *Euclid* and NASA's *Wide Field Infrared Survey Telescope*.

Toni Feder PT


Get Baked.
More than ordinary, RediVac® Vacuum-Baked Screws & O-Rings set the standard for clean-critical environments to reduce outgassing and increase reliability.
• Vacuum Baked Screws
• Vacuum Baked O-Rings
• Vented, Coated, Plated and Polished Screws
• RediVac® – Cleaned & Packaged
• Custom bake-out options
UC COMPONENTS
RediVac
408-782-1929
www.uccomponents.com


DUNIWAY STOCKROOM CORP.
Supplying reliable vacuum equipment since 1976
Mechanical Pumps
Ion Pumps
Turbo Pumps
Gauge Controls
D
Vacuum Sensors
Hardware
Supplies
Diffusion Pumps
www.duniway.com
800.446.8811 (Toll Free)
650.969.8811 (Local)
650.965.0764 (Fax)


OXFORD INSTRUMENTS
The Business of Science®
4 K Cryofree® optical cryostat
for sample-in-exchange-gas applications
NEW Optistat™Dry – the TLEX model
• Ideal for low thermal conductivity samples including powders – also perfect for organic, soft matter and biological samples
• Minimise time between experiments and maximise sample throughput via top loading probe
Optimised f1 optical access
OXFORD INSTRUMENTS
OptistatDry
nanoscience@oxinst.com
www.oxinst.com/pt-optidry
4083

BETWEEN RESEARCH AND DEVELOPMENT: IBM AND JOSEPHSON COMPUTING

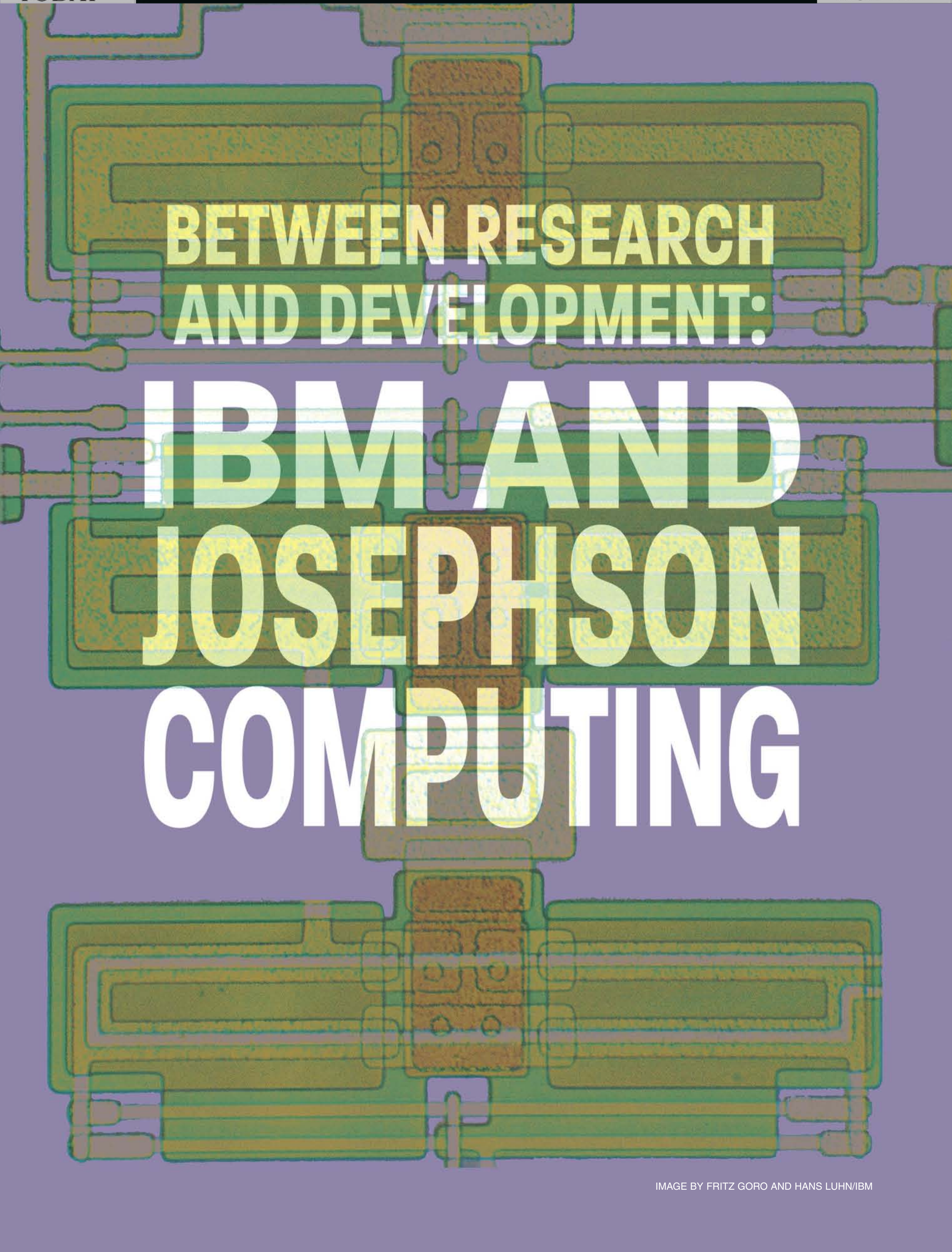


IMAGE BY FRITZ GORO AND HANS LUHN/IBM

Cyrus Mody is a professor and the chair of history of science, technology, and innovation at Maastricht University, in Maastricht, the Netherlands.

Cyrus C. M. Mody

For years the dream of turning the semiconductor industry into a superconductor industry has been only that. In the 1970s IBM—with help from the National Security Agency—made a run at turning that dream into reality.

The early 1960s were a period of intense ferment in superconductivity research. In 1957 John Bardeen, Leon Cooper, and J. Robert Schrieffer at the University of Illinois offered the first microscopic theory of superconductivity. Around the same time Alexei Abrikosov at the Institute for Physical Problems in Moscow explained phenomenologically how certain materials can admit some magnetic flux without losing their superconductivity. Experimentally, techniques for growing superconducting films were improving rapidly at the corporate laboratories of firms such as General Electric (GE), Ford Motor Co, Arthur D. Little, and AT&T.

Thus when future Nobel laureate Philip Anderson took a sabbatical from Bell Laboratories in 1961–62 to teach at Cambridge University, he encountered a classroom of graduate students eager to learn about the latest developments in low-temperature physics. Even among those high achievers, one student stood out: a brusque, brilliant 22-year-old named Brian Josephson. As Anderson wrote in PHYSICS TODAY (November 1970, page 23), "Everything had to be right or he would come up and explain it to me after class."

A few months after Anderson's arrival in Cambridge, Josephson approached him with calculations of the behavior of electrons as they traveled through a superconducting wire interrupted by a very thin insulating barrier—behavior later known as the Josephson effect. Josephson made several predictions, the most well known of which is that if the barrier is thin enough, pairs of electrons can tunnel through it together without resistance to form a supercurrent. Josephson also showed that if a voltage is placed across the barrier, then the supercurrent will be an alternating current with microwave frequency.

The story of Josephson and Anderson's meeting, the articulation of the Josephson effect, and Josephson's colorful career both before and after sharing the 1973 Nobel Prize in Physics at age 33 have entered physicists' communal oral tradition. Less well known, though, is the practical aftermath of Josephson's discovery.

Building on the cryotron

The Josephson effect was discovered in an era when US corporate labs had the resources, the expertise, and the desire to apply superconductivity to something useful. Within months of Anderson's return to Bell Labs in 1962, his colleague John Rowell fabricated a circuit with which to demonstrate Josephson's predictions. Just two years later, researchers at Ford invented the superconducting quantum interference device, or SQUID. Based on the Josephson effect, SQUIDs are sensitive magnetometers used today in fields from astronomy to antisubmarine warfare to epilepsy research.

From early on, the application that captured the imagination of many researchers was Josephson-based computing. Circuits that incorporate the Josephson effect are phenomenally sensitive; if that sensitivity could be tamed, perhaps such circuits could be turned into extremely fast, low-power switches. But as historian David Brock has observed, Josephson computing is like fusion—extraordinarily promising and always just a few years from realization.[1] With the slowing of Moore's law in semiconductor devices, however, interest in Josephson computing is today experiencing a renaissance.

Interest in superconducting computing predates the Josephson

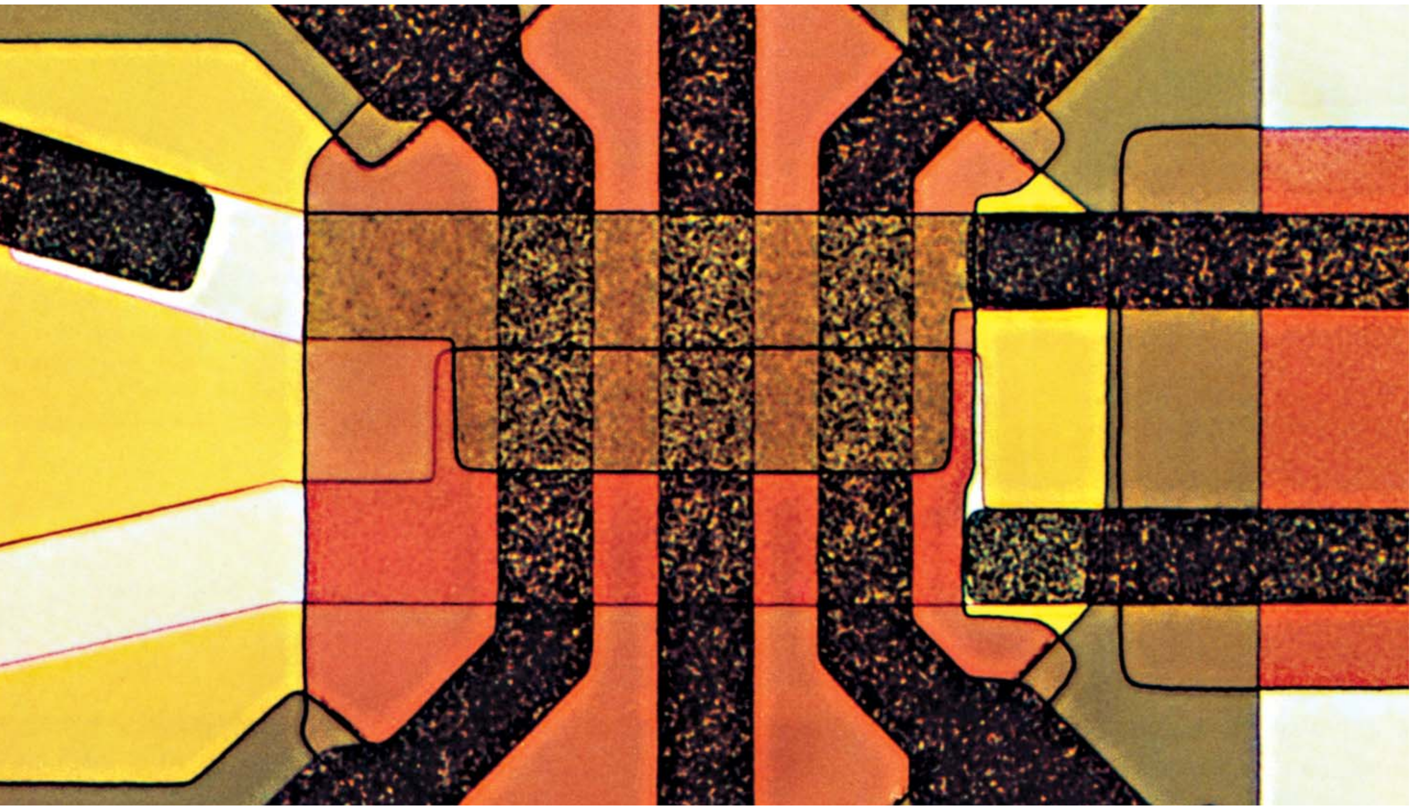


FIGURE 1. IBM JOSEPHSON CIRCUIT from 1974. Josephson junctions are formed at the intersection of perpendicular superconducting strips (dark areas) with an insulating oxide layer sandwiched between the two. (Courtesy of IBM.)

effect. In the late 1950s, GE, Arthur D. Little, and other firms pursued a switching device invented at MIT called the cryotron. It worked by wrapping one superconducting wire around another. A small change in the current through the coiled wire would quench the supercurrent in the straight one, making the cryotron an effective switch or amplifier, much like a vacuum tube or transistor. Brock has shown that by 1961 GE researchers had demonstrated a working integrated memory circuit made with thin-film cryotrons that were at least as sophisticated as some silicon circuits of the time.[1] But within about a year—just as Josephson was articulating his effect—GE and most of its competitors gave up on the cryotron. As one GE participant put it, once he understood the potential of the silicon integrated circuit—"which, unlike cryotrons, worked at room temperature—to work in large arrays, I could see the end of cryotrons."[2] Silicon's potential for mass manufacturability doomed the first attempt at superconducting computing.

Ironically, the failure of the cryotron contributed indirectly to a nearly 20-year exploration of Josephson computing at IBM that ended in much the same place the cryotron had: abandonment in the face of silicon's inexorable progress. IBM, with funding from the National Security Agency's (NSA's) Project Lightning, had enthusiastically pursued the cryotron. In fact, Richard Garwin—a theorist better known for his contributions to thermonuclear weapons, gravitational radiation astronomy, and critiques of antiballistic missile defense programs—headed a 100-person cryotron program at IBM before stepping aside to work on parity violation in meson decay. The effort continued for a time, but in the early 1960s, IBM dropped its commitment to cryotron logic, and then in early 1965 it halted work on cryotron memory as well.

IBM catches up

At around the same time, but independently, IBM began transferring some of its magnetics researchers from the Thomas J. Watson Research Center in Yorktown Heights, New York, to the company's San Jose Research Laboratory in California. The relocation was meant to bring the researchers closer to the firm's data-storage manufacturing operation. Back then, data storage largely meant magnetic storage, so that was a logical move. A few of the magnetics researchers left in Yorktown, however, persuaded management not to ship them west. In many companies, such stubbornness would have been grounds for dismissal, but IBM was large enough and tolerant enough toward its scientific talent that it granted the request.

But what to do with the rump magnetics group? A research manager named Philip Seiden proposed reorienting them toward superconductivity, despite their lack of expertise in that area. After all, magnetism and superconductivity are related: Magnetic fields are expelled from a material when it becomes superconducting. Moreover, the giant corporate labs of that era encouraged top researchers to dive into new fields.

In giving himself a crash course in superconductivity, Juri Matisoo, a member of that group, ran across Josephson's recently published ideas and began speculating about ways to apply them in real-world circuits. To test whether he could make a simple flip-flop, register, or other digital logic or memory circuit based on the Josephson effect, Matisoo needed specialized equipment for growing thin films. Luckily, some of the cryotron project's evaporators were being stored, unused, in

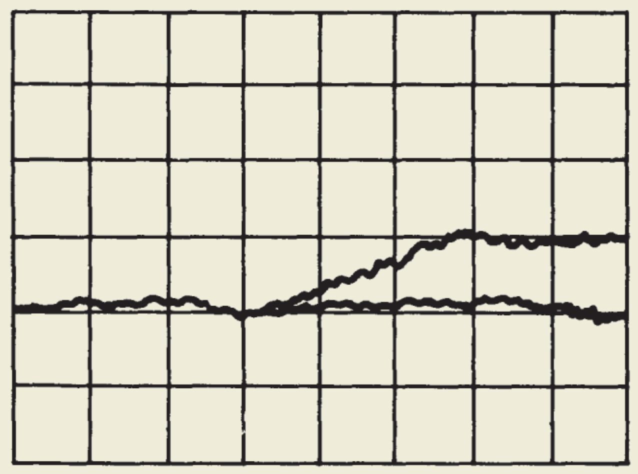


FIGURE 2. PROOF OF CONCEPT. This oscilloscope trace—gridline spacings are 1 mV (vertical) and 0.4 ns (horizontal)—from Juri Matisoo's 1966 paper demonstrated that Josephson junctions could switch from a supercurrent, pair-tunneling state (0 V signal) to a dissipative, single-particle-tunneling state (1 mV signal) in less than 1 ns. (From J. Matisoo, *Appl. Phys. Lett.* **9**, 167, 1966.)

the Yorktown lab. Matisoo appropriated the equipment and began using it to deposit thin films of aluminum, tin, and lead in configurations that he hoped would allow him to follow the path being blazed at GE, Ford, Bell Labs, the University of Pennsylvania, and elsewhere.

By April 1965 Matisoo had caught up enough to file an IBM internal invention disclosure for what he called a "cryotron-like logic element" based on the Josephson effect. As it happened, another IBM employee, Marshal Merriam, had filed an IBM technical disclosure for a similar device almost a year earlier. Yet managers in the Yorktown lab encouraged Matisoo to keep going—though one of them, Wilhelm Anacker, suggested that he avoid the term "cryotron" because that technology had been abandoned. Matisoo eventually adopted a more poetic name for his superconductor-insulator-superconductor sandwiches: the Josephson junction.

At first, Matisoo faced a significant challenge simply making Josephson junctions. On paper, fabricating a superconductor-insulator-superconductor sandwich seemed simple: Take a substrate (Matisoo initially used gold and later, silicon), deposit a strip of superconducting material on it (at first, Matisoo usually used lead or tin), grow or deposit a very thin insulating layer on top of the superconducting strip, and then deposit a second superconducting strip crosswise, leaving a superconductor-insulator-superconductor stack at the intersection of the two strips (see figure 1). Often, but not always, the second superconductor would be the same as the first. When possible, the insulating layer would be an oxide of the first superconductor.

But there's the rub. Silicon transistors and integrated circuits have been such a successful technology in part because silicon dioxide, an insulator, grows so readily on semiconducting silicon. But nature isn't so cooperative when it comes to superconductors—it's not so easy to grow an oxide layer on the kinds of materials that are suitable for Josephson junction logic. Luckily for Matisoo, the superconductivity community of the 1960s rapidly churned out innovative ways to grow insulating layers on superconducting materials. Yet simply growing an insulating barrier wasn't sufficient—it had to be thin enough to allow electron tunneling, but not so thin that it lost integrity and shorted out.

Despite those difficulties, by 1967 Matisoo had made a demonstration junction with subnanosecond switching and a more complex Josephson-based flip-flop, a circuit to store binary information. Figure 2 shows an oscilloscope trace Matisoo published in 1966 that demonstrated the fast switching capability of a Josephson junction. As Anacker noted later, the results indicated that Josephson logic "could be competitive with projected semiconductor integrated circuits."[3] Anacker therefore formed an exploratory program to see whether Matisoo's rudimentary devices could be turned into a real computer architecture. Under Anacker, more personnel were gradually drafted into the effort, they started patenting inventions, and the IBM publicity machine started highlighting their work.

The most likely candidate

Before 1967 Matisoo had been on his own, working hard to catch up with the leaders in the field. As Anacker's group ramped up, though, IBM shifted from trailing to trailblazing. All eyes turned to Matisoo, Anacker, and their colleagues. Yet the eyes of different groups saw the IBM Josephson program in very different lights. The global superconductivity research community, for instance, began to see IBM as a place where graduate students could get jobs. Other microelectronics firms, somewhat burnt from the cryotron, declined to commit fully to Josephson computing, but they started to develop small defensive efforts out of wariness that IBM would achieve a runaway success. Two firms in particular—AT&T and Sperry—ran Josephson projects about 10% the size of IBM's.

Two other categories of observer proved especially influential. One category was federal grant officers who thought superconducting circuits might further their agencies' interests better than conventional silicon. In particular, Fernand "Doc" Bedard, Nancy Welker, and John Pinkston at the NSA began following the IBM program closely in the early 1970s, in hopes that a Josephson computer would have the speed needed to break Soviet codes. The NSA team began traveling regularly to Yorktown while building up their own small in-house research capacity. Then in late 1972, the NSA agreed to bear about a quarter of the costs of the IBM program.

The other, even more influential category of observers were senior researchers and managers within IBM. Indeed, the negative views of superconducting computing expressed by some IBM figures who were not associated with the Josephson program have become almost as famous as the program itself. In particular, Rolf Landauer—otherwise best known for his work on the thermodynamics of information processing that disproved Maxwell's demon—is today often cited for his criticisms of unconventional microelectronics. He suggested, for instance, that descriptions of quantum computing schemes, some of which incorporate Josephson junctions, include this disclaimer: "This proposal, like all proposals for quantum computation, relies on speculative technology, does not in its current form take into account all possible sources of noise, unreliability and manufacturing error, and probably will not work."[4]

As Landauer's obituarists pointed out, "He understood what was needed to build a computer very well and along with Robert Keyes tried to pass such knowledge to the promoters of every cockamamie scheme that emerged. As a result he took a dim view of optical computing, [and] logic based on threshold devices, such as Esaki diodes and Josephson junctions."[5] Keyes, also an IBM physicist, is less well known in the general scientific community, but in certain fields—such as molecular electronics—he has a well-earned reputation as a skeptic and scourge. That reputation rests on comments like the following from 2008, which could apply equally to both today's molecular electronics and quantum computing and to the Josephson effort of the 1970s: "No solid state rival of the transistor has appeared in the four decades since transistors replaced relays and the vacuum tube. The transistor is unique, and is essential to solid state electronics."[6]

Yet it is not entirely accurate that Landauer, Keyes, or their peers at IBM were so skeptical of Josephson computing at the time. As late as 1975, Keyes was writing that "superconducting devices based on the Josephson tunneling cryotron appear to be the most likely candidate for logic that will make a much larger, faster computer possible."[7] That's not a ringing endorsement, but it also doesn't make Josephson computing sound like a "cockamamie scheme." Rather, Keyes, Landauer, and other senior IBM researchers and managers were unconvinced but convincible—they wanted Anacker and Matisoo to have a chance to show what Josephson junctions could do.

With the NSA's enthusiastic endorsement and the more lukewarm support of IBM peers, the Josephson program made rapid progress in the early to mid 1970s. A group at the IBM research lab outside Zürich joined the effort, focusing more on advanced materials and memory, while Yorktown emphasized logic and system architecture. With new personnel came more rapid innovation—the effort's rate of patenting from 1973–78 was approximately twice that of 1968–73. In 1977 Ralph Gomory, IBM's director of research, approved a further expansion with the aim of proving or disproving the commercial feasibility of a Josephson computer once and for all. The number of personnel peaked at around 125 people in the early 1980s. By that point, the effort cost approximately $20 million per year (more than $50 million in today's dollars), about a quarter of which was supplied by the NSA.

How far, how fast?

By 1980 IBM's investment in Josephson logic had become big enough that upper management wanted to know just how competitive with silicon it actually was. The task of formally making the comparison between Josephson logic and silicon logic fell to Emerson Pugh—presumably because he was a physicist and a manager with experience in product development. Incidentally, Pugh was also an accomplished historian of product development at IBM. He assembled a team of semiconductor and superconductor specialists to conduct an "extendability study" that compared Josephson logic with silicon bipolar-transistor logic. Extendability here meant that Pugh's committee had to predict how far silicon bipolar logic would improve over the next 15 years and to figure out whether Josephson logic had any chance to improve on a steeper curve that would overtake silicon.

The results were ambiguous. Pugh's committee estimated that a Josephson chip could, someday, be anywhere from three to six times as fast as a bipolar chip with the same power dissipation. However, the extendability study also outlined several potential obstacles to mass-producing Josephson chips. One problem stemmed from the fact that all the gates in a chip were supposed to reset at the end of every clock cycle—but in a situation known as punch through, individual gates had a small but nonzero probability of failing to reset.

The study team also found reasons to be more optimistic about bipolar technology than had seemed justified when the Josephson program began. The industry's ability to miniaturize silicon circuits without running into crippling power dissipation problems had surpassed all hopes. A switch to superconducting circuits thus seemed less necessary.

As might be expected, the ambiguous predictions were interpreted quite differently by advocates and critics of Josephson computing. The NSA and the leadership of IBM's Josephson effort seem not to have found anything in the extendability study to imply that the program should be shut down. By contrast, senior silicon specialists seem to have felt that Pugh's committee had demonstrated that Josephson logic was unlikely to outcompete silicon and that IBM should therefore downsize its efforts in superconducting computing. As physicist Robert Gunther-Mohr wrote in a letter to Gomory,

> I believe this has been [a] useful effort. It has increased mutual awareness between the Silicon and the Josephson efforts in IBM and has helped us understand both opportunities and limitations more comprehensively than before. . . . I believe a factor of at most 3 between CIL/JSP [Josephson] Technology and Silicon, with all the technical uncertainties, gives an insufficient justification for [the Josephson effort without] . . . significant changes in program directions.[8]

Again, like Keyes and Landauer, Gunther-Mohr doesn't sound like someone who considered Josephson computing a "cockamamie scheme." He remained unconvinced, but perhaps still convincible. Nevertheless, the window in which people like Gunther-Mohr could be convinced was starting to close. One of Pugh's recommendations had been for a task force to weigh continuation or cancellation of the program within nine months. When that task force met at the end of 1980, 12 of its 15 members voted for cancellation.

One of the three who favored continuing was Joseph Logue, an electrical engineer and manager who had contributed to IBM's transition to transistors in the 1950s and to integrated circuits in the 1960s—for which he was made an IBM fellow, the company's highest honor. Logue's reasoning was that "the program had been so badly mismanaged that it was difficult to determine if the basic problem was mismanagement or technology" and that therefore he couldn't vote for cancellation until a more competent manager had shown the technology's true potential.[9] Now, that's not a view of Anacker's management abilities that I've heard affirmed by any of the Josephson project veterans I've talked with. But, of course, many of Anacker's subordinates were fellow researchers who, Logue felt, weren't sufficiently committed to getting a product to market. "Many of the 50 PhDs on the team," he said, "were more interested in work that would lead to an individual publication than in working as a team to advance the program."[9]

Again, most of the veterans of the Josephson effort whom I've met would disagree with that characterization. But they

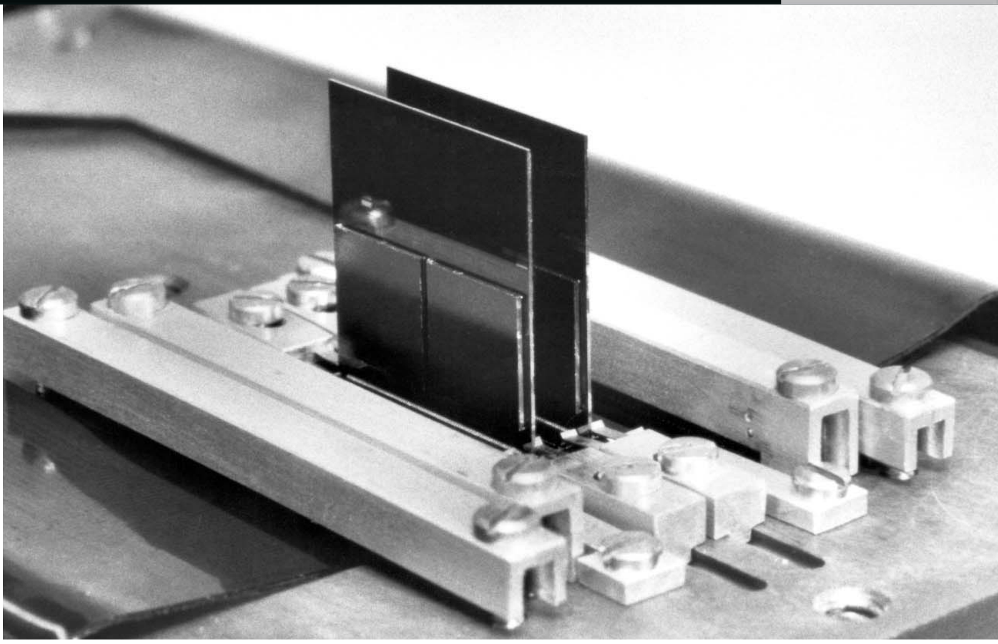


FIGURE 3. PROTOTYPE CHIPS. In the early 1980s, IBM fabricated experimental Josephson chips to test their performance and identify potential manufacturing problems. This photograph shows a chip assembly containing two cards (large squares). Two 6.4 mm × 6.4 mm Josephson chips (small squares), are attached to each card. (Courtesy of IBM.)

also acknowledge that under Anacker various basic design choices—such as whether to make the Josephson junctions out of lead or niobium—had remained undecided for long periods of time. For someone like Logue, the ability to finalize design decisions and move on to figuring out manufacturing issues would've been a minimum standard of competent management. Thus Logue convinced Gomory not to cancel the program but to find a new director—and, as it turned out, Logue himself was "the only one insane enough" to take on the job, on condition that he be given "two years to determine if the program would fly."[9]

Discovered by expensive experience

Naturally, manufacturing took a higher priority under Logue. To acquaint themselves with manufacturing considerations, the Yorktown researchers actually built a small fabrication line inside the Watson Research Center. The Yorktown line only made small numbers of devices—its purpose was not to mass manufacture chips but to help the researchers understand what problems might crop up as chips were made. Figure 3 shows a completed assembly of four Josephson chips. However, a true pilot line was built at IBM's manufacturing facility in East Fishkill, New York, and some Yorktown researchers were transferred there to oversee the line's construction and operation.

Thanks to IBM's publicity machine, all that activity drew the attention of the press. Newspapers and magazines from *Science* to the *Economist* to *Business Week* published frequent articles in the late 1970s and early 1980s extolling IBM and predicting that Josephson logic "may initiate a new era of extremely rapid processing equipment." As *National Geographic*, of all places, put it in October 1982,

> Researchers at Bell Labs, IBM, and elsewhere are refining Josephson junctions—electronic switches made of metals that lose all resistance to electric current when chilled to near absolute zero. Chips with these devices can switch signals in seven-trillionths of a second, presaging ultrafast telephone switching equipment, or a refrigerated supercomputer. Its chilled circuits could be packed into the volume of a grapefruit, cutting travel time for signals and enabling the machine to carry out 60 million instructions a second, ten times as many as current high-performance computers.
>
> IBM hopes to build a prototype in a few years. "Could it be of commercial significance?" IBM's Dr. [Lewis] Branscomb baited me. "I'll tell you in the 1990s."[10]

In fact, in less than a year the program would be dissolved. After Logue's stipulated two years directing the effort, Pugh was called on again to conduct an extendability study, this time comparing both Josephson and gallium arsenide circuits with conventional silicon bipolar circuits. And this time the results were unambiguous. Josephson technology now seemed less certain to work, and even the most optimistic estimates made it seem less competitive with silicon. Resolving punch through and other noise problems with Josephson circuits would require manufacturing compromises that decreased their top speed, and it seemed less likely than before that Josephson-based memory cells could be miniaturized much further. On 23 September 1983, the program was canceled.

So how should we understand IBM's Josephson computing program? It was, at first glance, a very expensive failure, costing something on the order of a quarter billion of today's dollars. All the program veterans I've talked to have come around to the conclusion that canceling it was justified—though many were not so reconciled at the time. Even today they can't all agree on why the decision was justified: Some point to the problems with miniaturizing Josephson memory, some to the punch-through problem, some to the surprisingly long continuation of Moore's law in silicon.

Already in 1983 there were some at IBM who thought the program had gone on for far too long. At the time of the second extendability study, one wag sent Pugh a series of cartoons that had been doctored to humorously criticize him for not killing the program in 1980. One cartoon showed a man seated at a desk labeled "E. Pugh" talking to a colleague while an elephant drank water behind him: "Okay . . . but except for **that** when have I ever made a bad mistake?" Pugh's friend signed the cartoon "To Emerson—one more time" and also included a *New York Times* article that contained the warning that in New York State, "the code of Criminal Procedure provides that persons 'pretending to forecast the future' shall be . . . liable to a fine of $250 and/or six months in prison."

Perhaps the wag's most perceptive cartoon was one showing a depressed man trapped in a bottle labeled "Josephson." Another man points gleefully at him; both men, though, are trapped in a larger bottle labeled "silicon." That is, silicon integrated circuits do have real limitations. It wasn't clear at the start of the Josephson program which bottle was inside the other. As Keyes recollected in 1985, "The speed advantage of a Josephson computer may not be as great as was hoped when silicon circuitry was in an earlier stage. It is hard to see such restrictions on the applicability of a technology in advance, they must be discovered by expensive experience."[11] Landauer, too, seems to have agreed that IBM's effort had been costly but worthwhile:

> There are many advanced technology proposals which become major thrusts, only to be abandoned again subsequently. An adventurous technological climate has to reward the taking of risk, and must allow failures.… Some technological candidates, such as Josephson junction logic, magnetic bubble storage, or the battery powered automobile, did deserve real examination. When they are discarded, it is done with trepidation, and knowledge that the decision may not last forever.[12]

Indirect benefits

Indeed, not everyone agreed that IBM had made the right choice. Reportedly, some NSA personnel were displeased with the program's cancellation. Similarly, a National Research Council study commissioned by the US Navy the next year called for the federal government to step into the void left by the absence of IBM and Sperry, which canceled its smaller program at the same time. That never happened. The Japanese government did fund a Josephson computing effort from 1981 to 1989, but it ended with the same conclusion as IBM's program. Silicon had just progressed too fast for superconducting computing to catch up.

Still, it's difficult to evaluate the IBM Josephson program solely on the basis of whether it was wise to try to beat silicon over the long haul. Prediction, after all, can land you in jail. Yet the value of the program can nevertheless be inferred, in part, from the benefits it brought IBM even though it didn't yield a product. Most obviously, the two Nobel Prizes in Physics shared among four IBM researchers—in 1986 for the scanning tunneling microscope (STM) and in 1987 for high-T_c superconductors—were related to the Josephson program, if indirectly. None of the four recipients was a member of the Josephson effort, but all four worked with people who were. One inspiration for the STM was the Zürich Josephson team's need to fabricate very thin films. And according to the joint Nobel lecture by Alex Müller and Georg Bednorz, Müller "started working in the field of superconductivity" during a sabbatical at Yorktown in 1978–79, where he was well known to members of the Josephson effort.

More directly, Josephson computing generated a stack of around 90 patents and valuable, mostly free advertising for IBM in *Business Week*, the *Economist*, and other magazines. It contributed to the storehouse of knowledge too. Particularly valuable to IBM managers was the knowledge that silicon was here to stay. But the rest of us learned something as well: As a retrospective account noted, "Near the end of the Josephson computer program there was a realization by the IBM management and technical workers that good science could be done with technology developed by the Josephson computer team."[13]

Most valuable, I would argue, were the personnel who participated in the Josephson program. Some later contributed to IBM's intellectual-property portfolio in areas quite unrelated to superconductivity. Some, particularly IBM fellow Carl Anderson, helped save IBM from bankruptcy in the early 1990s by transitioning its product line from chips based on bipolar transistors to ones based on MOSFETs. A few were able to apply their experience in the Josephson program directly—for instance, in IBM's later, similar forays into compound semiconductors. When a bandwagon formed around high-T_c superconductors in the late 1980s, Josephson program veterans represented IBM in Washington, DC, as the science-policy establishment tried to fashion a response. They also ensured IBM's participation in the products of post-high-T_c policy, such as the George H. W. Bush administration's baby, the Consortium for Superconducting Electronics. Several Josephson program veterans climbed high in IBM's ranks, including Matisoo, who went on to run the firm's Almaden research lab.

What chance today?

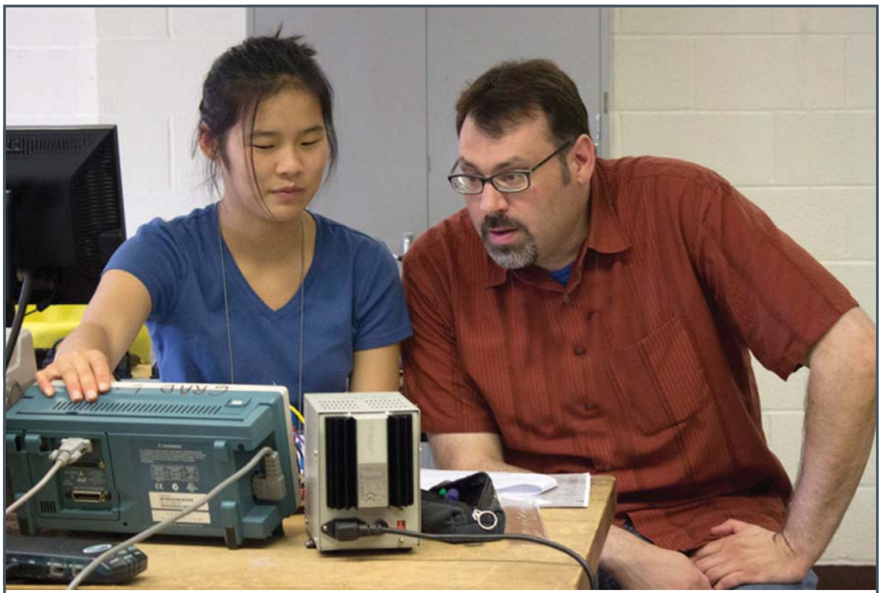
It's not clear that we still live in a world that can afford expensive, if valuable, failures such as IBM's Josephson computing program. Corporate basic research has declined considerably since the 1960s. The employer of a present-day Matisoo would probably not give him permission to grab some unused evaporators and try to make a circuit based on the seemingly far-fetched ideas of a 22-year-old Welshman. A present-day Anacker would have a much harder time forming a program to overthrow silicon integrated circuits, bringing the NSA on as a patron, and building it up over 15 years to a 125-person, \$50 million per year effort.

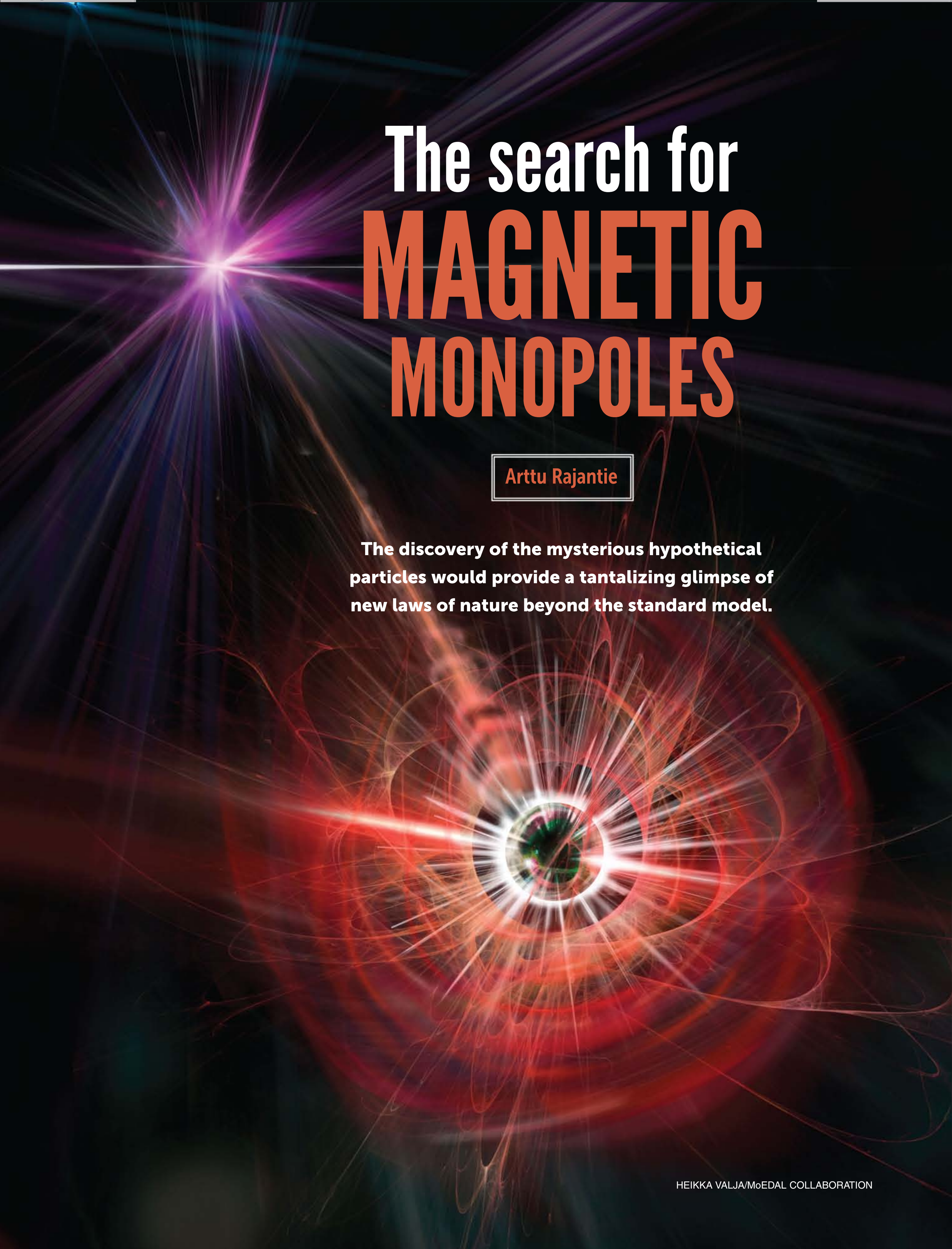
The assumption in industry and science policy circles today is that universities and consortia can take on much of the science-based technology development work that firms like IBM used to do in-house. But what university could sustain even a fraction of IBM's Josephson effort? If we want to entertain the possibility of beyond-CMOS microelectronics, then examples such as the IBM Josephson program should remind us of what might be needed to attain that possibility. As Landauer advised, "An adventurous technological climate has to reward the taking of risk, and must allow failures."

This article is an adaptation of a chapter from the author's upcoming book, The Long Arm of Moore's Law: Microelectronics and American Science, *MIT Press.*

REFERENCES

1. D. C. Brock, *IEEE Spectr.* **51**(4), 54 (2014).
2. J. Bremer, *IEEE Hist. Cent. Newsl.* **75**, 6 (November 2007).
3. W. Anacker, *IBM J. Res. Dev.* **24**, 107 (1980).
4. S. Lloyd, *Nature* **400**, 720 (1999).
5. C. H. Bennett, A. B. Fowler, *Rolf W. Landauer 1927–1999: A Biographical Memoir*, National Academy of Sciences (2009), p. 10.
6. R. W. Keyes, *J. Comput. Electron.* **7**, 449 (2008), p. 453.
7. R. W. Keyes, *Proc. IEEE* **63**, 740 (1975), p. 760.
8. G. R. Gunther-Mohr to R. E. Gomory (9 June 1980), Folder 6, Box 476, IBM Corporate Archives, Somers, NY.
9. J. C. Logue, *IEEE Ann. Hist. Comput.* **20**(3), 55 (1998), pp. 66–67.
10. A. A. Boraiko, *Natl. Geogr.* **162**(4), 42 (1982), p. 444.
11. R. W. Keyes, *Opt. Acta* **32**, 525 (1985), p. 534.
12. R. Landauer, *Physica A* **168**, 75 (1990), pp. 76, 78.
13. A. P. Malozemoff et al., *IEEE/CSC ESAS Eur. Supercond. News Forum* **6**(21), RN28-2 (2012), p. 4.





The search for MAGNETIC MONOPOLES

Arttu Rajantie

The discovery of the mysterious hypothetical particles would provide a tantalizing glimpse of new laws of nature beyond the standard model.

HEIKKA VALJA/MoEDAL COLLABORATION

Arttu Rajantie is a professor in the department of physics at Imperial College London and a member of the MoEDAL collaboration.

Electricity and magnetism appear everywhere in the modern world and form the basis of most of our technology. Therefore, it would be natural to assume that they are already fully understood and no longer pose unanswered fundamental physics questions. Indeed, for most practical purposes they are perfectly well described by classical electrodynamics, as formulated by James Clerk Maxwell in 1864. At a deeper level, a consistent quantum mechanical account is given by quantum electrodynamics, part of the standard model of particle physics. The theory works so well that it predicts the magnetic dipole moment of the electron accurately to 10 significant figures. Nevertheless, there is still an elementary aspect of electromagnetism that we do not understand: the question of magnetic monopoles.[1]

That magnets always have two poles—north and south—seems like an obvious empirical fact. Yet we do not know any theoretical reason why magnetic monopoles, magnets with a single north or south pole, could not exist. Are we still missing some crucial fundamental aspect of the theory? Or do magnetic monopoles exist and we simply have not managed to find them yet?

Magnetic mystery

Nothing in classical electrodynamics prohibits magnetic monopoles; in fact, they would make the theory more symmetric. As Maxwell noted, the laws governing electricity and magnetism are identical. That can be seen in the Maxwell equations of electrodynamics, which in vacuum have a duality symmetry—the electric terms can be replaced with magnetic terms, and vice versa, in such a way that the equations are left unchanged. That symmetry is broken only in the presence of electric charges and currents, which have no magnetic counterparts. If magnetic monopoles existed, they would carry the magnetic equivalent of an electric charge, and they would restore the duality symmetry (see figure 1). On aesthetic grounds, one would therefore expect their existence.

The duality symmetry provides clues to the likely traits of the hypothetical magnetic charges and currents. They would behave in exactly the same way as electrically charged particles: The magnetic charge would be conserved, so the lightest magnetic monopole would be a stable particle; opposite monopoles would attract each other and like monopoles would repel each other; their trajectories would bend in an electric field, and so forth. Indeed, a hypothetical universe in which all electric charges were replaced by magnetic charges of the same strength would be completely indistinguishable from ours. The word "electric" is simply a label for the type of charge that exists, and the word "magnetic" for the type that apparently does not. Of course, if they both existed, there would be genuinely new electromagnetic phenomena.

If Maxwell's theory of electrodynamics is perfectly compatible with magnetic charges, why did he not include them? Simply because experiments at the time suggested that the charges didn't exist. Those experiments were simple by today's standards—they involved things like floating magnets and cutting long magnets to pieces. But in spite of vast improvements in technology and experimental techniques, his assumption still seems to hold. And despite equally dramatic advances in our understanding of fundamental physics, we still don't understand why.

Quantum quandary

At first sight, magnetic monopoles seem to be incompatible with quantum mechanics. That is because in quantum mechanics, electromagnetic fields have to be described in terms of a scalar potential ϕ and vector potential $\mathbf{A}$. The magnetic field is given by the curl of the vector potential, $\mathbf{B} = \nabla \times \mathbf{A}$, and it follows from elementary vector calculus that the field must then be sourceless, $\nabla \cdot \mathbf{B} = 0$. In other words, magnetic field lines cannot end. So how can there be magnetic monopoles?

The same problem appears in classical electrodynamics, where potentials are often used as mathematical tools. But in classical physics the use of potentials is optional, because any system can be described using electric and magnetic fields instead. By contrast, in quantum physics the potentials couple directly to the complex phase of the quantum wavefunction—with real physical consequences—and therefore their use cannot be avoided.

In 1931, however, British physicist Paul Dirac ingeniously showed that the requirement for unbroken magnetic field lines doesn't rule out monopoles.[2] Quantum mechanics allows them to exist, but only if their magnetic charge has exactly the right strength.

In Dirac's model, illustrated in figure 2, each magnetic north pole is connected to a magnetic south pole by a line of singularity called a Dirac string. That string is effectively an idealized solenoid with zero thickness, and it carries magnetic flux from the south pole to the north pole so that the field lines remain continuous. In classical physics, such a string would be easily observable because of the effect it would have on electrically charged particles. But in quantum physics, if the magnetic charge g of the poles has exactly the right value, electrically charged particles are unaffected by the string's presence. That value is given by the so-called Dirac quantization condition

$$g = \frac{2\pi\hbar}{\mu_0 e}\, n,$$

where e is the electric charge of a particle used to probe the string, $\hbar$ is Planck's constant, and n is any integer. If the Dirac condition is satisfied by the electric charges of all particles, no experiment can observe the string. Thus, Dirac argued, the string is not really there: It is a mathematical artifact, a consequence of the variables chosen for the theoretical description. Only the two poles at the ends of the string are real, and physically they appear as two separate particles—free magnetic monopoles.

The quantization condition has important consequences. First, it tells us what the charge g of a magnetic monopole should be, which turns out to be very strong: The magnetic force between two monopoles, each with a single Dirac charge g_D of $2\pi\hbar/\mu_0 e$, would be 4700 times as strong as the Coulomb force between two electrons.

Second, the condition implies that if monopoles exist, the electric charge must be quantized. In other words, all particles must have an electric charge that's an integer multiple of the elementary charge $e_0 = 2\pi\hbar/\mu_0 g_D$. And indeed, experiments show that all particle charges are integer multiples of the electric charge of the electron. The only exceptions are quarks, which have fractional charges but aren't subject to the quantization condition because they are permanently confined. The observed quantization of electric charge can therefore be seen as evidence for the existence of magnetic monopoles.

$$\mathbf{E} \to c\mathbf{B},\ c\rho \to \rho_M,\ c\mathbf{J} \to \mathbf{J}_M$$

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0} \qquad \nabla \cdot \mathbf{B} = \mu_0 \rho_M$$

$$\frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t} - \nabla \times \mathbf{B} = -\mu_0 \mathbf{J} \qquad \frac{\partial \mathbf{B}}{\partial t} + \nabla \times \mathbf{E} = -\mu_0 \mathbf{J}_M$$

$$c\mathbf{B} \to -\mathbf{E},\ \rho_M \to -c\rho,\ \mathbf{J}_M \to -c\mathbf{J}$$

FIGURE 1. MAXWELL'S EQUATIONS OF ELECTRODYNAMICS, amended to include magnetic monopoles. The terms on the right-hand sides of the equations at right arise due to magnetic monopoles. The arrows indicate transformations that obey duality symmetry. Here, **E** and **B** are the electric and magnetic fields, respectively; ϵ_0 and μ_0 are the permittivity and permeability of vacuum; c is the speed of light; ρ and **J** are the electric charge and current densities; and ρ_M and $\mathbf{J}_M$ are the magnetic charge and current densities.

Fiendish fields

Dirac's construction does not imply that magnetic monopoles must exist, only that they may. It was not a prediction in the same sense as his famous prediction of the positron, which he showed to be an unavoidable consequence of relativistic quantum mechanics. Nor did it show how to describe the monopole as a dynamical, quantum mechanical particle. That problem turns out to be thorny.

One complication is the monopole's strong magnetic charge. Quantum field theory calculations in particle physics can use perturbation theory whenever interactions are weak. For electrically charged particles, the interaction strength is characterized by the fine-structure constant $\alpha = e^2/4\pi\hbar c\epsilon_0 \approx 1/137$. Because α is much smaller than one, perturbation theory works well. By contrast, the Dirac quantization condition implies a magnetic fine-structure constant that is much greater than one: $\alpha_M = \mu_0 g^2/4\pi\hbar c = 1/4\alpha \approx 34$. Perturbation theory is therefore not applicable. That said, the same is true for strong nuclear forces, but physicists have made progress on that front nonetheless; instead of perturbation theory, they use numerical lattice Monte Carlo simulations. Similar methods are being developed for magnetic monopoles.[3]

Another, deeper problem is that monopoles must be attached to Dirac strings. Quantum fields describe point-like elementary particles, but the Dirac string is a line-like extended object. Including it in the theory in a way that respects its fundamental symmetries—the Lorentz invariance of special relativity and the gauge invariance of electrodynamics—is difficult. Furthermore, the Dirac string has to be included in such a way that it becomes completely unobservable if the Dirac quantization condition is satisfied. Although theoretical formulations dating back to the 1960s satisfy those criteria, they are cumbersome and haven't been studied much.

Could the difficulty of finding a field theoretical description of magnetic monopoles reflect some deeper fundamental incompatibility with quantum field theory? Again, the answer is no. In 1974 Gerard 't Hooft and Alexander Polyakov found so-called hedgehog solutions for quantum field theories in which the electromagnetic field is a part of a larger unified interaction.[4] Such solutions are "lumps" of field with finite, nonzero size, each lump consisting of a large number of elementary quanta. At the center of the lump, the electromagnetic field loses its identity, which allows magnetic field lines to end; consequently, the lump acquires a magnetic charge. If the lumps are small enough, they appear as point-like magnetic monopoles. Figure 3 shows a 't Hooft–Polyakov monopole simulated using lattice field theory.

The 't Hooft–Polyakov solutions demonstrate that magnetic monopoles are compatible with renormalizable, relativistic quantum field theory. In fact, the theory in which they were found is similar to the electroweak sector of the standard model of particle physics. The only difference is that the theory's Higgs field had three real components, whereas the standard model Higgs has two complex components. As a result, the standard model does not have 't Hooft–Polyakov monopole solutions and does not predict the existence of monopoles. We know perfectly well, however, that the standard model cannot be the complete theory of everything, because it does not include gravity and does not account for dark matter, cosmological inflation, or the origin of the preponderance of matter over antimatter. There must be undiscovered physics beyond the standard model.

One widely studied hypothesis is grand unification. According to grand unified theories (GUTs), the strong and electroweak forces merge at very high energies into a single unified force. Remarkably, one can show that every GUT has 't Hooft–Polyakov monopole solutions, and therefore, magnetic monopoles are an inevitable consequence of grand unification.

The mass of GUT monopoles is determined by the energy scale of grand unification and is thus very high, around 10^{17} GeV/c^2. (The mass of the proton is approximately 1 GeV/c^2.) That makes the monopoles far too heavy to be produced in experiments. The Large Hadron Collider (LHC), the world's largest particle accelerator, has a maximum proton–proton collision energy on the order of 10^4 GeV.

On the other hand, we do not know what new physics lies waiting beyond the standard model. It is perfectly possible that there are monopoles unrelated to grand unification. And if they are elementary particles, not lumps of quanta, they could be much lighter than GUT monopoles.

Cosmic conundrum

One important difference between magnetic monopoles and most other elementary particles is that monopoles, if they exist, would be absolutely stable. Whereas the Higgs boson, for example, has a lifetime of just 10^{-22} s, a magnetic monopole could be destroyed only if it came in contact with another monopole of opposite charge. In that case they would annihilate each other and produce a burst of lighter elementary particles and radiation.

The monopoles' stability means that if they were produced at any time in the history of the universe, they would still be present. Such a scenario is by no means far-fetched. In the same way that nucleosynthesis in the early universe yielded light elements, thermal processes would have produced magnetic monopoles if ever the temperature was high enough. As the universe cooled down, the monopoles' density would have initially decreased by pair annihilation. But once they were sufficiently depleted, the monopoles would no longer have been able to find annihilation partners, and they would have survived indefinitely.

The present-day number density of the relic monopoles would depend on their mass. According to traditional Big Bang theory—in which the temperature of the universe was initially close to the Planck scale of quantum gravity and there was no inflationary epoch—the monopoles would have to have a relatively light mass, M, of no more than 10^{10} GeV/c^2; otherwise, they would exceed the observed matter density of the universe.[5]

The fact that the upper limit on mass is well below the GUT monopole masses rules out grand unification in the context of the traditional Big Bang. That so-called monopole problem was one key motivation for the theory of cosmological inflation, which posits that the early universe went through a phase of accelerating expansion. The expansion would have diluted any preexisting monopole density to unobservably low levels, and provided the universe didn't subsequently reheat to temperatures high enough to produce new ones, at most a few monopoles would remain in the observable universe today. The monopole problem would be solved.

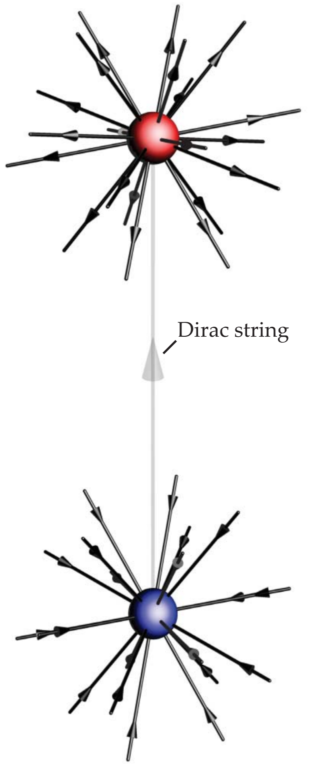


FIGURE 2. DIRAC MONOPOLES. The north monopole (red) is connected to a south monopole (blue) by a line singularity known as a Dirac string, which carries magnetic flux and preserves the continuity of the magnetic field lines. If the magnetic charge of the monopoles satisfies the Dirac quantization condition, the Dirac string is unobservable and does not affect the motion or behavior of the monopoles it connects.

Today the theory of inflation is strongly supported by observed temperature anisotropies in the cosmic microwave background and by other cosmological observations. Those observations show that the reheat temperature, the maximum temperature of the universe after inflation, was less than approximately 10^{16} GeV/k_B, not high enough to produce typical GUT monopoles. (Here, k_B is the Boltzmann constant.) The reheat temperature may even have been much lower, as low as 1 to 100 GeV/k_B, in which case even significantly lighter monopoles would pose no problem.

Lowered limits

Several physicists have attempted to improve on the matter-density constraints by searching for monopoles both directly and indirectly, through their astrophysical implications. One of the best constraints is the Parker bound, which is based on observed traits of galactic magnetic fields and named after the astrophysicist Eugene Parker.[6] Observations indicate that galaxies typically have magnetic fields of around a few microgauss. Sufficiently light magnetic monopoles would be accelerated by such fields to high velocities. That process would gradually drain energy from the field and cause it to dissipate. Therefore, the strength of present-day galactic magnetic fields gives an upper bound (see figure 4) on the monopole flux $\mathcal{F}$ through a unit area per unit time per unit solid angle. The flux can be related to the number density n of monopoles through $\mathcal{F} \approx nv/(4\pi)$, where v is the typical monopole velocity and is close to the speed of light for monopoles of mass 10^{11} GeV/c^2 or less accelerating in galactic magnetic fields.

The Parker bound can be tightened further by considering how the galactic magnetic fields were generated from a small initial seed field.[7] The resulting extended Parker bound is so stringent that it excludes all monopoles at cosmic densities predicted by traditional Big Bang theory (see figure 4).

If magnetic monopoles are present in the universe today, we should be able to find them in cosmic rays hitting Earth. In 1973 a team at the University of California, Berkeley, led by P. Buford Price, appeared to find one in a balloon-based cosmic-ray experiment.[8] The team's stack of nuclear track detector (NTD) sheets had an unusual track corresponding to a highly ionizing particle moving downward at relativistic speed. The track

PHYSICS TODAY Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page PHYSICS TODAY

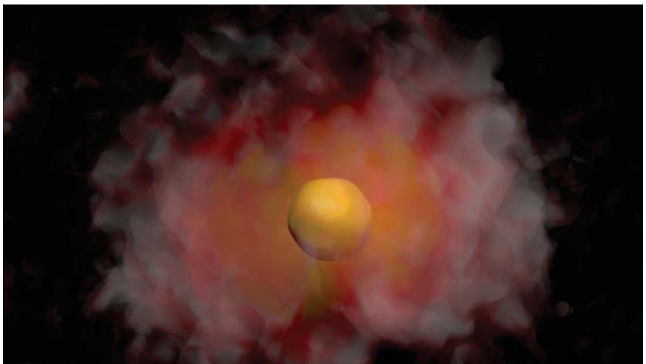


FIGURE 3. A 'T HOOFT–POLYAKOV MONOPOLE surrounded by a quantum field cloud, simulated using lattice field theory.

seemed consistent with a magnetic monopole having the Dirac charge, g_D, and a mass of no more than 200 GeV/c^2. However, closer analysis showed that the track was probably produced instead by a platinum nucleus.

Another monopole candidate was seen in 1982 in an experiment with a superconducting ring carried out by Blas Cabrera of Stanford University.[9] The current in the ring jumped by exactly the amount that would be induced by the passage of a magnetic monopole with a Dirac charge.

Cabrera's result has since been cast into doubt by subsequent, more extensive searches that found no further candidate monopoles.[10,11] The MACRO experiment in Gran Sasso, Italy, ran from 1989 to 2000 and gave an upper bound on the monopole flux of 10^{-16} cm^{-2} s^{-1} sr^{-1} over a wide range of monopole masses, and the ANITA, ANTARES, and IceCube neutrino detectors have provided even stricter limits on relativistic monopoles (see figure 4). Researchers have also attempted to find monopoles trapped in polar rocks, moon rocks, and seawater and through the tracks they might leave in mica, all to no avail. Because of highly uncertain systematics, however, it is not possible to turn those studies into precise limits on the monopole flux. Some GUT monopoles are predicted to catalyze nucleon decay, and the effects on the interiors of white dwarfs, neutron stars, and even the Sun place strong bounds on their number density.

Taken together, the above experiments and observations thoroughly rule out the monopole densities predicted by traditional Big Bang theory, for all realistic masses. Therefore, if monopoles exist, the reheat temperature would have to be so low that they would not be produced after inflation. Whether magnetic monopoles exist in principle, in practice they cannot be present in the universe today.

MoEDAL moment

Even if magnetic monopoles aren't present in the cosmos, one might be able to produce them in collider experiments, just as one would produce, say, Higgs bosons. Because of magnetic charge conservation, monopoles would always be produced in north–south pairs, and only if the collision energy is higher than the combined mass of the two monopoles. Therefore, the LHC, with its maximum proton–proton collision energy of 13 TeV, could produce monopoles only if their mass is at most a few TeV/c^2. That's many orders of magnitude too small to observe GUT monopoles, but elementary magnetic monopoles could have masses within the accessible range.

That collider experiments have yet to find magnetic monopoles places an upper bound on the probability of producing them in a single collision. Because of quantum uncertainty in the position of the colliding particles, that probability is most naturally expressed as the production cross section ϕ. For realistic monopole masses, experiments currently place the upper bound on pair production at just a few femtobarns. In other words, the probability of a single collision producing a monopole is, at most, about the same as the likelihood that the centers of two colliding particles will pass within 10^{-22} m of one another.

Unfortunately, one cannot apply perturbation theory to calculate the monopole pair production cross section. To get a rough estimate, however, one can consider the Drell–Yan mechanism, in which a quark and an antiquark annihilate, forming a short-lived virtual photon that decays into a monopole–antimonopole pair. That picture rather accurately describes the production of electrically charged particles, but because of the strength of the magnetic charge, it cannot be very accurate for monopoles.

For 't Hooft–Polyakov monopole pairs, which consist of a large number of elementary quanta, theoretical arguments suggest that the production cross section is exponentially small—suppressed by the factor $\exp(-1/\alpha) \sim 10^{-60}$. That would make them practically impossible to produce even if enough energy was available. Any monopoles found at the LHC would likely be elementary particles, not semiclassical 't Hooft–Polyakov monopoles.

Since 2010 the ATLAS experiment at the LHC has sought magnetic monopoles in the debris of 8 TeV proton–proton collisions by looking for highly charged particles captured in an electromagnetic calorimeter.[12] That search is sensitive only to

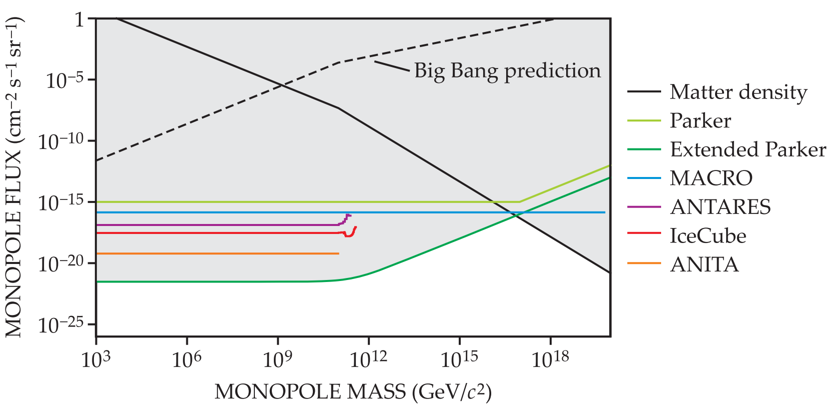


FIGURE 4. ASTROPHYSICAL OBSERVATIONS and cosmic-ray experiments have placed stringent upper bounds on the cosmic monopole flux. The dotted line shows the predicted monopole density according to the traditional Big Bang theory; that prediction lies entirely within the gray shaded area representing the densities that have been excluded by observations. The conflict between theory and observation is solved by introducing cosmological inflation, which reduces the predicted flux to an unobservable level. (Data from refs. 6, 7, 10, and 11.)

FIGURE 5. THE MoEDAL EXPERIMENT, pictured here in a panoramic photo, looks for monopoles and other exotic, highly charged particles in the debris of proton–proton collisions at CERN's Large Hadron Collider. After a brief test run in 2012, the experiment began collecting data last year. (Image courtesy of CERN.)

monopoles with charge equal to the Dirac magnetic charge; monopoles of higher charge would stop before reaching the calorimeter. Assuming a leading-order Drell–Yan production cross section, the ATLAS results constrain the monopole mass to be no less than 1340 GeV/c^2 for spin-½ monopoles with a single Dirac charge and no less than 1050 GeV/c^2 for spin-0 monopoles with a single Dirac charge. However, the Drell–Yan result relies on perturbation theory, whose applicability to monopoles is questionable.

Now upgraded to 13 TeV, the LHC experiments can reach even higher monopole masses. There is also a new, dedicated experiment called MoEDAL—for Monopole and Exotics Detector at the LHC—located next to the LHCb experiment and designed specifically to look for magnetic monopoles and other stable, highly ionizing particles[13] (see figure 5). It uses two passive methods: plastic NTD sheets and aluminum trapping detectors.

Altogether, 400 six-sheet stacks of NTDs, each 25 cm × 25 cm, have been placed around LHCb's Vertex Locator (VELO) detector. If a monopole is produced in a collision and flies through the sheets, it will leave a track that should be observable when the sheets are later etched and analyzed with an optical scanning microscope. The search for monopole tracks will be carried out with the help of a new citizen science project hosted by the Zooniverse web platform.

The MoEDAL trapping detector consists of some 800 kg of Al bars placed around the VELO detector. When a monopole travels through the Al, it loses energy and eventually binds to an Al nucleus, because of the atom's anomalously high magnetic moment. The monopole can then be detected by scanning the Al bars through a sensitive superconducting magnetometer. A passing magnetic monopole would induce a telltale jump in the magnetometer's electric current. If such a jump is observed, the measurement can be repeated multiple times to eliminate any possibility of a false detection.

MoEDAL began full operation in June 2015 with the start of the LHC's second science run. It has not yet published results from 13 TeV collisions, but in 2012 a smaller, 160 kg test array of trapping detectors was exposed to 8 TeV proton–proton collisions for a short period.[14] The results, shown in figure 6, indicate that MoEDAL can search for monopoles of higher mass and magnetic charge than could ATLAS. The test run also demonstrated that the scanning method should be more than sensitive enough to detect a single magnetic monopole trapped in the aluminum. The full installation of trapping detectors will have a larger trapping volume, cover a larger solid angle, and

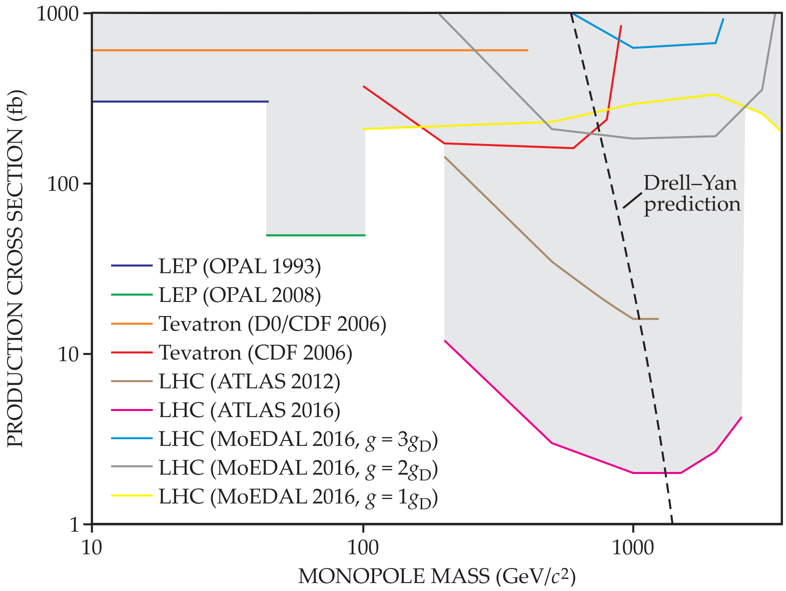


FIGURE 6. COLLIDER EXPERIMENTS have placed upper bounds on the monopole production cross section, expressed here in conventional units of femtobarns (1 fb = 10^{-43} m^2). With the exception of the MoEDAL test-run results, the observations apply to spin-½ monopoles with a single Dirac magnetic charge g_D. (The MoEDAL experiment also applies to higher charges.) The dotted line shows a crude theoretical prediction for the cross section from proton–proton collisions, and the gray shaded area corresponds to cross sections that have been excluded by observations. Because the cross section depends on both the energy and type of collider, however, results from different colliders are not directly comparable. (Data from refs. 11, 12, 14, and 17.)

be supplemented by NTDs, all of which should strengthen the bounds on monopole production even further.

The search continues

The discovery of magnetic monopoles would have a huge effect on physics. Not only would monopoles provide the first glimpse of the new laws of nature beyond the standard model, but their special properties would allow us to explore that new physics in ways not possible with other particles. Because monopoles are stable and interact with the electromagnetic field, they could easily be extracted from the trapping detectors and used for a wide range of further experiments. Furthermore, their interactions with electrically charged fermions, including the possible catalysis of proton decay, would depend sensitively on physics at very high energies. Given the technological importance of electricity and magnetism, it also seems likely that magnetic monopoles could have real practical applications, although they would necessarily be specialized because of the very high cost of producing the particles.

Even without a discovery, magnetic monopoles have already influenced fields ranging from high-energy physics to condensed-matter physics. They have provided new insight into the problem of quark confinement by the strong nuclear force, and they've shed light on properties of superstring theory and supersymmetric quantum field theories, where generalizations of the concept of duality have proven useful.

Magnetic monopoles have also inspired condensed-matter physicists to discover analogous states and excitations in systems such as spin ices[15] and Bose–Einstein condensates.[16] However, despite the importance of those developments in their own fields, they do not resolve the question of the existence of real magnetic monopoles. Therefore, the search continues.

REFERENCES

1. A. Rajantie, *Contemp. Phys.* **53**, 195 (2012); J. Preskill, *Annu. Rev. Nucl. Part. Sci.* **34**, 461 (1984); Y. M. Shnir, *Magnetic Monopoles*, Springer (2005); K. A. Milton, *Rep. Prog. Phys.* **69**, 1637 (2006).
2. P. A. M. Dirac, *Proc. R. Soc. Lond. A* **133**, 60 (1931).
3. A. Rajantie, D. J. Weir, *Phys. Rev. D* **85**, 025003 (2012).
4. G. 't Hooft, *Nucl. Phys. B* **79**, 276 (1974); A. M. Polyakov, *JETP Lett.* **20**, 194 (1974).
5. J. Preskill, *Phys. Rev. Lett.* **43**, 1365 (1979).
6. E. N. Parker, *Astrophys. J.* **160**, 383 (1970); M. S. Turner, E. N. Parker, T. J. Bogdan, *Phys. Rev. D* **26**, 1296 (1982).
7. F. C. Adams et al., *Phys. Rev. Lett.* **70**, 2511 (1993).
8. P. B. Price et al., *Phys. Rev. Lett.* **35**, 487 (1975).
9. B. Cabrera, *Phys. Rev. Lett.* **48**, 1378 (1982).
10. MACRO collaboration, *Eur. Phys. J. C* **25**, 511 (2002); M. Detrixhe et al. (ANITA collaboration), *Phys. Rev. D* **83**, 023513 (2011); S. Adrián-Martínez et al. (ANTARES collaboration), *Astropart. Phys.* **35**, 634 (2012); M. G. Aartsen et al. (IceCube collaboration), *Eur. Phys. J. C* **76**, 133 (2016); S. Burdin et al., *Phys. Rep.* **582**, 1 (2015).
11. K. A. Olive et al. (Particle Data Group), *Chin. Phys. C* **38**, 090001 (2014).
12. G. Aad et al. (ATLAS collaboration), *Phys. Rev. D* **93**, 052009 (2016).
13. B. Acharya et al. (MoEDAL collaboration), *Int. J. Mod. Phys. A* **29**, 1430050 (2014).
14. B. Acharya et al. (MoEDAL collaboration), *J. High Energy Phys.* **2016** (8), 67 (2016).
15. C. Castelnovo, R. Moessner, S. L. Sondhi, *Nature* **451**, 42 (2008).
16. M. W. Ray et al., *Nature* **505**, 657 (2014).
17. M. Fairbairn et al., *Phys. Rep.* **438**, 1 (2007).

PT

Michael Riordan is a physicist and science historian who taught at Stanford University and the University of California, Santa Cruz. He lives in Eastsound, Washington, where he writes about science, technology, and public policy. This article is adapted in part from his recent book coauthored with Lillian Hoddeson and Adrienne W. Kolb, *Tunnel Visions: The Rise and Fall of the Superconducting Super Collider* (University of Chicago Press, 2015).

A BRIDGE TOO FAR

The demise of the Superconducting Super Collider

Michael Riordan

The largest basic scientific project ever attempted, the supercollider proved to be beyond the management capacity of the US high-energy physics community. A smaller proton collider would have been substantially more achievable.

When the US Congress terminated the Superconducting Super Collider (SSC) in October 1993 after about $2 billion had been spent on the project, it ended more than four decades of American leadership in high-energy physics. To be sure, US hegemony in the discipline had been deteriorating for more than a decade, but the SSC cancellation was the ultimate blow that put Europe unquestionably in the driver's seat and opened the door to the discovery of the Higgs boson at CERN (see PHYSICS TODAY, September 2012, page 12). The causes and consequences of the SSC's collapse, a watershed event in the history of science, have been discussed and debated ever since it happened.

At least a dozen good reasons have been suggested for the demise of the SSC.[1–4] Primary among them are the project's continuing cost overruns, its lack of significant foreign contributions, and the end of the Cold War. But recent research and documents that have come to light have led me to an important new conclusion: The project was just too large and too expensive to have been pursued primarily by a single nation, however wealthy and powerful. Wolfgang "Pief" Panofsky, founding director of SLAC, voiced that possibility during a private conversation in the months after the project's demise; he suggested that perhaps the SSC project was "a bridge too far" for US high-energy physics. That phrase became lodged firmly in my mind throughout the many years I was researching its history.

Some physicists will counter that the SSC was in fact being pursued as an international project, with the US taking the lead in anticipation that other nations would follow; it had done so on large physics projects in the past and was doing so with the much costlier International Space Station.[5] But that argument ignores the inconvenient truth that the gargantuan project was

VIEW ALONG THE SUPERCONDUCTING SUPER COLLIDER main-ring tunnel, in early 1993. (Courtesy of Fermilab Archives.)

launched by the Reagan administration as a deliberate attempt to reestablish US leadership in a scientific discipline the nation had long dominated. If other nations were to become involved, they would have had to do so as junior partners in a multibillion-dollar enterprise led by US physicists.

That fateful decision, made by the leader of the world's most powerful government, established the founding rhetoric for the SSC project, which proved difficult to abandon when it came time to enlist foreign partners.[6]

ROSE GARDEN CEREMONY. Secretary of energy John Herrington (at lectern) and President Ronald Reagan (next to him) stress the importance of building the Superconducting Super Collider to an audience of top high school students, Nobel laureates, and others on 30 March 1988. Joining them, from left, are Samuel Ting (MIT), Steven Weinberg (University of Texas at Austin), and Burton Richter (then director of SLAC). (Courtesy of the Ronald Reagan Presidential Library.)

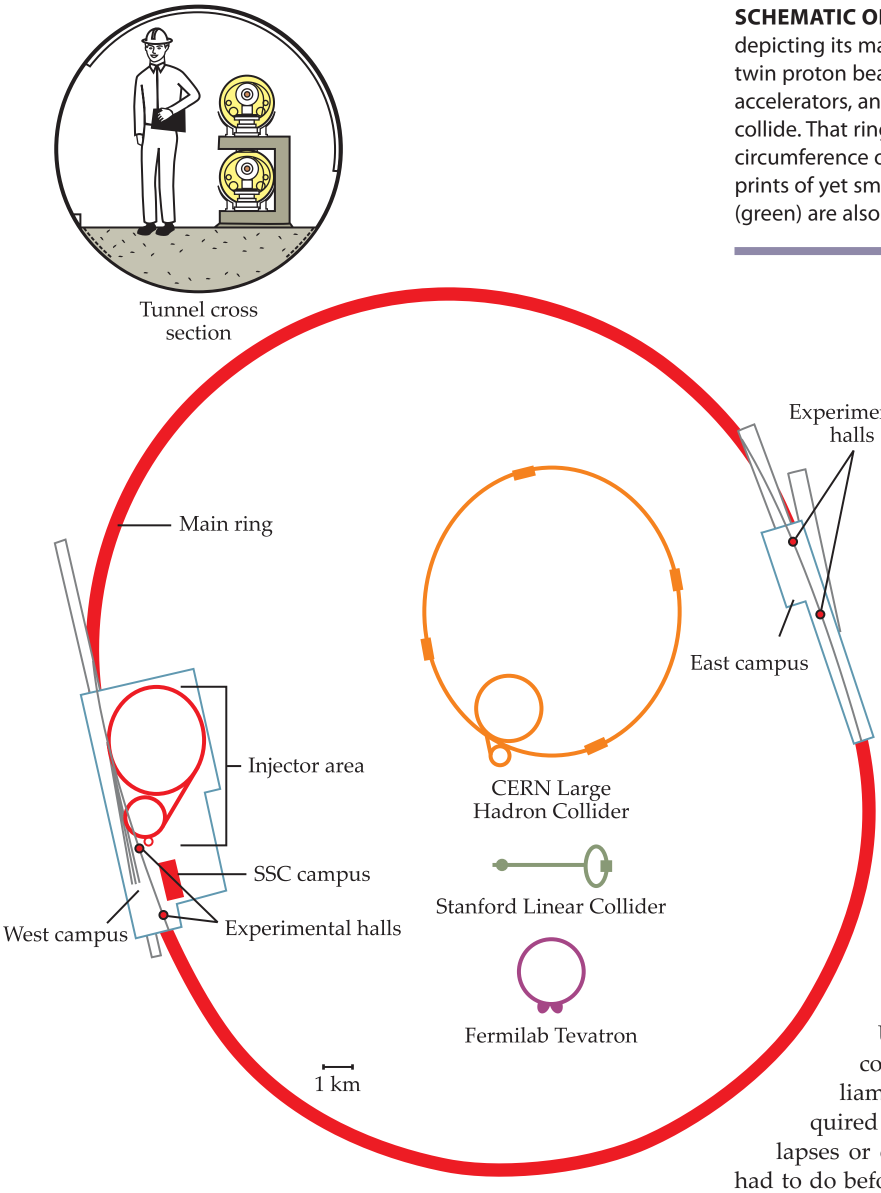
The SSC and the LHC

In contrast, CERN followed a genuinely international approach in the design and construction of its successful Large Hadron Collider (LHC), albeit at a much more leisurely pace than had been the case for the SSC. Serious design efforts begun during the late 1980s and early 1990s ramped up after the SSC's termination. Although the LHC project also experienced trying growth problems and cost overruns—its cost increased from an estimated 2.8 billion Swiss francs ($2.3 billion at the time) in 1996 to more than 4.3 billion Swiss francs in 2009—it managed to survive and become the machine that allowed the Higgs-boson discovery using only about half of its originally designed 14 TeV energy.[7] (The SSC, by comparison, was designed for 40 TeV collision energy.) When labor costs and in-kind contributions from participating nations are included, the total LHC price tag approached $10 billion, a figure often given in the press. Having faced problems similar to, though not as severe as, what the SSC project experienced, the LHC's completion raises an obvious question: Why did CERN and its partner nations succeed where the US had failed?

From the SSC's early days, many scientists thought it should have been sited at or near Fermilab to take advantage of the existing infrastructure, both physical and human. University of Chicago physicist and Nobel laureate James Cronin explicitly stated that opinion in a letter he circulated to his fellow high-energy physicists in August 1988. CERN has followed that approach for decades, building one machine after another as extensions of its existing facilities and reusing parts of the older machines in new projects, thereby reducing costs. Perhaps as important, CERN had also gathered and developed some of the world's most experienced accelerator physicists and engineers, who work together well. During the late 1980s, Fermilab had equally adept machine builders—plus substantial physical infrastructure—who could have turned to other productive endeavors when the inevitable funding shortfalls occurred during the annual congressional appropriations process.

Troublesome clashes occurred at the SSC between the high-energy physicists and engineers who had been recruited largely from the shrinking US military–industrial complex as the Cold War wound down during the late 1980s and early 1990s.[8] For example, the methods by which SSC general manager Edward Siskin and magnet division director Thomas Bush managed large projects and developed sophisticated components differed greatly from those customarily employed by high-energy physicists. A particular bone of contention was the project's initial lack of a cost-and-schedule control system, which by then had become mandatory practice for managing large military-construction and development projects overseen by the Department of Defense. Such clashes would probably not have erupted in the already well-integrated Fermilab high-energy physicist culture, nor would the disagreements have been as severe.

Those pro-Fermilab arguments, however, ignore the grim realities of the American political process. A lucrative new project that was to cost more than $5 billion and promised more than 2000 high-tech jobs could not be sole-sourced to an existing US laboratory, no matter how powerful its state congressional delegation. As politically astute leaders of the Department of Energy recognized, the SSC project had to be offered up to all states able to provide a suitable site, with the decision based (at least publicly) on objective, rational criteria. Given the political climate of the mid 1980s, a smaller project costing less than $1 billion and billed as an upgrade of existing facilities might have been sole-sourced to Fermilab, but not one as



SCHEMATIC OF THE SUPERCONDUCTING SUPER COLLIDER, depicting its main 87 km ring—designed to circulate and collide twin proton beams, each at energies up to 20 TeV—the injector accelerators, and experimental halls, where the protons were to collide. That ring circumference is more than three times the 27 km circumference of CERN's Large Hadron Collider (orange). The footprints of yet smaller particle colliders at Fermilab (purple) and SLAC (green) are also shown for comparison. (Adapted from ref. 2.)

prominent and costly as the SSC. It *had* to be placed on the US auction block, and Texas made the best bid according to the official DOE criteria.

Unlike the SSC, the LHC project benefited from the project management skills of a single physicist, Lyndon Evans, who came to the task with decades of experience on proton colliders. Despite the facility's major problems and cost overruns, Evans enjoyed the strong support of the CERN management and a deeply experienced cadre of physicists and engineers. On the LHC project, engineers reported ultimately to physicists, who as the eventual users of the machine were best able to make the required tradeoffs when events did not transpire as originally planned. The project encountered daunting difficulties and major delays, including the September 2008 quench of dozens of superconducting magnets. But the core management team led by Evans worked through those problems, shared a common technological culture, and understood and supported the project's principal scientific goals.

Similar observations cannot be made regarding the military–industrial engineers who came to dominate the SSC lab's collider construction. Until 1992 a succession of acting or ineffectual project managers could not come to grips with the demands of such a complex, enormous project that involved making countless decisions weekly. Secretary of energy James D. Watkins deliberately had Siskin inserted into the SSC management structure in late 1990 in an effort to wrest control of the project from the high-energy physicists. After SLAC physicist John Rees stepped in as the SSC project manager in 1992, he and Siskin began working together effectively and finally got a computerized cost-and-schedule control system up and running—and thus the project under better control. But it proved to be too late, as the SSC had already gained a hard-to-shake reputation in Congress as being mismanaged and out of control.

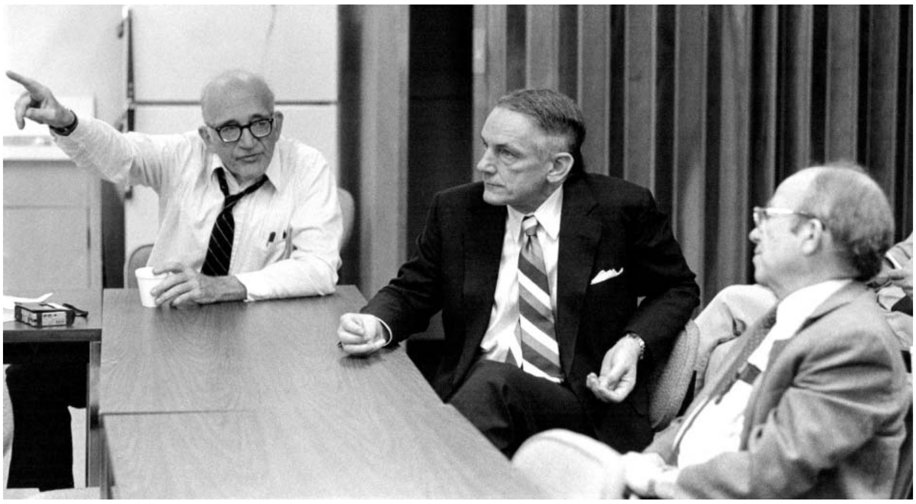
CERN also enjoys an enviable internal structure, overseen by its governing council, that largely insulates its leaders and scientists from the inevitable political infighting and machinations of member nations. Unlike in the US, the director general or project manager could not be subpoenaed to appear before a parliamentary investigations subcommittee or be required to testify under oath about its management lapses or cost overruns—as SSC director Roy Schwitters had to do before Congress. Nor did the LHC project face annual congressional appropriations battles and threats of termination, as did major US projects like the SSC and the space station. Serious problems that arose with the LHC—for example, a large cost overrun in 2001—were addressed in the council, which represents the relevant ministries of its member nations and generally operates by consensus, especially on major laboratory initiatives. That supple governing structure helps keep control of a project within the hands of the scientists involved and hinders government officials from intervening directly.

Because the council must also address the wider interests of individual European ministries, CERN leaders have to be sensitive to the pressures that the annual budget, new projects, and cost overruns can exert on other worthy science. In that manner, European scientists in other disciplines have a valuable voice in CERN governing circles. The LHC project consequently had to be tailored to address such concerns before the council would grant it final approval. In the US, the only mechanism available was for disgruntled scientists to complain openly, which Philip Anderson of Princeton University, Theodore Geballe of Stanford University, Rustum Roy of the Pennsylvania State University, and others did in prominent guest editorials or in congressional hearings when SSC costs got out of hand between 1989 and 1991. The resulting polarization of the US physics community helped undermine what had been fairly broad support for the SSC project in the House of Representatives, which in 1989 had voted 331–92 to proceed with construction.

Because of financial pressures, CERN had to effectively internationalize the LHC project—obtaining monetary and material commitments from such nonmember nations as Canada, China, India, Japan, Russia and the US—before the council would give approval to go ahead with it. When that approval finally came in 1996, the LHC was a truly international scientific project with firm financial backing from more than 20 nations. Those contributions enabled Evans and his colleagues to proceed with the design of a collider able to reach the full 14 TeV collision energy as originally planned.

Scale matters

In hindsight, the LHC was (somewhat fortuitously) more appropriately sized to its primary scientific goal: the discovery of the Higgs boson. The possibility that this elusive quarry could turn up at a mass as low as 125 GeV was not widely appreciated until the late 1980s, when theories involving supersymmetry began to suggest the possibility of such a light Higgs boson emerging from collisions. But by then the SSC die had been cast in favor of a gargantuan 40 TeV collider, 87 km in circumference, that would be able to uncover the roots of spontaneous symmetry breaking even if the long-anticipated phenomenon required the protons' constituent quarks and gluons to collide with energies[9] as high as 2 TeV. When it became apparent in late 1989 that roughly $2 billion more would be needed to reduce design risks that could make it difficult for the SSC to attain its intended collision rate, Panofsky argued that the project should be down-scoped to 35 TeV to save hundreds of millions of dollars. But nearly everyone else countered that the full 40 TeV was required to make sure users could discover the Higgs boson—or whatever else was responsible for spontaneous symmetry breaking and elementary-particle masses.



SLAC DEPUTY DIRECTOR SIDNEY DRELL (left) and emeritus director Wolfgang Panofsky (right) talk in late 1992 with Louisiana senator J. Bennett Johnston, the Superconducting Super Collider's leading supporter in Congress. (Courtesy of Ed Souza, Stanford News Service.)

A US High-Energy Physics Advisory Panel (HEPAP) subpanel, chaired by SLAC deputy director Sidney Drell, unanimously endorsed that fateful decision in 1990. The US high-energy physics community had thus committed itself to an enormous project that became increasingly difficult to sustain politically amid the worsening fiscal climate of the early 1990s. With the end of the Cold War and subsequent absence of a hoped-for peace dividend during a stubborn recession, the US entered a period of fiscal austerity not unlike what is now occurring in many developed Western nations. In that constrained environment, a poorly understood basic-science project experiencing large, continuing cost overruns and lacking major foreign contributions presented an easy political target for congressional budget cutters.

A 20 TeV proton collider—or perhaps just a billion-dollar extension of existing facilities such as the 4–5 TeV Dedicated Collider proposed by Fermilab in 1983—would likely have survived the budget axe and discovered the light Higgs boson long ago.[10] Indeed, another option on the table during the 1983 meetings of a HEPAP subpanel chaired by Stanford physicist Stanley Wojcicki was for Brookhaven National Laboratory to continue construction of its Isabelle collider while Fermilab began the design work on that intermediate-energy proton–antiproton collider, whose costs were then projected at about $600 million.

That more conservative, gradual approach would have maintained the high-energy physics research productivity of the DOE laboratories for at least another decade. And such smaller projects would certainly have been more defensible during the economic contractions of the early 1990s, for they aligned better with the high-energy physics community's diminishing political influence in Washington. Their construction would also have been far easier for physicists to manage and control by themselves without having to involve military–industrial engineers.

The Wojcicki subpanel had originally recommended that the US design a 20–40 TeV collider, but that was before European physicists led by CERN decided in 1984 to focus their long-range plans on a 14 TeV proton collider that they could eventually achieve by adding superconducting magnets to the Large Electron–Positron Collider (LEP) then under construction. (Actually, they considered 18 TeV achievable when they made this decision.) Lowering the SSC energy as Panofsky suggested thus risked Congress raising the awkward question that had already been voiced by SSC opponents, "Why don't US physicists just join the LHC project and save US taxpayers billions of dollars?" Although justified on purely physics grounds, the 1990 decision to keep the original SSC energy clearly had a significant political dimension, too.

PHYSICS TODAY Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page PHYSICS TODAY

SUPERCONDUCTING SUPER COLLIDER DIRECTOR ROY SCHWITTERS (right) guides President George H. W. Bush (center) on a tour of the SSC magnet test laboratory on 30 July 1992. Accompanying them are, from left, presidential science adviser D. Allan Bromley, Texas congressman Joe Barton, and deputy undersecretary of energy Linda Stuntz. (Courtesy of Fermilab Archives.)

The US high-energy physics community therefore elected to "bet the company" on an extremely ambitious 40 TeV collider, so large that it ultimately had to be sited at a new laboratory in the American Southwest, as was originally envisioned in 1982. Such a choice, however, meant abandoning the three-laboratory DOE system that had worked well for nearly two decades and had fostered US leadership in high-energy physics. (That was Cronin's primary concern when he urged his fellow physicists and DOE to site the SSC at Fermilab.) But perceived European threats to US hegemony and Reagan administration encouragement tipped the balance toward making the SSC a national project and away from it becoming the truly international "world laboratory" that others had long been advocating.

Infrastructure problems

In retrospect, the SSC leadership faced two daunting tasks in establishing a new high-energy physics laboratory in Waxahachie, Texas:

- Building the physical infrastructure for a laboratory that would cost billions of US taxpayer dollars and was certain to be a highly visible, contentious project.
- Organizing the human infrastructure needed to ensure that the SSC became a world-class laboratory where scientists could do breakthrough high-energy physics research.

Addressing those tasks meant having to draw resources away from other worthy programs and projects that competed with the SSC during a period of tight annual budgets. Reagan administration officials had insisted that the project would be funded by new money, but that was only a convenient fiction. Congress, not the president, holds the federal purse strings, so the SSC always had to compete against other powerful interests—especially energy and water projects—for its annual funding. And it usually came up short, which further delayed the project and increased its costs.

Schwitters and other managers attempted to attract top-notch physicists to staff the laboratory, but after 1988 many of its original, primary advocates in the SSC Central Design Group (CDG) returned to their tenured positions in universities and national labs. For example, CDG director Maury Tigner, who returned to Cornell University, might have been the best choice for the original project manager. (Second-tier CDG managers did go to Texas, however, as did many younger, untenured physicists.) Despite the promise and likely prestige of building a world-class scientific laboratory, the Dallas–Fort Worth area was viewed as an intellectual backwater by many older, accomplished high-energy physicists. They might have come to work there on a temporary or consulting basis, as did Rees originally, but making a permanent, full-time commitment and bringing their spouses and families with them proved a difficult choice for many.

Achieving the first daunting task in a cost-effective way thus required bringing in an alien, military–industrial culture that made realizing the second task much more difficult. Teaming with EG&G and Sverdrup Corporations helped the SSC laboratory to tap the growing surplus of military–industrial engineers. It was crucial to get capable engineers working on the project quickly so that all the detailed design and construction work could occur on schedule and costs could be controlled. But the presence of military–industrial engineers at high levels in the SSC organization served as an added deterrent to established physicists who might otherwise have moved to Texas to help organize and build the laboratory.[11]

Estimates of the infrastructure costs that could have been saved by siting the SSC adjacent to Fermilab range from $495 million to $3.28 billion. The official DOE figures came in at the lower end, from $495 million to $1.03 billion, but they ignored the value of the human infrastructure then available at Fermilab. In hindsight, the costs of establishing such infrastructure anew at a green-field site were not small. In *Tunnel Visions*, my coauthors and I estimate that the total added infrastructure costs—physical plus human—of building the SSC in Texas would have been about $2 billion.[12]

Unlike historians gazing into the past, however, physicists do not enjoy the benefit of hindsight when planning a new machine. Guided in part by the dominant theoretical paradigm, they work with a cloudy crystal ball through which they can only guess at phenomena likely to occur in a new energy range, and they must plan accordingly. And few can foresee what may transpire in the economic or political realms that could jeopardize an enormous project that requires about a decade to complete and will cost billions of dollars, euros, or Swiss francs—or, relevant today, a trillion yen. That climate of uncertainty thus argues for erring on the side of fiscal conservatism and for trying to reduce expenses by building a new machine at or near an existing laboratory. Such a gradual, incremental approach has been followed successfully at CERN for six decades now, and to a lesser extent at other high-energy physics labs.

But US physicists, perhaps enticed by Reagan administration promises, elected to stray from that well-worn path in the case of the SSC. It took a giant leap of faith to imagine that they could construct an enormous new collider at a green-field site where everything had to be assembled from scratch—including the SSC management team—and defend the project before Congress in times of increasing fiscal austerity. A more modest project sited at Fermilab would likely have weathered less opposition and still be operating today.

In the multibillion-dollar realm it had entered, the US high-energy physics community had to form uneasy alliances with powerful players in Washington and across the nation. And those alliances involved uncomfortable compromises that led, directly or indirectly, to the SSC project's demise. That community of a few thousand physicists had a small and diminishing supply of what Beltway insiders recognize as "political capital." It could not by itself lay claim to more than 5 billion taxpayer dollars when many other pressing demands were being made on the federal purse. Thus for the SSC to move forward as a principally national project meant that those physicists had to give up substantial control to powerful partners with their own competing agendas. The Texans' yearning for high-tech jobs, for example, helped congressional opponents paint the SSC as a pork-barrel project in the public mind. In the process, the high-energy physics community effectively lost control of its most important project.

A personal perspective

Part of the problem driving up the SSC costs was the project's founding rhetoric: the intention to leapfrog European advances and reassert US leadership in high-energy physics. The Reagan administration in particular was promoting US competitiveness over international cooperation; treating other nations as equal partners would not have gained the administration's support. And a smaller, say 20 TeV, proton collider would not have sufficed either, for that was much too close in energy to what CERN could eventually achieve in the 27 km LEP tunnel then under construction. The SSC therefore had to shoot for 40 TeV, which was presented as a scientific necessity but was in fact mainly a political choice. That energy was more than 20 times the energy of the Fermilab Tevatron, and the SSC proved to be nearly 20 times as expensive. And along with its onerous price tag came other, unanticipated complications—managerial as well as political—that US physicists were ill-equipped to confront. As Panofsky suggested, the SSC was indeed "a bridge too far"—a phrase he probably borrowed from the title of Cornelius Ryan's 1974 book about a disastrous Allied campaign to capture the Arnhem Bridge over the Rhine River during World War II.

I became convinced of that interpretation only in April 2014, when previously suppressed documents surfaced at the William J. Clinton Presidential Library. The documents were memos to Clinton's chief of staff regarding a draft letter being circulated among top administration officials in early 1993 by new secretary of energy Hazel O'Leary. In the letter, Clinton was to request a billion-dollar SSC contribution from Japanese prime minister Kiichi Miyazawa. Such a contribution would have helped tremendously to reassure House members that major foreign support was indeed forthcoming and perhaps would have kept the project alive. But the memos, one from science adviser John Gibbons and the other from assistant to the president John Podesta and staff secretary Todd Stern, recommended against the president sending such a letter. The latter memo was particularly adamant:

> NSC [the National Security Council] agrees that we should convey to the Japanese our firm backing for the SSC, <u>but still objects strongly</u> [emphasis in the original] to sending a letter to Miyazawa. Such a letter could be seen as suggesting that we attach greater importance to Japanese participation in the SSC than we do to Japanese efforts on other fronts, such as aid to Russia.[13]

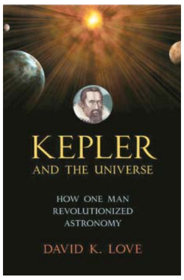
The document underscored for me what insurmountable competition the SSC faced in securing the required billions of dollars in federal and foreign funding. Despite their political influence reaching back to the years after World War II, high-energy physicists were not accustomed to playing in the major leagues of US politics. No such letter was ever sent.

In the final analysis, the Cold War model of doing Big Science projects, with the US taking the lead unilaterally and expecting other Western nations to follow in its footsteps, was no longer appropriate. By the 1980s the global scientific community had begun an epochal transition into a multipolar world in which other nations expect to be treated as equal partners in such major scientific endeavors—especially considering the large financial contributions involved. As US high-energy physicists have hopefully learned from the 1993 termination of the SSC, it should have been promoted from day one as a genuinely international world-laboratory project.

REFERENCES

1. D. J. Kevles, *The Physicists: The History of a Scientific Community in Modern America*, 2nd ed., Harvard U. Press (1995), p. ix.
2. M. Riordan, *Phys. Perspect.* **2**, 411 (2000).
3. S. Wojcicki, *Rev. Accel. Sci. Technol.* **2**, 265 (2009).
4. M. Riordan, L. Hoddeson, A. W. Kolb, *Tunnel Visions: The Rise and Fall of the Superconducting Super Collider*, U. Chicago Press (2015), especially pp. 264–73.
5. J. M. Logsdon, *Together in Orbit: The Origins of International Participation in the Space Station*, NASA (1998).
6. For more details, see ref. 4, chaps. 1, 5, and 7.
7. On LHC costs, see L. Evans, ed., *The Large Hadron Collider: A Marvel of Technology*, EPFL Press (2009), especially chap. 3.1.
8. M. Riordan, *Hist. Stud. Phys. Biol. Sci.* **32**, 125 (2001).
9. The 20 TeV energy of each colliding proton is shared among its quark and gluon constituents such that only about 1/10th of the proton collision energy is available to create new particles.
10. Although as originally designed, the Fermilab Dedicated Collider probably did not have a sufficient collision rate to discover the 125 GeV Higgs boson, an upgraded 6 TeV proton–proton collider proposed by Lee Teng in 1988, which used superconducting magnets like those then being designed for the SSC, would likely have sufficed, given the LHC success at collision energies of 7–8 TeV.
11. D. Ritson, *Nature* **366**, 607 (1993).
12. Ref. 4, p. 265.
13. T. Stern, J. Podesta, "Hazel O'Leary/Superconducting Super Collider," memorandum for Mack McLarty (18 March 1993), William J. Clinton Presidential Library digital archives. PT

BOOKS



Kepler and the Universe

How One Man Revolutionized Astronomy

David K. Love

Prometheus Books, 2015. $24.00 (253 pp.).
ISBN 978-1-63388-106-8

For a major part of the 20th century, Max Caspar's *Kepler* was considered the standard biography of Johannes Kepler. In part it was stitched together from the introductions to the many volumes of the *Gesammelte Werke* (*Collected Works*) edited by the Kepler Commission of the Bavarian Academy of Sciences. It was comprehensive, solid, and yes, stolid. Occasionally there were flights of brilliant prose, as when Caspar wrote concerning the *Harmonice mundi* (*Harmony of the World*), "So his *Harmonice* appears as a great cosmic vision. . . . It belongs to the most sublime, which has been thought and devised by the human intellect, locked in the material world and desiring to lift itself out of it. It is a grandiose fugue on the theme 'world, soul, God' with a maestro finale" (Abelard-Schuman, page 290). But in general it was not fun to read.

Then, in 1959, Hutchinson published Arthur Koestler's *The Sleepwalkers: A History of Man's Changing Vision of the Universe*. The book included a section called "The Watershed," a master storyteller's reworking of Caspar's text that roused up considerable interest in Kepler. Of the variety of accounts that have followed in English, the best—and these are fun to read—are Kitty Ferguson's *Tycho and Kepler: The Unlikely Partnership That Forever Changed Our Understanding of the Universe* (Walker Books, 2002), and the subject of this review, David Love's *Kepler and the Universe: How One Man Revolutionized Astronomy*.

Love, who holds a degree in astronomy, gave up his career as an accountant to become a lecturer and writer in astronomy. He is obviously a fan of Kepler. His book is sprinkled with his own photographs of Keplerian sites throughout Europe. And when it comes to technical Kepleriana, he has produced the clearest mathematical outline that I've ever seen of Kepler's major book, *Astronomia nova* (*The New Astronomy*).

Kepler's professional accomplishments ranged far beyond the three planetary laws for which he is famous. His observations of the supernova of 1604 enabled 20th-century astronomers to find its remnant; his discussion of six-cornered snowflakes is seen as a pioneering treatise on crystallography; his book on optical theory analyzed the astronomical telescope; his discussion of wine measures is part of the prehistory of integral calculus; and he published one of the first tables of logarithms. Apart from the logarithms, it's all here. The book has just a few slips: For example, the inventor of the telescope is Lipperhey, not Lipershey, and Kepler's great book that includes his third planetary law should be abbreviated as *Harmonice mundi*, not *Harmonices mundi* and translated as *Harmony of the World*, not *Harmonies of the World*. But those mostly originate with other authors.

Love is more of an astronomy enthusiast than historian of science; perhaps that's why he takes umbrage when Kepler gets carried away with supposing that the regular polyhedra could control the spacing of the planets. Of course it was part of Kepler's genius to notice that something just as arbitrary "explained" the spacing of the planets in the Ptolemaic system. Namely, one could assume that the planetary spheres, with thickness defined by their epicycles, were nested in a way so as to fill all space. In the Copernican system the relative spacings were known, and it was Kepler's brilliance to try to find a geometrical explanation, nutty as the explanation might appear to us today. Tycho Brahe had also thought about using regular polyhedra in some way, and hence the idea resonated with him when Kepler's letter looking for a job arrived. Without his crazy idea, maybe Kepler would never have got access to Tycho's fabulous observations of Mars!

Likewise Love is impatient with Kepler's infatuation with astrology, and he gives it short shrift despite one of the volumes of the *Gesammelte Werke* being full of hundreds of Kepler's horoscopes. It's not really possible to explore Kepler's unusual mind without including such exotica. One way to get a broad appreciation of Kepler's genius is to read Love's engaging biography, and then to look at Patrick J. Boner's *Kepler's Cosmological Synthesis: Astrology, Mechanism, and the Soul* (Brill, 2013).

Owen Gingerich
Harvard–Smithsonian Center for Astrophysics
Cambridge, Massachusetts

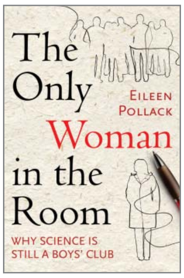
The Only Woman in the Room

Why Science Is Still a Boys' Club

Eileen Pollack

Beacon Press, 2015. $25.95 (266 pp.).
ISBN 978-0-8070-4657-9

All science, technology, engineering, and mathematics (STEM) fields are white-male dominated, but physics is particularly homogeneous. According to NSF, in 2013, 90% of PhD-level employed physicists were men and 74% were white. Many studies have been conducted to investigate that discrepancy, and many books have been written to explain it.



A recent addition to the literature is Eileen Pollack's *The Only Woman in the Room: Why Science Is Still a Boys' Club*. The book has three parts. The first is a memoir of Pollack's experiences in the 1970s at a small high school in western New York State and as a physics major at Yale University. In the second, Pollack, now a successful writer, returns to her high school and college to interview many of her teachers. The last part is an informal summary of the existing literature on why women leave physics for other careers.

Pollack attended Liberty High School "in the heart of the Jewish Catskills." There she was barred from advanced science and math classes because, according to the principal, "girls never go on in science and math." Despite that barrier, she accomplished enough—teaching herself calculus and doing independent projects—to become a member of the fourth class of women admitted to Yale. There she decided to major in physics and became one of the first two women to do so.

Pollack's time at Yale sounds like a nightmare; she endured eating disorders, anxiety attacks, and a constant fear of failing. She describes never feeling like she was doing well and never receiving any encouragement from professors or fellow students. Yet multiple signs indicated that she was doing remarkably well. For example, several teachers invited her to work with them on independent research projects. She graduated from Yale *summa cum laude*. A reader could be excused for wondering about the cause of her lack of confidence, her inability to read the signs of success, and her constant self-doubt.

During her senior year, Pollack began to take writing courses, in which her experience was totally different. Her classes included other women, and teachers and fellow students were encouraging and supportive. Based on that experience Pollack abandoned her ambition to go to graduate school in physics and become an astrophysicist. She's not very clear on the reasons for her decision; I suspect she herself still doesn't know. In any case, she has become a successful, award-winning writer and teaches writing at the University of Michigan.

In the second part of the book, Pollack goes back to Liberty High School and Yale and interviews her high school and college teachers. At her high school, she finds encouraging changes—the physics instructor is female and the advanced class includes three girls. But one of the math teachers tells her that "guys are more hard-wired to build things."

At Yale, Pollack finds a similar mixture of exciting changes and more of the same. The physics department chair is Meg Urry, a woman who, in addition to having a distinguished career in astrophysics, has made significant contributions to the cause of women in physics. Pollack gets to know a group of girls who "don't give a crap," who take pleasure in their ability to do math and physics, and who are not crippled by self-consciousness as she was. And yet, in numerous ways, nothing has changed; many a girl still worries that "if she's perceived to be a feminist, the boys won't ask her out."

In the third and last part of the book, Pollack moves beyond her own personal experience to review much of the literature and offer alternative reasons why women in physics are so rare and why they so often drop out. Her preferred explanation is that "female science majors need far more encouragement than men, even as their instructors perceive any need for praise as a sign that the student lacks the seriousness or commitment to succeed in research."

Pollack is an engaging writer with an eye for an apt anecdote. Her personal story should convince skeptics that the culture of physics makes it difficult for women—even talented and enthusiastic women—to persist and succeed. On the back of the book, former Harvard University president Lawrence Summers is quoted as saying, "I certainly understand many aspects of the issue better for reading Pollack's work." I sincerely hope that others will feel the same, that they will find her discussion of being "the only woman in the room" compelling, and that they will be inspired to think differently about women in physics.

Barbara L. Whitten
Colorado College
Colorado Springs, CO

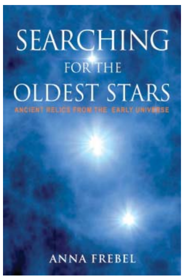
Searching for the Oldest Stars

Ancient Relics from the Early Universe

Anna Frebel

Princeton U. Press, 2015. $29.95 (302 pp.).
ISBN 978-0-691-16506-6

"Metal-poor stars are a girl's best friend! Who still needs diamonds?" Those final two sentences of Anna Frebel's *Searching for the Oldest Stars: Ancient Relics from the Early Universe* express the author's love of and passion for stellar archaeology, the quest to constrain the origin of elements through archaeological "digs" of the night sky. Throughout her book, Frebel conveys her enthusiasm in the way she interweaves a story of the cosmic origin of elements with a personal account of scientific discovery and methodology that gives readers a glimpse into the life and thrills of a modern-day astronomer.



All elements, except for hydrogen, helium, and lithium, have their origin in the interiors of stars: The iron in our blood, the calcium in our bones, and the carbon, nitrogen, and oxygen that make up the amino acids that are crucial for life itself—all were created in the interior furnaces of stars and then released by stellar explosions. As Carl Sagan put it in *The Cosmic Connection: An Extraterrestrial Perspective* (Doubleday, 1973), "We are made of star-stuff." Although Frebel gives a detailed description of how various elements are synthesized in stellar interiors, she neglects to provide a physical description of primordial nucleosynthesis. It would have been fitting, in particular, to include an explanation of why elements heavier than lithium cannot have formed during the first three minutes after the Big Bang.

As one of the world's leading researchers in the field of stellar archaeology, Frebel uses large telescopes to take spectra of stars and to search for the most metal-poor stars—that is, stars poorest in elements heavier than helium. Absorption lines in those spectra are the fingerprints that reveal the stars' elemental makeup, and they take central stage in a captivating detective story of how the first stars formed only a few million years after the Big Bang.

Metal abundances in the universe build up over time, as more and more stars shed the elemental yields from which newer generations of stars form. As a consequence, metal-poor stars are also old. The astrophysicist's hunt for the most metal-poor stars is thus much like the archaeologist's hunt for the oldest forms of life. Frebel discovered several of the most metal-poor stars known, some of which have metal abundances, relative to hydrogen, that are less than 1/250 000 of that in the Sun. Such stars are cosmic fossils that may well have been enriched by the ejecta of only a single supernova; thus they provide important insight regarding the elemental yields of the first population of exploding stars in the universe.

A unique aspect of *Searching for the Oldest Stars* is that each chapter is intended to stand alone, so the chapters need not be read in any particular order. Some chapters outline the detailed physical processes by which stars form and evolve. Others tell enthralling stories, such as the author's account of the Australian bushfires that destroyed the Mount Stromlo Observatory in 2003 or her description of what it is like to spend weeks on end on a remote mountaintop observing the night skies. Readers of PHYSICS TODAY should have no problem with the physical concepts that feature in the chapters describing the various nucleosynthetic burning stages in a star's life or the neutron-capture processes that are responsible for the synthesis of elements heavier than iron. But readers less versed in basic physics and astronomy will find those chapters challenging and may find themselves flipping among chapters to weave a comprehensive picture.

Frebel's delightful blend of science and personal stories has plenty to offer for readers ranging from nonscientists to professional astronomers. In addition, by highlighting the important role of women astronomers in the development of stellar spectroscopy, Frebel clearly strives to motivate and inspire future generations of female scientists. Laden with passion and excitement, *Searching for the Oldest Stars* accomplishes what it sets out to do—engage readers and provide insights into stellar archaeology and the motivations that propel scientists in their quest to answer fundamental questions.

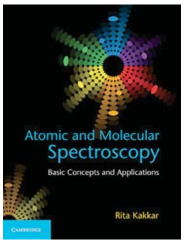
Frank van den Bosch
Yale University
New Haven, Connecticut

Atomic and Molecular Spectroscopy

Basic Concepts and Applications

Rita Kakkar

Cambridge U. Press, 2015. $75.00 (415 pp.).
ISBN 978-1-107-06388-4



In her preface to *Atomic and Molecular Spectroscopy: Basic Concepts and Applications*, Rita Kakkar writes that the book is primarily intended for graduate and advanced undergraduate students who have already taken a course in quantum mechanics and know how to apply elementary molecular point-group representation theory. Her text covers the basics of light–matter interactions; electronic spectroscopy of atoms; and rotational, vibrational, and electronic spectroscopies of diatomic and small polyatomic molecules. Raman spectroscopy, vibrational and rotational, receives its own chapter. That separation is common, but I prefer to integrate Raman with other absorption and emission spectroscopies. The book does not consider magnetic resonance spectroscopies or even the influence of nuclear moments on spectra.

The most attractive features of *Atomic and Molecular Spectroscopy* are that each chapter has many fully worked-out problems and each concludes with numerous exercises; the book includes 257 exercises in total. Mathematical derivations are presented in great detail, so even the weakest students should be able to follow them.

The cost of those features, however, is that the book treats most topics at a lower level of detail than comparable texts, such as Peter Bernath's *Spectra of Atoms and Molecules* (3rd edition, Oxford University Press, 2015). The organization and range of topics in the Kakkar and Bernath books are similar, but Kakkar's is less thorough and quantitative. For example, the Kakkar text does not present a mathematical statement of the Born–Oppenheimer approximation, the most important principle in molecular spectroscopy; in fact, its qualitative statement of the principle is potentially misleading. Furthermore, the book does not cover the traditional effective model used to justify a single term for spin–orbit coupling, nor does it explain why the coupling grows rapidly with atomic number. The discussion of rotational spectroscopy does not quantitatively treat asymmetric top molecules, in which all three principal moments of inertia differ.

Atomic and Molecular Spectroscopy covers only traditional, well-established topics. I did not find a single subject that has not been presented in texts more than 50 years old. Completely absent are coherent spectroscopies, the optical Bloch equations, nonlinear optics and multiphoton spectroscopies, multiresonance and time-resolved spectroscopies, studies of intramolecular and intermolecular dynamics, ions and radicals, spectroscopy of weakly bound complexes, and almost all the other topics that feature in modern molecular-spectroscopy research. I recognize from my own teaching that only a small number of such topics can be shoehorned into a one-semester course, but I believe ignoring all modern research is a great disservice. Most spectroscopy papers these days include a comparison of experimental results with predictions from quantum chemistry, but Kakkar's text includes no such comparisons.

Unfortunately, the book has several other weaknesses. First, it frequently compares quantities that have different units or talks about dimensional quantities being large or small with no explicit reference. Second, it contains many false statements. Some of those could be typographical errors or oversimplifications, but most cannot be so readily dismissed. Third, although the book includes a two-page bibliography, it does not include in-text references, an omission that blocks the path of the curious student eager to learn more. In addition, the text is poorly copyedited, and it includes many low-quality graphs and figures, several of which are copied from Colin N. Banwell's *Fundamentals of Molecular Spectroscopy* (McGraw-Hill, 1983).

I cannot recommend *Atomic and Molecular Spectroscopy*, on its own, to anyone, though it could be useful as a companion text for weaker students taking a course that is using a higher-level primary text such as Bernath's. More's the pity, as students would benefit from a truly modern molecular spectroscopy textbook that prepares them to read the current literature and work on modern research projects. At the moment, no such book exists.

Kevin Lehmann
University of Virginia
Charlottesville

NEW BOOKS

Astronomy and astrophysics

Archaeoastronomy: Introduction to the Science of Stars and Stones. G. Magli. Springer, 2016. $59.99 *paper* (246 pp.). ISBN 978-3-319-22881-5

Astronomical Data Analysis Software and Systems: XXIV. A. R. Taylor, E. Rosolowsky, eds. Astronomical Society of the Pacific, 2015. $88.00 (594 pp.). ISBN 978-1-58381-874-9

Astrophysical Black Holes. F. Haardt et al., eds. Springer, 2016. $59.99 *paper* (314 pp.). ISBN 978-3-319-19415-8

Atomic Diffusion in Stars. G. Michaud, G. Alecian, J. Richer. Springer, 2015. $99.00 (327 pp.). ISBN 978-3-319-19853-8

Breakthrough! 100 Astronomical Images That Changed the World. R. Gendler, R. J. GaBany. Springer, 2015. $34.99 (171 pp.). ISBN 978-3-319-20972-2

Building a Roll-Off Roof or Dome Observatory: A Complete Guide for Design and Construction. 2nd ed. J. S. Hicks. Springer, 2016. $34.99 *paper* (248 pp.). ISBN 978-1-4939-3010-4

Deep Sky Observing: An Astronomical Tour. 2nd ed. S. R. Coe. Springer, 2016. $44.99 *paper* (339 pp.). ISBN 978-3-319-22529-6

The Interstellar Medium, Expanding Nebulae and Triggered Star Formation: Theory and Simulations. T. G. Bisbas. Springer, 2016. $54.99 *paper* (71 pp.). ISBN 978-3-319-26140-9

An Introduction to Observational Astrophysics. M. Gallaway. Springer, 2016. $39.99 *paper* (204 pp.). ISBN 978-3-319-23376-5

Revolution in Astronomy with ALMA: The Third Year. D. Iono, K. Tatematsu, A. Wootten, L. Testi, eds. Astronomical Society of the Pacific, 2015. $88.00 (364 pp.). ISBN 978-1-58381-882-4

A Stargazing Program for Beginners: A Pocket Field Guide. J. Carter. Springer, 2015. $44.99 *paper* (419 pp.). ISBN 978-3-319-22071-0

Tidal Streams in the Local Group and Beyond: Observations and Implications. H. J. Newberg, J. L. Carlin, eds. Springer, 2016. $129.00 (250 pp.). ISBN 978-3-319-19335-9

Weird Astronomical Theories of the Solar System and Beyond. D. Seargent. Springer, 2016. $34.99 *paper* (270 pp.). ISBN 978-3-319-25293-3

Atomic and molecular physics

Spectroscopy and Optical Diagnostics for Gases. R. K. Hanson, R. M. Spearrin, C. S. Goldenstein. Springer, 2016. $89.99 (279 pp.). ISBN 978-3-319-23251-5

Biological and medical physics

II Latin American Conference on Bioimpedance. F. Simini, P. Bertemes-Filho, eds. Springer, 2016. $199.00 *paper* (83 pp.). ISBN 978-981-287-926-4

Advances in Nanotheranostics I: Design and Fabrication of Theranosic Nanoparticles. Z. Dai, ed. Springer, 2016. $179.00 (336 pp.). ISBN 978-3-662-48542-2

Electrophysiology of Unconventional Channels and Pores. A. H. Delcour, ed. Springer, 2015. $179.00 (385 pp.). ISBN 978-3-319-20148-1

Fundamentals of Protein Structure and Function. 2nd ed. E. Buxbaum. Springer, 2015. $119.00 (521 pp.). ISBN 978-3-319-19919-1

Lasers in Cardiovascular Interventions. O. Topaz, ed. Springer, 2015. $159.00 (363 pp.). ISBN 978-1-4471-5219-4

Physical Models of Cell Motility. I. S. Aranson, ed. Springer, 2016. $129.00 (201 pp.). ISBN 978-3-319-24446-4

Physical Sciences and Engineering Advances in Life Sciences and Oncology: A WTEC Global Assessment. P. Janmey et al., eds. Springer, 2016. $179.00 (403 pp.). ISBN 978-3-319-17929-2

Physiology for Engineers: Applying Engineering Methods to Physiological Systems. M. Chappell, S. Payne. Springer, 2016. $89.99 (167 pp.). ISBN 978-3-319-26195-9

Chemical physics

Chemical Science of π-Electron Systems. T. Akasaka et al., eds. Springer, 2015. $279.00 (777 pp.). ISBN 978-4-431-55356-4

Physical Chemistry from a Different Angle: Introducing Chemical Equilibrium, Kinetics and Electrochemistry by Numerous Experiments. G. Job, R. Rüffler. Springer, 2016. $119.00 (641 pp.). ISBN 978-3-319-15665-1

Rare-Earths and Actinides in High Energy Spectroscopy. C. Bonnelle, N. Spector. Springer, 2015. $259.00 (380 pp.). ISBN 978-90-481-2878-5

Computers and computational physics

Isogeometric Analysis and Applications 2014. B. Jüttler, B. Simeon, eds. Springer, 2015. $119.00 (281 pp.). ISBN 978-3-319-23314-7

Multimedia Signals and Systems: Basic and Advanced Algorithms for Signal Processing. 2nd ed. S. Stanković, I. Orović, E. Sejdić.

Springer, 2016. $159.00 (391 pp.). ISBN 978-3-319-23948-4

A Primer on Radial Basis Functions with Applications to the Geosciences. B. Fornberg, N. Flyer. SIAM, 2015. $79.00 *paper* (221 pp.). ISBN 978-1-611974-02-7

Spline Functions: Computational Methods. L. L. Schumaker. SIAM, 2015. $83.00 (413 pp.). ISBN 978-1-611973-89-1

Condensed-matter physics

Energy Landscapes, Inherent Structures, and Condensed-Matter Phenomena. F. H. Stillinger. Princeton U. Press, 2016. $99.50 (509 pp.). ISBN 978-0-691-16680-3

Fluctuation Mechanisms in Superconductors: Nanowire Single-Photon Counters, Enabled by Effective Top-Down Manufacturing. H. Bartolf. Springer Spektrum, 2016. $89.99 (328 pp.). ISBN 978-3-658-12245-4

Soft Matter at Aqueous Interfaces. P. R. Lang, Y. Liu, eds. Springer, 2016. $119.00 *paper* (555 pp.). ISBN 978-3-319-24500-3

Cosmology and relativity

Understanding the Epoch of Cosmic Reionization: Challenges and Progress. A. Mesinger, ed. Springer, 2016. $129.00 (280 pp.). ISBN 978-3-319-21956-1

Device physics

Design of Organic Complementary Circuits and Systems on Foil. S. Abdinia, A. H. M. van Roermund, E. Cantatore. Springer, 2015. $99.00 (131 pp.). ISBN 978-3-319-21187-9

Feedback in Analog Circuits. A. Ochoa. Springer, 2016. $94.99 (164 pp.). ISBN 978-3-319-26250-5

Lattices of Dielectric Resonators. A. Trubin. Springer, 2016. $99.00 (171 pp.). ISBN 978-3-319-25146-2

Sinusoidal Oscillators and Waveform Generators Using Modern Electronic Circuit Building Blocks. R. Senani, D. R. Bhaskar, V. K. Singh, R. K. Sharma. Springer, 2016. $149.00 (622 pp.). ISBN 978-3-319-23711-4

Energy and environment

Hybrid Electric Vehicles: Energy Management Strategies. S. Onori, L. Serrao, G. Rizzoni. Springer, 2016. $54.99 *paper* (112 pp.). ISBN 978-1-4471-6779-2

Production of Hydrogen from Renewable Resources. Z. Fang, R. L. Smith Jr, X. Qi, eds. Springer, 2015. $159.00 (368 pp.). ISBN 978-94-017-7329-4

Fluids

Fundamentals of Modern Unsteady Aerodynamics. 2nd ed. Ü. Gülçat. Springer, 2016. $179.00 (395 pp.). ISBN 978-981-10-0016-4

Hemo-Dynamics. M. Zamir. Springer, 2016. $229.00 (407 pp.). ISBN 978-3-319-24101-2

The Modes of Gaseous Combustion. N. M. Rubtsov. Springer, 2016. $179.00 (297 pp.). ISBN 978-3-319-25932-1

Stratification, Rollover and Handling of LNG, LPG and Other Cryogenic Liquid Mixtures. R. G. Scurlock. Springer, 2016. $54.99 *paper* (134 pp.). ISBN 978-3-319-20695-0

Visualization of Conventional and Combusting Subsonic Jet Instabilities. V. V. Kozlov, G. R. Grek, Y. A. Litvinenko. Springer, 2016. $54.99 *paper* (126 pp.). ISBN 978-3-319-26957-3

Geophysics

Acoustic, Electromagnetic, Neutron Emissions from Fracture and Earthquakes. A. Carpinteri, G. Lacidogna, A. Manuello, eds. Springer, 2015. $179.00 (264 pp.). ISBN 978-3-319-16954-5

Current Topics on Deformation Monitoring and Modelling, Geodynamics and Natural Hazards. P. J. González, G. Herrera, F. Luzón, P. Tizzani, eds. Birkhäuser, 2016. $74.99 *paper* (303 pp.). ISBN 978-3-0348-0956-6

Instrumentation in Earthquake Seismology. 2nd ed. J. Havskov, G. Alguacil. Springer, 2016. $129.00 (413 pp.). ISBN 978-3-319-21313-2

The Making of India: Geodynamic Evolution. 2nd ed. K. S. Valdiya. Springer, 2016. $279.00 (924 pp.). ISBN 978-3-319-25027-4

History and philosophy

Breaking the Chains of Gravity: The Story of Spaceflight before NASA. A. S. Teitel. Bloomsbury Sigma, 2016. $27.00 (304 pp.). ISBN 978-1-4729-1117-9

Chaos Imagined: Literature, Art, Science. M. Meisel. Columbia U. Press, 2016. $45.00 (585 pp.). ISBN 978-0-231-16632-4

Continuum Mechanics Through the Ages—From the Renaissance to the Twentieth Century: From Hydraulics to Plasticity. G. A. Maugin. Springer, 2016. $129.00 (306 pp.). ISBN 978-3-319-26591-9

Enhancing Hubble's Vision: Service Missions That Expanded Our View of the Universe. D. J. Shayler, D. M. Harland. Springer, 2016. $44.99 *paper* (333 pp.). ISBN 978-3-319-22643-9

Essays on the History of Mechanical Engineering. F. Sorge, G. Genchi, eds. Springer, 2016. $109.00 (409 pp.). ISBN 978-3-319-22679-8

Exploring the History of New Zealand Astronomy: Trials, Tribulations, Telescopes and Transits. W. Orchiston. Springer, 2016. $179.00 (688 pp.). ISBN 978-3-319-22565-4

The Hubble Space Telescope: From Concept to Success. D. J. Shayler, D. M. Harland. Praxis/Springer, 2016. $39.99 *paper* (414 pp.). ISBN 978-1-4939-2826-2

The Human Side of Science: Edison and Tesla, Watson and Crick, and Other Personal Stories behind Science's Big Ideas. A. W. Wiggins, C. M. Wynn Sr. Prometheus Books, 2016. $25.00 (360 pp.). ISBN 978-1-63388-156-3

Interkosmos: The Eastern Bloc's Early Space Program. C. Burgess, B. Vis. Praxis/Springer, 2016. $39.99 *paper* (321 pp.). ISBN 978-3-319-24161-6

Philosophy of Science for Scientists. L.-G. Johansson. Springer, 2016. $69.99 (257 pp.). ISBN 978-3-319-26549-0

Wisdom of the Martians of Science: In Their Own Words with Commentaries. B. Hargittai, I. Hargittai. World Scientific, 2016. $34.00 *paper* (252 pp.). ISBN 978-981-4723-81-7

Instrumentation and techniques

Coordinate Metrology: Accuracy of Systems and Measurements. J. A. Sładek. Springer, 2016. $149.00 (471 pp.). ISBN 978-3-662-48463-0

Experimental Methods of Shock Wave Research. O. Igra, F. Seiler, eds. Springer, 2016. $179.00 (478 pp.). ISBN 978-3-319-23744-2

Hard X-Ray Photoelectron Spectroscopy (HAXPES). J. C. Woicik, ed. Springer, 2016. $229.00 (571 pp.). ISBN 978-3-319-24041-1

Reviews in Fluorescence 2015. C. D. Geddes, ed. Springer, 2016. $179.00 (380 pp.). ISBN 978-3-319-24607-9

Surface-Enhanced Raman Spectroscopy: Bioanalytical, Biomolecular and Medical Applications. M. Procházka. Springer, 2016. $129.00 (221 pp.). ISBN 978-3-319-23990-3

Understanding Phase Contrast MR Angiography: A Practical Approach with MATLAB Examples. J. Suresh Paul, S. Gouri Raveendran. Springer, 2016. $54.99 *paper* (92 pp.). ISBN 978-3-319-25481-4

Materials science

Carbon Nanomaterials for Biomedical Applications. M. Zhang, R. R. Naik, L. Dai, eds. Springer, 2016. $179.00 (576 pp.). ISBN 978-3-319-22860-0

Extreme States of Matter: High Energy Density Physics. 2nd ed. V. E. Fortov. Springer, 2016. $229.00 (700 pp.). ISBN 978-3-319-18952-9

Fundamentals of the Mechanics of Solids. P. M. Mariano, L. Galano. Birkhäuser, 2015. $79.99 (422 pp.). ISBN 978-1-4939-3132-3

Information Science for Materials Discovery and Design. T. Lookman, F. J. Alexander, K. Rajan, eds. Springer, 2016. $149.00 (307 pp.). ISBN 978-3-319-23870-8

Low-Dimensional and Nanostructured Materials and Devices: Properties, Synthesis, Characterization, Modelling and Applications. H. Ünlü, N. J. M. Horing, J. Daboswki, eds. Springer, 2016. $179.00 (674 pp.). ISBN 978-3-319-25338-1

Multiscale Paradigms in Integrated Computational Materials Science and Engineering: Materials Theory, Modeling, and Simulation for Predictive Design. P. A. Deymier, K. Runge, K. Muralidharan, eds. Springer, 2016. $179.00 (300 pp.). ISBN 978-3-319-24527-0

Nanomaterials in Extreme Environments: Fundamentals and Applications. R. A. Andrievski, A. V. Khatchoyan. Springer, 2016. $99.00 (107 pp.). ISBN 978-3-319-25329-9

Photonic Materials for Sensing, Biosensing and Display Devices. M. J. Serpe, Y. Kang, Q. M. Zhang, eds. Springer, 2016. $179.00 (364 pp.). ISBN 978-3-319-24988-9

Proceedings of the III Advanced Ceramics and Applications Conference. W. E. Lee, R. Gadow, V. Mitic, N. Obradovic, eds. Atlantis Press, 2016. $199.00 (383 pp.). ISBN 978-94-6239-156-7

Production, Handling and Characterization of Particulate Materials. H. G. Merkus, G. M. H. Meesters, eds. Springer, 2016. $139.00 (548 pp.). ISBN 978-3-319-20948-7

A Second-Order EΔ ADC Using Sputtered IGZO TFTs. A. P. P. Correia, P. M. C. Barquinha, J. C. da Palma Goes. Springer, 2016. $54.99 *paper* (75 pp.). ISBN 978-3-319-27190-3

Miscellaneous

Buildings for Advanced Technology. A. Soueid, E. C. Teague, J. Murday, eds. Springer, 2015. $94.99 (185 pp.). ISBN 978-3-319-24890-5

The DelFly: Design, Aerodynamics, and Artificial Intelligence of a Flapping Wing Robot. G. C. H. E. de Croon et al. Springer, 2016. $119.00 (218 pp.). ISBN 978-94-017-9207-3

Nonlinear science and chaos

Markov Chain Aggregation for Agent-Based Models. S. Banisch. Springer, 2016. $89.99 (195 pp.). ISBN 978-3-319-24875-2

Nonlinear Resonances. S. Rajasekar, M. A. F. Sanjuan. Springer, 2016. $129.00 (409 pp.). ISBN 978-3-319-24884-4

The Physics of Stocks and Flows of Energy Systems: Applications in Energy Policy. H. Qudrat-Ullah. Springer, 2016. $54.99 *paper* (77 pp.). ISBN 978-3-319-24827-1

Selforganization in Complex Systems: The Past, Present, and Future of Synergetics. A. Pelster, G. Wunner, eds. Springer, 2016. $259.00 (364 pp.). ISBN 978-3-319-27633-5

The Unity of Science and Economics: A New Foundation of Economic Theory. J. Chen. Springer, 2016. $89.99 (136 pp.). ISBN 978-1-4939-3464-5

Optics and photonics

Diffractive Optics and Nanophotonics: Resolution Below the Diffraction Limit. I. Minin, O. Minin. Springer, 2016. $54.99 *paper* (65 pp.). ISBN 978-3-319-24251-4

Nuclear-Pumped Lasers. M. Prelas. Springer, 2016. $199.00 (417 pp.). ISBN 978-3-319-19844-6

Quantum States of Light. A. Furusawa. Springer, 2015. $54.99 *paper* (104 pp.). ISBN 978-4-431-55958-0

Particle physics

Effective Field Theories. A. A. Petrov, A. E. Blechman. World Scientific, 2016. $118.00 (303 pp.). ISBN 978-981-4434-92-8

New Dualities of Supersymmetric Gauge Theories. J. Teschner, ed. Springer, 2016. $129.00 (467 pp.). ISBN 978-3-319-18768-6

Particles and the Universe: From the Ionian School to the Higgs Boson and Beyond. S. Narison. World Scientific, 2016. $38.00 *paper* (369 pp.). ISBN 978-981-4644-69-3

Plasmas and fusion

Elements of Plasma Technology. C. S. Wong, R. Mongkolnavin. Springer, 2016. $54.99 *paper* (123 pp.). ISBN 978-981-10-0115-4

Fundamental Aspects of Plasma Chemical Physics: Kinetics. M. Capitelli et al. Springer, 2016. $129.00 (318 pp.). ISBN 978-1-4419-8184-4

Introduction to Plasma Physics and Controlled Fusion. 3rd ed. F. F. Chen. Springer, 2016. $99.00 (490 pp.). ISBN 978-3-319-22308-7

Numerical Modeling of Space Plasma Flows ASTRONUM-2014. N. V. Pogorelov, E. Audit, G. P. Zank, eds. Astronomical Society of the Pacific, 2015. $77.00 (252 pp.). ISBN 978-1-58381-880-0

Relativistic Nonlinear Electrodynamics: The QED Vacuum and Matter in Super-Strong Radiation Fields. 2nd ed. H. K. Avetissian. Springer, 2016. $179.00 (506 pp.). ISBN 978-3-319-26382-3

Popularizations

The Best Writing on Mathematics 2015. M. Pitici, ed. Princeton U. Press, 2016. $24.95 *paper* (363 pp.). ISBN 978-0-691-16965-1

A Brief History of Creation: Science and the Search for the Origin of Life. B. Mesler, H. J. Cleaves II. W. W. Norton, 2016. $27.95 (312 pp.). ISBN 978-0-393-08355-2

Searching for the Oldest Stars: Ancient Relics from the Early Universe. A. Frebel. Princeton U. Press, 2015. $29.95 (336 pp.). ISBN 978-0-691-16506-6

Slap Shot Science: A Curious Fan's Guide to Hockey. A. Haché. Johns Hopkins U. Press, 2015. $28.95 *paper* (176 pp.). ISBN 978-1-4214-1792-9

The Starlight Night: The Sky in the Writings of Shakespeare, Tennyson, and Hopkins. 2nd ed. D. H. Levy. Springer, 2016. $179.00 (214 pp.). ISBN 978-3-319-19877-4

Quantum physics

Gauge Invariance and Weyl-Polymer Quantization. F. Strocchi. Springer, 2016. $39.99 *paper* (97 pp.). ISBN 978-3-319-17694-9

Introduction to Information Retrieval and Quantum Mechanics. M. Melucci. Springer, 2015. $109.00 (232 pp.). ISBN 978-3-662-48312-1

Lectures in Quantum Mechanics: A Two-Term Course. L. E. Picasso. Springer, 2016. $79.99 (354 pp.). ISBN 978-3-319-22631-6

Principles and Methods of Quantum Information Technologies. Y. Yamamoto, K. Semba, eds. Springer, 2016. $89.99 *paper* (624 pp.). ISBN 978-4-431-55755-5

The Quantum Handshake: Entanglement, Nonlocality and Transactions. J. G. Cramer. Springer, 2016. $69.99 (218 pp.). ISBN 978-3-319-24640-6

Quantum Kinetic Theory. 2nd ed. M. Bonitz. Springer, 2016. $109.00 (406 pp.). ISBN 978-3-319-24119-7

Quantum Theory: Informational Foundations and Foils. G. Chiribella, R. W. Spekkens, eds. Springer, 2016. $129.00 (528 pp.). ISBN 978-94-017-7302-7

Society and government

Celebrating Science: Putting Education Best

Practices to Work. G. Schultz, S. Buxner, L. Shore, J. Barnes, eds. Astronomical Society of the Pacific, 2015. $77.00 (296 pp.). ISBN 978-1-58381-884-8

Space and planetary science

Dawn of Small Worlds: Dwarf Planets, Asteroids, Comets. M. Moltenbrey. Springer, 2016. $39.00 *paper* (273 pp.). ISBN 978-3-319-23002-3

Human Missions to Mars: Enabling Technologies for Exploring the Red Planet. 2nd ed. D. Rapp. Springer, 2016. $229.00 (582 pp.). ISBN 978-3-319-22248-6

Imaging Convection and Magnetism in the Sun. S. Hanasoge. Springer, 2015. $54.99 *paper* (131 pp.). ISBN 978-3-319-27328-0

Mars via the Moon: The Next Giant Leap. E. Seedhouse. Springer, 2016. $34.99 *paper* (170 pp.). ISBN 978-3-319-21887-8

The Moon's Largest Craters and Basins: Images and Topographic Maps from LRO, GRAIL, and Kaguya. C. J. Byrne. Springer, 2016. $34.99 (246 pp.). ISBN 978-3-319-22031-4

SpaceX's Dragon: America's Next Generation Spacecraft. E. Seedhouse. Praxis/Springer, 2016. $29.99 *paper* (188 pp.). ISBN 978-3-319-21514-3

Statistical physics and thermodynamics

Mechanothermodynamics. L. Sosnovskiy, S. Sherbakov. Springer, 2016. $99.00 (155 pp.). ISBN 978-3-319-24979-7

Texts and education

2016 Graduate Programs in Physics, Astronomy, and Related Fields. AIP, 2015. $82.00 *paper* (658 pp.). ISBN 978-0-7354-1307-8

Cell Biology by the Numbers. R. Milo, R. Phillips. Garland Science, 2016. $49.95 *paper* (356 pp.). ISBN 978-0-8153-4537-4

Conductors, Semiconductors, Superconductors: An Introduction to Solid State Physics. 2nd ed. R. P. Huebener. Springer, 2016. $79.99 *paper* (237 pp.). ISBN 978-3-319-24008-4

From Quarks to the Universe: A Short Physics Course. 2nd ed. E. N. Economou. Springer, 2016. $109.00 (326 pp.). ISBN 978-3-319-20653-0

Mathematics of Planet Earth: Mathematicians Reflect on How to Discover, Organize, and Protect Our Planet. H. Kaper, C. Rousseau, eds. SIAM, 2015. $39.00 *paper* (206 pp.). ISBN 978-1-611973-70-9

Ordinary Differential Equations and Linear Algebra: A Systems Approach. T. Kapitula. SIAM, 2015. $79.00 *paper* (300 pp.). ISBN 978-1-611974-08-9

Principles of Adaptive Optics. 4th ed. R. K. Tyson. CRC Press/Taylor & Francis, 2016. $153.95 (360 pp.). ISBN 978-1-4822-5233-0

A Student's Guide Through the Great Physics Texts. Volume III: Electricity, Magnetism and Light. K. Kuehn. Springer, 2016. $89.99 (471 pp.). ISBN 978-3-319-21815-1

A Student's Guide Through the Great Physics Texts. Volume IV: Heat, Atoms and Quanta. K. Kuehn. Springer, 2016. $89.99 (463 pp.). ISBN 978-3-319-21827-4

Theory and mathematical methods

Central Configurations, Periodic Orbits, and Hamiltonian Systems. J. Llibre, R. Moeckel, C. Simó. Birkhäuser, 2015. $31.99 *paper* (232 pp.). ISBN 978-3-0348-0932-0

The Defocusing Nonlinear Schrödinger Equation: From Dark Solitons to Vortices and Vortex Rings. P. G. Kevrekidis, D. J. Frantzeskakis, R. Carretero-González. SIAM, 2015. $98.00 *paper* (429 pp.). ISBN 978-1-611973-93-8

Error Estimates for Well-Balanced Schemes on Simple Balance Laws: One-Dimensional Position-Dependent Models. D. Amadori, L. Gosse. Springer, 2015. $54.99 *paper* (110 pp.). ISBN 978-3-319-24784-7

Evolution Equations of von Karman Type. P. Cherrier, A. Milani. Springer, 2015. $39.99 *paper* (140 pp.). ISBN 978-3-319-20996-8

Hamiltonian Partial Differential Equations and Applications. P. Guyenne, D. Nicholls, C. Sulem, eds. Springer, 2015. $129.00 (449 pp.). ISBN 978-1-4939-2949-8

Handbook of Mathematics. 6th ed. I. N. Bronshtein, K. A. Semendyayev, G. Musiol, H. Mühlig. Springer, 2015. $129.00 *paper* (1207 pp.). ISBN 978-3-662-46220-1

Hyperspherical Harmonics Expansion Techniques: Application to Problems in Physics. T. K. Das. Springer, 2016. $89.99 (159 pp.). ISBN 978-81-322-2360-3

An Introduction to Domain Decomposition Methods: Algorithms, Theory, and Parallel Implementation. V. Dolean, P. Jolivet, F. Nataf. SIAM, 2015. $79.00 *paper* (238 pp.). ISBN 978-1-611974-05-8

Introduction to Uncertainty Quantification. T. J. Sullivan. Springer, 2015. $79.99 (342 pp.). ISBN 978-3-319-23394-9

The Inverse Problem of the Calculus of Variations: Local and Global Theory. D. V. Zenkov, ed. Atlantis Press, 2015. $109.00 (289 pp.). ISBN 978-94-6239-108-6

Linear Canonical Transforms: Theory and Applications. J. J. Healy, M. A. Kutay, H. M. Ozaktas, J. T. Sheridan, eds. Springer, 2016. $179.00 (453 pp.). ISBN 978-1-4939-3027-2

Path Integrals for Pedestrians. E. Gozzi, E. Cattaruzza, C. Pagani. World Scientific, 2016. $34.00 *paper* (143 pp.). ISBN 978-981-4603-93-5

Permittivity and Permeability Tensors for Cloaking Applications. B. Choudhury, P. V. Reddy, R. M. Jha. Springer, 2016. $54.99 *paper* (71 pp.). ISBN 978-981-287-804-5

Rate-Independent Systems: Theory and Application. A. Mielke, T. Roubíček. Springer, 2015. $149.00 (660 pp.). ISBN 978-1-4939-2705-0

Quantum Lie Theory: A Multilinear Approach. V. Kharchenko. Springer, 2015. $59.99 *paper* (302 pp.). ISBN 978-3-319-22703-0

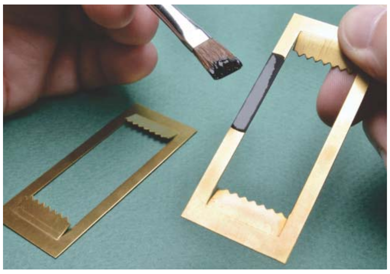
Wave Dynamics of Generalized Continua. A. G. Bagdoev, V. I. Erofeyev, A. V. Shekoyan. Springer, 2016. $179.00 (274 pp.). ISBN 978-3-642-37266-7 PT

NEW PRODUCTS

Focus on materials, semiconductors, vacuum, and cryogenics

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

Andreas Mandelis



Conductive nickel epoxy

Featuring a nickel filler, Master Bond's EP21TDCN-LO is an electrically conductive, two-component adhesive and sealant for grounding, shielding, and static dissipation applications. The epoxy can withstand rigorous thermal cycling, mechanical vibration, and shock. It passes ASTM E595 tests for NASA low outgassing, so it is suitable for the aerospace, electronics, and specialty OEM industries, including in vacuum and clean-room environments. The epoxy has a low volume resistivity of 5–10 Ωcm and a thermal conductivity of 1.59 W/(m·K). It bonds well to substrates such as metals, composites, ceramics, and many plastics; features a high strength profile, with tensile lap shear, tensile, and T-peel strengths of 1400–1600 psi, 3000–4000 psi, and 15–20 pli, respectively; and resists exposure to various chemicals such as fuels, organic solvents, and water. Easy to handle, the EP21TDCN-LO can cure at room temperature or more rapidly at elevated temperatures. It is serviceable from −73 °C to +135 °C. ***Master Bond Inc,*** *154 Hobart St, Hackensack, NJ 07601, www.masterbond.com*

Semiconductor test system

National Instruments (NI) has released its NI PXIe-6570 Digital Pattern Instrument and Digital Pattern Editor software for semiconductor test system development. NI combined the digital test paradigm established in the semiconductor industry with the open PXI platform used in the company's Semiconductor Test System (STS) and added a pattern editor and debugger. The innovations provide users with cutting-edge PXI instrumentation that helps reduce test costs and increases throughput for RF and analog-centric integrated circuits. Users can add as many devices as they need to meet the device pin and site counts required in a test configuration. The digital pattern instrument features 100 MVector/s pattern execution with independent source and capture engines and voltage/current parametric functions at up to 256 synchronized digital pins in a single subsystem. ***National Instruments Corporation,*** *11500 Mopac Expy, Austin, TX 78759-3504, www.ni.com*

High-compression turbopump

According to Pfeiffer Vacuum, its compact HiPace 300 H is the highest compression turbopump currently available in the pumping speed class of 300 l/s. With a compression ratio of 10^7 for hydrogen, it can produce high and ultrahigh vacuum for applications in research, analytics, and industry. For example, the high compression ratio generates a low residual gas spectrum in the chamber, which is desirable for mass spectrometry applications. The turbopump is also suitable for particle accelerators. A very high backing pressure compatibility of 30 hPa helps it achieve ultrahigh vacuum when operating with diaphragm pumps under high-pressure conditions. An integrated "intermittent operation" function allows the vacuum system's energy consumption to be decreased up to 90%. The HiPace 300 H's robust hybrid bearing combines a ceramic ball bearing on the fore-vacuum side and a permanently magnetic radial bearing on the high-vacuum side. ***Pfeiffer Vacuum Inc,*** *24 Trafalgar Sq, Nashua, NH 03063, www.pfeiffer-vacuum.com*

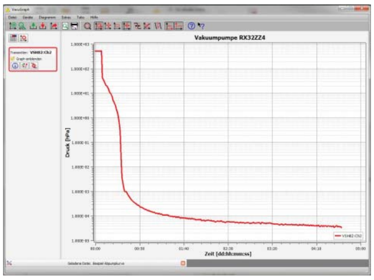
Vacuum pumps for scientific applications

Edwards has unveiled new vacuum pumps for analytical instrument and R&D applications. Building on the company's EXT75DX model, the nEXT85 turbomolecular pump offers improved performance in a smaller package, with the same high level of reliability. The flexible device also delivers the benefits, such as field serviceability and built-in intelligence, of the company's larger nEXT pumps. The nEXT85 is offered in split-flow and other customized versions. The air-cooled, single-phase nXLi dry pump operation is based on the iXL range currently used in semiconductor applications. It is a suitable backing pump for Edwards' nEXT hybrid bearing and STP maglev turbomolecular pumps. The nXL110i and nXL200i are optimized for various scientific applications, including liquid chromatography–mass spectrometry and inductively coupled plasma mass spectrometry. They can handle gas loads of up to 25 slm in a compact footprint. ***Edwards Limited,*** *Manor Royal, Crawley, West Sussex RH10 9LW, UK, www.edwardsvacuum.com*

Circular sputtering source

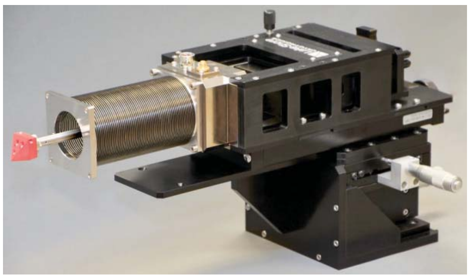
Kurt J. Lesker has designed its Torus Mag Keeper circular magnetron sputtering source to be flexible, user-friendly, and suitable for a broad range of R&D applications. It has a quick target change feature, an enhanced cooling design, a low operating pressure capability, and a compact footprint. Since it is engineered with no O-rings and all-ceramic insulators, the source is UHV compatible. For magnetic film deposition, the Mag Keeper offers enhanced high-strength magnet options for sputtering iron up to 3 mm thick. Its configuration conforms to the standard used in the company's other products, so it can be used in existing systems. A broad range of options allows the source to be integrated to any existing mounting arrangement. The new Mag Keeper is offered in 2-, 3-, and 4-inch target sizes. ***Kurt J. Lesker Company,*** *1925 Rte 51, Jefferson Hills, PA 15025, www.lesker.com*

Vacuum leakage software



VacuGraph software from Thyracont Vacuum Instruments can be used to calculate, without elaborate programming, the leakage rates of vacuum pumps. In combination with the company's vacuum gauges, the software can visualize, analyze, and save measurements on a PC. The program's base has been changed to C++, and according to the company, VacuGraph 11 is lean, stable, and fast. A new, intuitively operated user interface offers a choice of languages and many improvements. The software can communicate simultaneously with any amount of active gauges, VD8 compact vacuum meters, and display and control units. Users can track measurement data online in real time and read out VD8 data loggers for quality assurance at a later time. The leakage calculation feature can determine the application's tightness. The software calculates the leakage rate by means of the rate-of-rise method and can make leak detectors unnecessary. ***Thyracont Vacuum Instruments GmbH,*** *Max-Emanuel-Str 10, 94036 Passau, Germany, www.thyracont-vacuum.com*

Terahertz on-wafer probe arm



Lake Shore Cryotronics now offers a terahertz-frequency probe-arm option for its CPX, CPX-VF, CRX-4K, and CRX-VF cryogenic probe stations. The arm enables precise probing and measurement of millimeter-wave devices at 75–110 GHz or 140–220 GHz frequencies within a tightly controlled cryogenic test environment. It allows users to perform calibrated S-parameter and other high-frequency measurements as a function of low temperature and in high magnetic field. According to the company, the probe arm is especially suitable for the development of next-generation electronics, including new monolithic microwave integrated circuits, MEMS, low-noise amplifiers, and terahertz detector devices. It uses cryogenically rated ground-signal-ground T-Wave probes from Cascade Microtech for wafer probing. Various versions are available depending on the frequency band and probe pitch needed for the device being measured. ***Lake Shore Cryotronics Inc,*** *575 McCorkle Blvd, Westerville, OH 43082, www.lakeshore.com*

NEW PRODUCTS

Semiconductor wafer AFM scanner

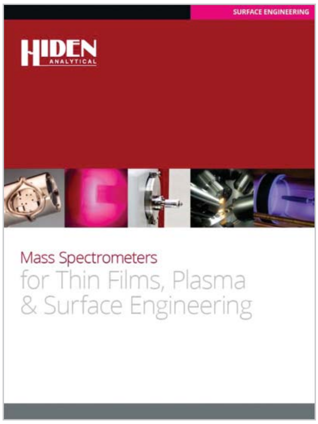
Park Systems has announced that its Park NX20 300mm is the first research atomic force microscope (AFM) able to scan the entire sample area of 300 mm wafers. It keeps the system noise level below 0.5 Å rms, and it can improve and compare site-to-site and sample-to-sample height and surface-roughness measurements. New SmartScan software with automatic scan control and "batch mode" functionality lets users perform unlimited recipe-automated sequential multiple-site measurements over a 300 mm × 300 mm area. A motorized XY stage gives users access to any location on a 300 mm wafer. The AFM has a standard 300 mm vacuum chuck that can hold samples ranging in size from 300 mm to 100 mm, and with a vacuum hole it can support small coupon samples of arbitrary shapes, so it is suitable for laboratories that use various sample sizes. It is compatible with all the modes and options available to Park's other research AFM products. ***Park Systems Inc,*** *3040 Olcott St, Santa Clara, CA 95054, www.parkafm.com*

Cryogenic impedance bridge

The model 54 four-channel cryogenic impedance bridge from Cryogenic Control Systems measures resistance, inductance, and mutual inductance in ultralow temperature thermometry applications. Because of its four control-loop outputs, the bridge can be used as a temperature controller. Each of the four input channels is made with the company's proprietary signal processing chip that measures impedance by means of an auto-balancing, ratiometric AC bridge. Advanced functions are built into a digital signal processor. Model 54 uses a differential voltage-mode excitation scheme followed by bi-phase lock-in detection to prevent electrical noise pickup currents from flowing through the sensor. Thus it can achieve low-level excitation followed by precision signal recovery, which is often required to measure impedance in cryogenic systems. With an appropriate sensor, the instrument operates from less than 100 mK to more than 1200 K. ***Cryogenic Control Systems Inc,*** *17279 La Brisa, Rancho Santa Fe, CA 92067, www.cryocon.com*

NEW LITERATURE

Surface technology catalog



Hiden Analytical's *Mass Spectrometers for Thin Films, Plasma & Surface Engineering* describes the company's mass spectrometry–based products for vacuum coating and etching processes and for surface evaluation studies. New products include a UHV temperature-programmed desorption system for thermal desorption studies and two secondary ion mass spectrometer systems—the AutoSIMS and Compact SIMS—that provide surface diagnostics to the atomic-layer level and can be operated either automatically or manually. The RGA-series products address residual gas analysis through pressures from 1 mbar to full UHV/XHV. Direct plasma ion monitors—the EQP, PSM, and IMP series—provide real-time plasma ion diagnostics and etching end-point determination. The HPR-60 system with multistage pressure reduction extends the plasma diagnostics capability to pressures as high as 5 bar. The catalog can be downloaded at http://tinyurl.com/thin-films-184-3 or a free print copy requested at http://tinyurl.com/request-print-copy. ***Hiden Analytical Inc,*** *37699 Schoolcraft Rd, Livonia, MI 48150, http://hideninc.com*

Flow cryostat scanning probe microscope

The STREAM from Sigma Surface Science and its partner Mantis Deposition is a UHV low-temperature flow cryostat scanning probe microscope (SPM) built for high-resolution scanning tunneling microscopy, qPlus atomic force microscopy (AFM), and spectroscopy experiments in a temperature range between less than 10 K and 420 K. The cryostat can operate under conditions of stability with either liquid helium (less than 10 K) or liquid nitrogen (less than 90 K). The efficient thermal shielding allows for low liquid-helium consumption, provides high temperature stability, and results in low drift. STREAM combines an economical low-temperature flow cryostat platform with the company's TRIBUS SPM head and includes 3D coarse motion, high intrinsic stability, easy tip and sample exchange, and optical access. It is available as a complete research solution or as a bolt-on upgrade to an SPM-compatible UHV system. ***Mantis-Sigma,*** *10200 E Girard Ave, Bldg A, Ste 300, Denver, CO 80231, www.sigma-surface-science.com*

Cryogen-free fluorescence spectrometry

Originally designed for low-temperature spectroscopy applications, Oxford Instruments' optical cryostat, the OptistatDry, is now available as an upgrade to Edinburgh Instruments' FLS980 fluorescence spectrometer. Users of the upgraded spectrometer can perform experiments over a wide temperature range, from less than 3 K to 300 K, without the need for cryogenic liquids. Measurements at those temperatures are essential for many applications; for example, they are helpful for studying semiconductors and nonlinear crystals, both of which have weak photoluminescence at temperatures above 70 K. Integrating the cryofree OptistatDry with the FLS980 eliminates the need for a continuous supply of liquid helium for steady-state and time-resolved photoluminescence. New software allows the cryostat operation to be controlled directly by the FLS980's operating software, so users can run long experiments without interruption. ***Oxford Instruments plc,*** *Tubney Woods, Abingdon, Oxfordshire OX13 5QX, UK, www.oxford-instruments.com* PT

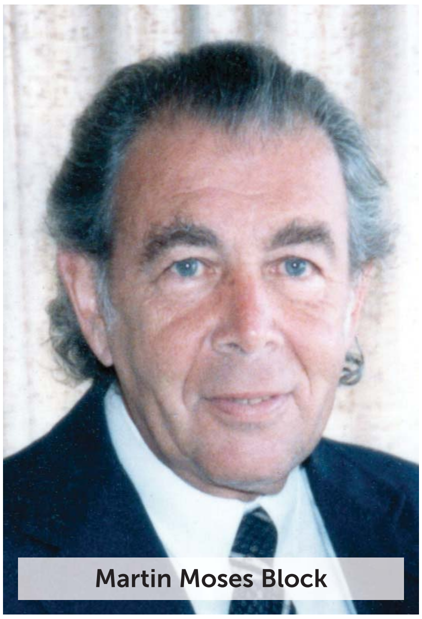
PHYSICS TODAY | SNAPSHOT | ADS

OBITUARIES

To notify the community about a colleague's death, subscribers can visit www.physicstoday.org/obituaries, where they can submit obituaries (up to 750 words), comments, and reminiscences. Each month recently posted material will be summarized here, in print. Select online obituaries will later appear in print.

Martin Moses Block

Particle physicist Martin Moses Block was born on 29 November 1925 in Newark, New Jersey, and died in Los Angeles on 22 July 2016 after a brief illness. His career was distinguished not only by many contributions but also by longevity: His first paper was published in September 1949, and his most recent in June 2016, 67 years later. Block really had two careers in physics: first, as an experimentalist, until he went emeritus in 1996, and second, as a theorist, carried out from home in his beloved Aspen, Colorado. He was active in the Aspen Center for Physics and was responsible for founding the center's enduring Aspen Winter Physics Conference series.



Martin Moses Block

Block received his BS in 1947, MA in 1948, and PhD, under William Havens, in 1952, all from Columbia University, where he also helped design the magnets for the Nevis cyclotron. As a young professor at Duke University, he contributed the revolutionary notion that parity wasn't conserved in weak interactions. While rooming with Richard Feynman at the Rochester Conference on High Energy Physics in 1956, he'd hatched the idea as a way to resolve the so-called tau–theta paradox: two otherwise identical particles that decayed into different parity states and thus were believed to be distinct. Feynman recounted the story in his 1985 memoir, *Surely You're Joking, Mr. Feynman! Adventures of a Curious Character* (W. W. Norton, page 247):

> I was sharing a room with a guy named Martin Block, an experimenter. And one evening he said to me, "Why are you guys so insistent on this parity rule? Maybe the tau and theta are the same particle. What would be the consequences if the parity rule were wrong?"
>
> I thought a minute and said, "It would mean that nature's laws are different for the right hand and the left hand, that there's a way to define the right hand by physical phenomena. I don't know that that's so terrible, though there must be some bad consequences of that, but I don't know. Why don't you ask the experts tomorrow?"
>
> He said, "No, they won't listen to me. You ask."
>
> So the next day, at the meeting . . . I got up and said, "I'm asking this question for Martin Block: What would be the consequences if the parity rule was wrong?"
>
> Murray Gell-Mann often teased me about this, saying I didn't have the nerve to ask the question for myself. But that's not the reason. I thought it might very well be an important idea.

Important, indeed! The 1957 Nobel Prize in Physics went to Tsung-Dao Lee and Chen-Ning Yang for their theoretical analysis of the process. But it was not shared by Chien-Shiung Wu for her 1956 experimental demonstration of parity violation in the beta decay of cobalt-60 nuclei, nor was Block's contribution acknowledged at the time. The episode was recounted in a bit of rueful doggerel by physicist Erich Harth (PHYSICS TODAY, August 1991, page 91).

At Duke, Block developed the first liquid-helium bubble chamber and used it to study the properties of several newly discovered particles. He left Duke in 1961 for Northwestern University, where he served on the faculty for the remainder of his experimental career. He codiscovered the eta meson, and he probed particles at ever-higher energies by using heavy-liquid bubble chambers and, eventually, modern counter detectors. His work took him to accelerators all over the world, with extended stints at Fermilab, CERN, and Lawrence Berkeley, Brookhaven, and Argonne National Laboratories.

Block's lifelong passion for the mountains, especially for downhill skiing and fly-fishing, eventually took him to Aspen, where he joined the Aspen Center for Physics in its nascent years. He purchased a family home there in 1964, and he spent many vacations in Aspen until he left Northwestern to spend full time in Colorado. At that point he took up a second career in theoretical and computational physics.

A central focus of his later work was on the forward-scattering amplitudes of hadron collisions, particularly at the highest energies available at the most powerful modern accelerators as well as from cosmic rays. He sought to understand scattering structure and, specifically, why the proton–proton interaction cross section grows with the square of the logarithm of the energy. After toying with models inspired by quantum chromodynamics, Block realized that the experimental data had become sufficiently precise to make a model-independent prediction of the asymptotic behavior of the cross section. His work anticipated quantitatively the measurements eventually performed at the Large Hadron Collider at CERN. In one of his final papers, he showed that the data

RECENTLY POSTED NOTICES AT www.physicstoday.org/obituaries

Ahmed H. Zewail
26 February 1946 – 2 August 2016

Bill Lee
15 June 1965 – 30 July 2016

John Madey
1943 – 5 July 2016

Stephen Gasiorowicz
10 May 1928 – 3 June 2016

Eugene M. Berstein
13 February 1931 – 20 February 2016

Philip Joel Greenberg
22 April 1942 – 26 December 2015

demonstrate convincingly that both the proton–proton and antiproton–proton scattering amplitudes asymptotically approach those of a so-called black disk, presumably as a consequence of gluon saturation.

Martin Block remained productive up until the end, when he and collaborators were revising drafts of his latest manuscript. He was, his friends and colleagues agree, quite a character, and something of a force of nature.

Francis L. Halzen
University of Wisconsin–Madison

Virginia Ruth Brown

Virginia Ruth Brown

Virginia Ruth Brown died on 8 February 2016 in Chevy Chase, Maryland, after a long battle with cancer. She was a wonderful colleague, friend, and distinguished theoretical nuclear physicist. During her long career, Virginia made important contributions to our understanding of the nucleon–nucleon interaction, nuclear reaction theory, and nuclear structure, among other accomplishments. She loved physics and had a deep commitment to getting to the heart of things.

Born on 11 March 1934 in Massachusetts, Virginia received her PhD, under the supervision of Bernard Margolis, from McGill University in 1964. She was a postdoctoral fellow at Yale University and then worked at Lawrence Livermore National Laboratory (LLNL) from 1964 until 1995. She was an NSF program officer for nuclear theory from 1995 to 1998. Following that, she was a visiting professor in the physics department of the University of Maryland in College Park and a visiting scientist in the Laboratory for Nuclear Science at MIT.

During Virginia's early work on nucleon–nucleon bremsstrahlung, she explored the effects of parity nonconservation and demonstrated the importance of meson exchange in neutron–proton bremsstrahlung. Her calculations showed that meson exchange currents contributed a factor of 2 and were not dominated by one-pion exchange. Throughout her career she continued refining and extending her calculations, including for relativistic effects and noncoplanarity. She compared her results with experiment, most notably with the data on neutron–proton bremsstrahlung that Stephen Wender, June Matthews, and their colleagues obtained at the Los Alamos Neutron Science Center. When Virginia was at MIT she interacted frequently with Matthews's group and directed the research of several of Matthews's undergraduate and graduate students.

Virginia's collaboration with experimentalists started soon after she joined LLNL; most prominently, she worked with John Anderson on charge-exchange reactions in nuclei.

Around 1973 Virginia also began her long partnership with theorist Victor Madsen. They developed the nuclear-structure and reaction theory needed to understand charge-exchange reactions; their breakthroughs included a model for mixing giant resonance states with the low-lying states that had been experimentally observed at the time. Their most important contribution was the systematic inclusion of isospin degrees of freedom that were required to understand the data. It was successfully applied to inelastic scattering processes without any additional modifications.

One of us (Bernstein) remembers how stimulating it was to work with Virginia. In the mid 1970s, he received a letter from her about how Madsen's and her isospin-dependence calculations could explain the puzzles and regularities that he had observed in inelastic alpha-particle scattering. Their collaboration started in their first meeting, and over many years it yielded a productive series of papers. They covered electromagnetic tests of the accuracy of the observed neutron and proton transition matrix elements and their observation using different hadronic probes and electromagnetic methods such as electron scattering and Coulomb excitation. He remembers with great pleasure his annual spring-break trip to the University of California, Berkeley, and LLNL to work with Virginia and to enjoy great dinners with her in Berkeley and San Francisco. Their friendship and collaboration were reinforced while she was working as a visiting scientist at MIT from 1998 until her death.

Virginia was a deeply involved member of the American Physical Society (APS), including as secretary/treasurer of the division of nuclear physics (DNP) from 1986 to 1995. Because of her numerous contributions, her colleagues chose her in 2003 to receive the division's first Distinguished Service Award.

Another of us (Gibson) saw firsthand Virginia's remarkable contributions to APS. He first met Virginia when he was a postdoctoral fellow at LLNL in 1968. Their closest connection came through the DNP, when he succeeded her as secretary/treasurer in 1995, and she mentored him in that time-consuming position.

Virginia's efforts as part of the DNP leadership strengthened the division's fall meetings, assisted in funding APS's Hans Bethe and Herman Feshbach Prizes and the division's Nuclear Physics Dissertation Award, initiated the Department of Energy and NSF's Nuclear Science Advisory Committee Long Range Plan town meetings, and established the DNP archive and historical record.

While at NSF, Virginia suggested exploring a joint meeting with the nuclear physicists of the Physical Society of Japan. She chaired the first of the resulting series of successful international physics meetings in 2001 and remained instrumental in their success through the 2014 joint meeting. After Virginia left NSF, she was a visiting scientist at Los Alamos National Laboratory, where she conducted research and shared meals with Gibson and another of us (Seestrom). During one visit, she and Gibson drafted a history of the DNP. Virginia's imprint on the division is indelible, and the DNP owes her a great debt of gratitude.

With her contagious enthusiasm and

laughter, Virginia was a dear friend who will be sorely missed.

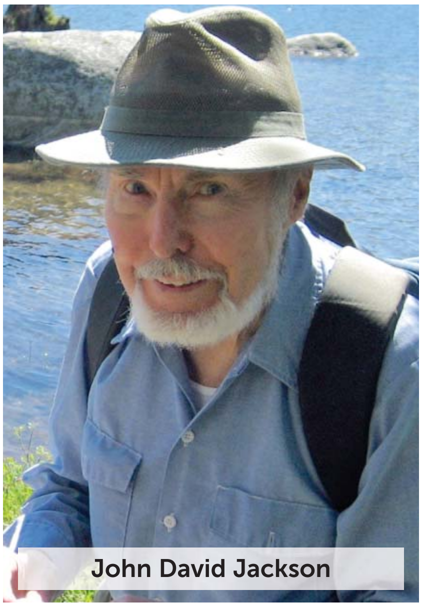
Aron M. Bernstein
Robert P. Redwine
Massachusetts Institute of Technology
Cambridge
Benjamin F. Gibson
Susan J. Seestrom
Los Alamos National Laboratory
Los Alamos, New Mexico

John David Jackson

John David Jackson, professor emeritus at the University of California, Berkeley, whose magisterial textbook *Classical Electrodynamics* has shaped graduate education for more than a half century, died on 20 May 2016 in Lansing, Michigan. His wide-ranging theoretical work combined fine craftsmanship, intuition born of meticulous scholarship, engagement with experiment, and respect for practical matters. He was a wise counselor and a tireless advocate for human rights and academic freedom.

Born on 19 January 1925 in London, Ontario, Canada, Jackson earned his BSc in honors physics and mathematics at the University of Western Ontario in 1946. The undergraduate curriculum's emphasis on electromagnetism pointed him toward MIT and its Research Laboratory of Electronics. His initial graduate research, carried out with Lan Jen Chu, concerned a field theory of traveling-wave tubes.

Victor Weisskopf's quantum mechanics course introduced Jackson to modern physics and attracted him to Weisskopf's nuclear theory group. With postdoc John Blatt, Jackson analyzed low-energy nucleon–nucleon scattering; for his dissertation in 1949 he used Julian Schwinger's variational method to investigate *S*- and *P*-wave proton–proton scattering.



NAN JACKSON

John David Jackson

Jackson was appointed in 1950 to the mathematics faculty at McGill University, where he continued research on atomic processes and nuclear reactions and began his career as a revered teacher and mentor. The lecture notes for his course on electricity and magnetism evolved into a first draft of the famous textbook.

In 1956–57 Jackson spent a sabbatical year at Princeton University and was free to focus on research. A *New York Times* account of Luis Alvarez and collaborators' observation of muon-catalyzed fusion, and the prospect it raised of a new energy source, stirred his imagination. Within a week, Jackson estimated that one muon could catalyze no more than 130 deuterium–tritium fusion reactions, insufficient for practical energy production. That work led him to form lasting bonds with other "Mu-sketeers," Russian physicists who pioneered and extended muon-catalysis theory. Following Chien-Shiung Wu and coworkers' discovery of parity nonconservation in beta decay, Jackson, Sam Treiman, and William Wyld analyzed possible signatures for violations of time-reversal invariance.

Jackson moved in 1957 to the University of Illinois at Urbana-Champaign. Inspired, he claimed, by the majesty of Midwestern thunderstorms, he developed the fearsome "Jackson problems" and in 1962 published the first edition of *Classical Electrodynamics*. His research interests included low-energy kaon–nucleon scattering, final-state interactions, and dispersion relations.

A 1963–64 sabbatical at CERN in Geneva marked another decisive turn in Jackson's research career. With Kurt Gottfried, he devised incisive methods to elucidate production mechanisms of resonances in two-body to two-body reactions. Insights they gained from the phenomenological analysis of resonances led them to develop the peripheral model with absorption of low partial waves to describe resonance production.

Jackson joined the Berkeley faculty and the Lawrence Berkeley Laboratory staff in 1967, when the ascendancy of Regge theory put his beloved special functions at the heart of theoretical physics. Lecturing graduate students in 1968, and having covered every blackboard in the room with arcane calculations that culminated in Legendre functions of the second kind, he mused, "Born a century too late!"

As leader of the Theory Year program at Fermilab in 1972–73, Jackson founded a lab institution, the Joint Experimental–Theoretical "Wine & Cheese" Seminar.

Back at Berkeley, Jackson was in at the very beginning of the "November Revolution" of 1974. Alerted by colleagues to the discovery-in-progress of the ψ resonance in electron–positron annihilations at SLAC, he deduced in real time that the new particle was astonishingly narrow—with a total width less than 100 keV. Drawing on his broad scientific culture, he provided diverse insights into polarization in electron storage rings and the nature of the charmonium and upsilon families of heavy mesons.

Jackson served the physics community at Berkeley and around the world in many ways. An early proponent of the Superconducting Super Collider, he served for two years as deputy director of operations for the SSC Central Design Group. He edited the *Annual Review of Nuclear and Particle Science* for 17 years.

Jackson became a naturalized US citizen in 1988. The American Association of Physics Teachers established the John David Jackson Award for Excellence in Graduate Physics Education in 2010. A certificate conferring the title of Honorary Woman, presented by female graduate students in recognition of his outstanding achievements as department chair, hung on his living room wall for three decades.

After his formal retirement in 1993, Jackson remained active in research and community service, and he published numerous articles on pedagogical insights and physics history. Throughout his life he enjoyed mountain photography and listening to jazz.

Dave's colleagues and students recall with affection the twinkle in his eyes conveying the joy of insight, his uncompromising standards, and his generous spirit. We celebrate his example as a physicist, teacher, and humane world citizen.

Chris Quigg
Fermi National Accelerator Laboratory
Batavia, Illinois PT

JOB OPPORTUNITIES

academic positions

Tenure Track Position in Experimental Particle Astrophysics
University of Alabama

The Department of Physics and Astronomy at the University of Alabama invites applications for a tenure-track position in experimental particle astrophysics (i.e. neutrino astrophysics, gamma ray astrophysics, cosmic rays) at the rank of assistant professor. This position is intended to strengthen or complement the existing efforts in this area (IceCube). The appointment will begin August 16, 2017. In addition to faculty working in experimental and theoretical particle astrophysics, we have related research groups in theoretical particle physics, experimental particle physics, experimental nuclear physics and astronomy. More information about the department can be found on the department's website physics.ua.edu. The minimum qualifications for this position are a Ph.D. or equivalent, postdoctoral experience, scholarly publications, and experience with modern techniques in astroparticle physics. Candidates for this position are expected to have an outstanding research record and exhibit potential for effective teaching at the undergraduate and graduate levels. The successful candidate is expected to develop a high quality, externally funded research program, as well as teach and mentor at the undergraduate and graduate levels. We will begin reviewing applications on **November 15, 2016** and the review process will continue until the position is filled. Applications should consist of a resume, including descriptions of the applicant's accomplishments, a complete list of publications including citations, research interests and teaching philosophy. Applicants should also arrange for at least three letters of recommendation to be sent electronically to **Prof. Dawn Williams** at **drwilliams3@ua.edu**, or by mail to **Prof. Dawn Williams, Department of Physics and Astronomy, Box 870324, Tuscaloosa, AL, 35487.** Applications must be submitted online at the University of Alabama website **http://facultyjobs.ua.edu/postings/39561**. *The University of Alabama is an Equal Opportunity Affirmative Action Employer and actively seeks diversity among its employees. Women and minorities are strongly encouraged to apply.* For additional information, contact the search committee chair, **Prof. Dawn Williams**, at **drwilliams3@ua.edu** or **(205)348-0826**.

Experimental Condensed Matter Physics
Central Michigan University
Tenure-track Assistant Professor

The Department of Physics at Central Michigan University (**www.phy.cmich.edu**) invites applications for a tenure-track position beginning August 2017 in an area of experimental condensed matter physics such as applied optics, magnetism, single crystal growth, energy conversion, and materials under extreme conditions. Other areas that would strengthen existing research activities in the department will be also considered. The Department is seeking candidates who can develop and maintain active, externally funded, on-campus research programs involving students. The position will be filled at the Assistant Professor level, with competitive startup, salary, and benefit packages. Candidates must hold a Ph.D. in physics or a closely related field; must have post-doctoral research experience in experimental condensed matter physics; and must have teaching experience at least at the level of a graduate teaching assistant. For the complete position announcement and submit an application, please visit **www.jobs.cmich.edu/postings/24574**. To ensure full consideration, applications should be received by **October 31, 2016**. *The University is proactive in exploring opportunities for the employment of spouses or domestic partners. Central Michigan University, an AA/EO institution, strongly and actively strives to increase diversity within its community (see www.cmich.edu/ocrie/). The University is proactive in exploring opportunities for the employment of spouses or domestic partners.*

The Department of Chemical and Physical Sciences at **University of Toronto Mississauga (UTM)** invites applications for a tenure-stream appointment at the rank of **Assistant Professor** in the area of **Computational Biophysics**. This appointment will begin on July 1, 2017. The successful candidate must have a Ph.D. in physics or chemistry, high profile post-doctoral experience in computational biophysics, a strong academic background, an excellent research record and excellence in teaching. The new hire will be a member in the Graduate Department of Physics at University of Toronto and will be part of a growing cluster of biophysics, biochemistry and medicinal chemistry researchers at UTM, including the new Centre for Cancer Stem Cell Therapeutics. His/her research program will benefit from access to Canada's largest supercomputer centre, SciNet. All qualified candidates are invited to apply by visiting **https://utoronto.taleo.net/careersection/10050/jobdetail.ftl?job=1600818**. Applicants should also ask three referees to send letters of recommendation directly to the department via email (on letterhead, signed and scanned) to **cps.utm@utoronto.ca** by the application deadline of **November 1st, 2016**.

Assistant Professor in the Energy Cluster at the
University of Pennsylvania

As part of a larger investment to create the new Vagelos Institute for Energy Science and Technology, the School of Arts and Sciences at the University of Pennsylvania seeks to add faculty to our newly formed Energy Cluster spanning the natural sciences. We invite applications for a tenure-track assistant professor position in one of the following departments: Biology, Chemistry, Earth and Environmental Science, or Physics & Astronomy. Exceptional senior candidates will also be given consideration. The successful candidate will mount an innovative program of fundamental scientific research that impacts our societal energy challenges, broadly defined, and in doing so will forge collaborative links with other Penn scientists and engineers involved in energy research. Applicants must apply online at **http://facultysearches.provost.upenn.edu/postings/937** . Required application materials include: curriculum vitae with a list of publications, a research statement that includes the candidate's perspective on how she or he fits into one of the four departments and identifies potential collaborative links with other natural science departments, and a teaching statement. Applicants should also submit the names and contact information for three individuals who will provide letters of recommendation. Review of applications will start on **October 15, 2016** and will continue until the position is filled. The School of Arts and Sciences is strongly committed to Penn's Action Plan for Faculty Diversity and Excellence and to establishing a more diverse faculty (for more information see: **http://www.upenn.edu/almanac/volumes/v58/n02/diversityplan.html**). *The University of Pennsylvania is an equal opportunity employer. Minorities/Women/Individuals with disabilities/Protected Veterans are encouraged to apply.*

The University of Texas at Austin

The Institute for Computational Engineering and Sciences (ICES) at **The University of Texas at Austin** is searching for exceptional candidates to fill a Moncrief endowed faculty position at the **Associate or Full Professor** rank with expertise in the area of **Computational Materials**. Candidates are expected to hold a PhD in computational or physical sciences, possess an exceptional record in interdisciplinary research, and show evidence of work involving applied mathematics and computational techniques targeting meaningful problems in materials starting from an atomistic perspective. Application review will begin **December 15, 2016** and continue until the position is filled. For more information and application instructions, please visit:

www.ices.utexas.edu/moncrief-endowed-positions-app/

This is a security sensitive position. The University of Texas at Austin is an Equal Employment Opportunity/Affirmative Action Employer.

UMASS AMHERST

Experimental Polymer Physics

Assistant Professor
Polymer Science & Engineering
University of Massachusetts, Amherst

The Polymer Science and Engineering Department at the University of Massachusetts, Amherst is seeking applications for an Assistant Professor-level, tenure-track position in experimental polymer physics to start from September 1, 2017. Under exceptional circumstances, highly qualified candidates at other ranks may receive consideration. Experimental polymer physics is to be broadly interpreted. A Ph.D. in Engineering, Physics, Materials, Chemistry or related discipline is required along with a strong publication record in peer-reviewed journals. The successful candidate is expected to contribute significantly to the Department's collaborative research, teaching, and service, which span the polymer field.

To apply, submit a letter of interest, curriculum vitae, statement of research and teaching interests and the names and contact information of three references to
http://umass.interviewexchange.com/jobofferdetails.jsp?JOBID=75871
Review of applications will begin on **October 18, 2016** and may continue until a suitable candidate pool has been established.

The University is committed to active recruitment of a diverse faculty and student body. The University of Massachusetts Amherst is an Affirmative Action/Equal Opportunity Employer of women, minorities, protected veterans, and individuals with disabilities and encourages applications from these and other protected group members. Because broad diversity is essential to an inclusive climate and critical to the University's goals of achieving excellence in all areas, we will holistically assess the many qualifications of each applicant and favorably consider an individual's record working with students and colleagues with broadly diverse perspectives, experiences, and backgrounds in educational, research or other work activities. We will also favorably consider experience overcoming or helping others overcome barriers to an academic degree and career.

KICP Postdoctoral Research Fellow
The University of Chicago, KICP

KICP Postdoctoral Research Fellow The KICP announces the 2017 Postdoctoral Research Fellowship opportunity. Scientists receiving a PhD in Physics, Astrophysics, or related fields between May 2013 and September 2017 are invited to apply. Successful applicants will be expected to conduct original research in experimental, observational, numerical, or theoretical cosmology in an active interdisciplinary environment. Postdoctoral Scholars are appointed to renewable one-year terms, up to three years. Our positions carry a salary and benefits package comparable to other prize fellowships. Research at the Kavli Institute for Cosmological Physics (KICP), based at the University of Chicago, is focused on interdisciplinary topics in cosmological physics: studying the inflationary era, characterizing dark energy, and identifying the constituents of the dark matter. Experimental studies of the CMB (polarization anisotropy and the Sunyaev-Zel'dovich effect); analysis of cosmological data including CMB data, large-scale structure survey data, and Type Ia supernova data; analysis of data from the Dark Energy Survey; gravitational lensing and gravitational wave studies; experimental particle astrophysics; direct detection of dark matter particles and numerous topics in theoretical cosmology constitute the current slate of activities. The KICP has an active program of visitors, symposia, and meetings. Fellows are encouraged to participate in the KICP's vibrant and extensive portfolio of Education and Outreach activities. Information about the KICP can be found at http://kicp.uchicago.edu/. To apply for a KICP Postdoctoral Research Fellowship, please complete the online application form at http://kicp-fellowship.uchicago.edu/. Requested information includes email contact information for 3 references who can independently write a letter of support for the applicant. Supplemental materials (Cover Letter; Curriculum Vitae; Research Statement; List of Publications) should be submitted as PDF files on the application form (each up to 10MB). If you have any questions, please contact centerfellow2017@kicp.uchicago.edu. The positions will remain open until filled; however applicants are strongly encouraged to submit all materials (and ensure that 3 letters of recommendation are received) by **October 31, 2016**. The positions are expected to begin in the Fall of 2017. *The University of Chicago is an Affirmative Action/Equal Opportunity Employer.*

BROWN UNIVERSITY
FACULTY POSITION
IN
EXPERIMENTAL CONDENSED MATTER PHYSICS

The Department of Physics at Brown University invites applications for a tenure-track Assistant Professor position in Experimental Condensed Matter Physics, starting in the summer of 2017. This position is part of an initiative for further growth in interdisciplinary condensed matter research at Brown University, including the upgraded clean-room microfabrication and electron microscopy facilities in the new School of Engineering building adjacent to the Physics Department. We seek candidates who have the potential to create a vigorous and sustainable research program at Brown. A strong commitment to teaching at the undergraduate and graduate levels is also required. Current research in condensed matter physics at Brown is very active across many topics, including strongly correlated electronic systems, spintronics, quantum liquids and solids, superconductivity, nanoscale physics, ultrafast and quantum optics, semiconductor physics and devices, and soft condensed matter. Candidates planning to pursue other condensed matter subfields are also strongly encouraged to apply. Application materials including a curriculum vita, a statement of research and teaching plans, and three letters of recommendation should be submitted electronically to apply.interfolio.com/35812. Inquiries about this position should be directed to Phys-search@brown.edu or to **Prof. Vesna Mitrovic, Chair of Condensed Matter Physics Search Committee, Department of Physics, Box 1843, Brown University, Providence, Rhode Island 02912.** Applications received by **December 1, 2016** will receive full consideration. *Brown University is committed to fostering a diverse and inclusive academic global community; as an EEO/AA employer, Brown considers applicants for employment without regard to, and does not discriminate on the basis of gender, race, protected veteran status, disability, or any other legally protected status.*

CALIFORNIA INSTITUTE OF TECHNOLOGY
INVITES APPLICATIONS FOR
POSTDOCTORAL PRIZE FELLOWSHIPS IN
EXPERIMENTAL PHYSICS
OR ASTROPHYSICS

The Division of Physics, Mathematics and Astronomy offers a number of Prize Fellowships at the Postdoctoral Scholar level in Experimental Physics or Astrophysics. These Fellowships are to begin in Fall 2017 and are for a three-year duration. They carry a substantive annual stipend and/or salary combination and offer an annual research expense fund. This fellowship program has been established to offer scientists, typically within a few years after receipt of the Ph.D., the opportunity to pursue new and innovative experimental research. It is expected that this research will require the support and use of facilities of one of the established experimental groups at Caltech. The faculty's research interests can be found via their web pages, accessible from http://www.pma.caltech.edu/people/professorial-faculty/all. In the case of astrophysics, only candidates whose focus involves instrumentation (is not purely observational) will be considered. Please apply online at https://applications.caltech.edu/job/experimental. Electronic copies of the curriculum vitae with email address and with citizenship indicated, publications list (indicate articles which appeared in refereed journals), and statement of research interests are required. The research statement should be no more than 5 pages, excluding references. Electronic Portable Document Format (PDF) submittals are preferred. The applicant is requested to ensure that at least three letters of recommendation are submitted via the web link provided in the electronic application. Deadline for the application is **OCTOBER 23, 2016**. Application materials may also be sent to **EXPERIMENTAL PHYSICS AND EXPERIMENTAL ASTROPHYSICS FELLOWSHIPS, Mail Code 103-33, California Institute of Technology, Pasadena, CA 91125,** to arrive by **OCTOBER 23, 2016**. Fellowship candidates will automatically be considered for other available postdoctoral positions in their fields of interest. Email inquiries in regards to the application process may be sent to **nell@caltech.edu**. *EOE of Minorities/Females/Protected Vets/Disability.*

Assistant/Associate Professor
University of Miami/Physics

Tenure-Track Assistant/Associate Professor The Department of Physics at the University of Miami invites applications from highly qualified persons for a faculty position in Astrophysics. This appointment will be made at the Assistant or Associate Professor rank to begin fall 2017. Targeted research topics include, but are not limited to, experimental or observational work that is synergistic with ongoing activities in the department: observational cosmology, mm-wave spectroscopy, x-ray astrophysics, studies of solar wind charge exchange, large scale structures, and detector development. Candidates must have a Ph.D. in physics or related discipline, a demonstrated record of research achievements, and a strong commitment to teaching and mentoring students at the undergraduate and graduate levels. The physics department is located within the University's attractive Coral Gables campus in the greater Miami area, and has a wide-ranging research expertise and established Ph.D. program. Application materials, including curriculum vitae with list of publications and statement of research plans, should be sent electronically (as a single PDF) to **astrosearch@physics.miami.edu** or to **Astrophysics Search Committee Chair, Department of Physics, University of Miami, Knight Physics Building, Coral Gables, FL 33124.** Applicants should arrange for three letters of recommendation to be sent to the same address. Review of applications will begin on **November 4, 2016** and continue until the position is filled. *The University of Miami is an Equal Opportunity Employer — Females/Minorities/Protected Veterans/Individuals with Disabilities are encouraged to apply. Applicants and employees are protected from discrimination based on certain categories protected by Federal law.*

TENURE TRACK PHYSICS FACULTY POSITION
CLARK UNIVERSITY

Clark University's Department of Physics invites applications for a tenure-track faculty position at the Assistant Professor level to begin in Fall 2017. We seek a candidate with a strong interest in soft matter with an approach which may be experimental, computational, or both. Areas of interest include, but are not limited to, active matter, bio-inspired design, soft robotics, non-equilibrium physics, self-assembly, and smart materials. The potential for complementing current departmental research and collaborating with colleagues outside the department is desirable. The candidate is expected to establish a vigorous research program with both graduate and undergraduate students. A very strong commitment to teaching and mentoring is expected. Candidates should have a PhD in Physics, or a related field, and postdoctoral experience is preferred. Further information about the department is available at http://physics.clarku.edu/. *We are especially interested in qualified candidates who can contribute, through their research, teaching, and/or service, to the diversity and excellence of the academic community. We are an affirmative action/equal employment opportunity university and we strongly encourage members from historically underrepresented communities which is inclusive of all women to apply.* Review of applications will begin **December 1, 2016**. Electronic submission of materials is preferred. Please send CV and a statement of research and teaching interests to **Professor Arshad Kudrolli, Search Committee Chair, Department of Physics, Clark University, 950 Main St., Worcester, MA 01610.** (email: physicssearch@clarku.edu). Candidates should arrange for three letters of recommendation to be sent to the same address.

BRIGHAM YOUNG UNIVERSITY
Research Computing Professional Faculty Position

The Department of Physics and Astronomy at Brigham Young University (BYU) in Provo, Utah, invites applications for a professional faculty position in research computing to begin in Fall 2017. This position is intended to strengthen and support existing research programs (see http://www.physics.byu.edu), with success being judged on that metric. The new faculty member will be expected to integrate into existing computational research groups within the department, assist these research groups with computationally based research, and mentor and assist students (undergraduate and graduate) in computationally based research. Successful applicants are also expected to be part of developing externally-funded research programs of significance. This position has no traditional teaching responsibilities. Interested candidates should complete an online faculty application at https://yjobs.byu.edu (search jobs - posting **57064**), with current CV, a cover letter outlining research experience and aspirations, and also the name and contacts of three people willing to provide letters of recommendations. Completed applications received by **November 1, 2016** will be given full consideration. For additional information contact the chair of the faculty search at physicsjob@byu.edu. *BYU, an equal opportunity employer, requires all faculty members to observe the university's honor code and dress and grooming standards. Preference is given to qualified candidates who are members in good standing of the affiliated church, The Church of Jesus Christ of Latter-day Saints.*

Faculty Position in Small-Scale Fundamental Physics
Northwestern University

The Northwestern Physics Department is soliciting applications for faculty members at the assistant professor level, able to set up and lead important and visible experimental research programs that fit within the mission of its new Center for Fundamental Physics at Low Energy (http://cfp.physics.northwestern.edu). The CFP specializes in small-scale, low-energy measurements that investigate the particles, interactions and symmetries of the universe. Interest in and ability to teach physics effectively is also essential. The preferred start date for this position is September 1, 2017. Interested applicants should submit their curriculum vitae, a list of publications, and both a research and a teaching statement. They should also arrange for a minimum of three reference letters to be sent in support of their application. Materials will be submitted at www.physics.northwestern.edu. Applications and questions about the position should be addressed to the CFP director, **Prof. Gerald Gabrielse**. For questions about the application process, contact **Gretchen Burnett** at gretchen-burnett@northwestern.edu. For full consideration all materials should be received by **November 1, 2016.** *AA/EOE. Northwestern University is an Equal Opportunity, Affirmative Action Employer of all protected classes including veterans and individuals with disabilities. Women and minorities are encouraged to apply. Hiring is contingent upon eligibility to work in the United States.*

Call for
Assistant Professors and Professors

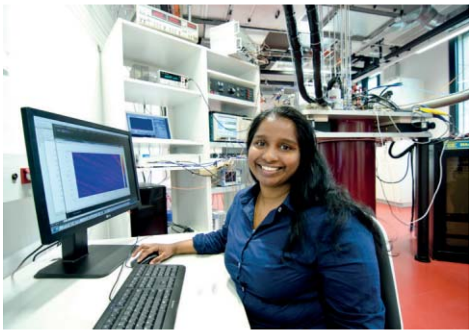
IST AUSTRIA
Institute of Science and Technology

IST Austria invites applications for **Tenure-Track Assistant Professor** and **Tenured Professor** positions to lead independent research groups in all areas of

PHYSICS

Applicants in condensed matter physics, bio- and soft matter physics, atomic physics and physical chemistry as well as cross-disciplinary areas are particularly encouraged to apply. IST Austria is in the process of building up a **new physics cluster including a micro- and nanofabrication facility** (300 m^2 clean room ISO classes 5-7). Our focus is on experimental physics, outstanding theoreticians will be considered as well.

IST Austria is a recently founded public institution dedicated to basic research and graduate education near Vienna. Currently active fields of research include biology, neuroscience, physics, mathematics, and computer science. IST Austria is committed to become a world-class centre for basic science and will grow to about 90 research groups by 2026. The institute has an interdisciplinary campus, an international faculty and student body, as well as state-of-the-art facilities. The working language is English.



Successful candidates will be offered competitive research budgets and salaries. Faculty members are expected to apply for external research funds and participate in graduate teaching. Candidates for tenured positions must be internationally accomplished scientists in their respective fields.

DEADLINES: Open call for Professor applications. For full consideration, Assistant Professor applications should arrive on or before November 3, 2016. Application material must be submitted online: www.ist.ac.at/professor-applications

IST Austria values diversity and is committed to equal opportunity.
Female researchers are especially encouraged to apply.

MATERIALS SCIENCE AND ENGINEERING
Faculty Positions - Open Rank
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

The Department of Materials Science and Engineering at the University of Illinois at Urbana Champaign is seeking exceptional candidates for faculty positions in the broad areas of materials science and engineering, materials chemistry or materials physics. Applications for positions as tenure-track assistant professors, tenured associate professors, and tenured full professors are welcome. Faculty members in the Department teach undergraduate and graduate courses and are expected to initiate and sustain a vigorous research program. Please visit the website **http://matse.illinois.edu/openings.html** to view the complete position announcement and application instructions.

Applications received prior to **December 5, 2016** will receive full consideration.

The University of Illinois conducts criminal background checks on all job candidates upon acceptance of a contingent offer.

Illinois is an EEO Employer/Vet/Disabled – www.inclusiveillinois.illinois.edu and committed to a family-friendly environment (http://provost.illinois.edu/worklife/index.html).

C4 Information Directorate
AIR FORCE RESEARCH LABORATORY

QUANTUM INFORMATION RESEARCH SCIENTISTS

The Computing and Communications Division of the Air Force Research Laboratory's (AFRL) Information Directorate is looking for outstanding quantum researchers to address cutting-edge computing and communications problems vital to the nation's security. AFRL is a basic and applied research laboratory that has been supporting the US Air Force for more than 60 years. The AFRL Information Directorate employs approximately 444 scientists and engineers, and is the Air Force's center of expertise for R&D of command, control, communications, computers, intelligence (C4I) technologies.

Emphasis area for open technical staff positions: *trapped-ion based quantum repeaters.*

Physics PhD degree holders in the above specific field are sought, for three-year term appointments with possible conversion to a permanent position. Candidates for NRC post-doc appointments are also of interest. AFRL also has strong summer employment programs, and graduate students and faculty working in the areas of interest are encouraged to apply for a summer appointment. AFRL Information Directorate staff members have been at the forefront of information science and technology developments. Staff members work on multi-disciplinary in-house teams. The successful candidates will be able to demonstrate depth in advanced quantum computing and communications, via self-motivation and collaborative efforts.

Located in upstate New York near Syracuse, the AFRL Information Directorate offers a suburban, four-season environment, superior grade and high schools, and several nearby collaborating universities with outstanding academic reputations. We offer stable employment, a competitive salary, excellent benefits, and a world-class professional environment. For an overview see: *http://tinyurl.com/j9b6nxf.*

US citizenship required. Must be eligible for a security clearance. AFRL is an equal opportunity employer. Please contact Dr. Kathy-Anne Soderberg, kathy-anne.soderberg@us.af.mil, (315)330-3687.

Approved for Public Release 18Aug2016 [88ABW-2016-4049], Distribution Unlimited.

Tenure-Track Faculty Position in Physics
Harvey Mudd College

The Department of Physics of Harvey Mudd College, one of the Claremont Colleges, has an opening for a tenure-track appointment at the assistant professor level, beginning September 2017. The department (https://physics.hmc.edu/) has thirteen full-time members; we graduate between 20 and 30 physics majors each year. We seek an experimental, theoretical, or computational physicist with broad intellectual interests who can excel at teaching outstanding undergraduates and who can establish an active research program involving undergraduates. Current areas of research in the department include biophysics, quantum and nonlinear optics, condensed matter physics, soft matter physics, geophysics, semiconductor physics and the environment, theoretical astrophysics and observational astronomy and cosmology, string theory, general relativity, and theoretical particle physics. Although we welcome applications from outstanding candidates regardless of subfield, we are particularly interested in a candidate who can develop a vibrant research program in AMO or condensed matter physics. For full consideration, applications should be received by **4 November 2016**, but applications will be accepted until the position is filled. On-campus interviews will include both teaching an upper-division physics class and presenting a research colloquium. Applicants should apply online (using the **AcademicJobsOnline.org** website, https://AcademicJobsOnline.org/ajo), where they should submit: (1) a curriculum vitæ; (2) a statement of teaching experience and interests, as part of which applicants are invited to comment on any experience with or demonstrated ability to effectively teach students from diverse backgrounds; (3) a statement of research interests that describes how undergraduates would be involved in the proposed research; and (4) three letters of reference, at least one of which addresses teaching ability or potential. Please address the cover letter to **Professor Theresa W. Lynn, Chair, Department of Physics, Harvey Mudd College, Claremont, CA 91711.** *Harvey Mudd College enthusiastically welcomes applications from talented individuals from all cultural backgrounds. The College is an Equal Opportunity / Affirmative Action employer providing access to education and employment without regard to age, race, color, gender, national origin, sexual orientation, veteran's status, disability, or any other characteristics protected by applicable law.*

Burke Fellows in Theoretical Physics and Astrophysics
California Institute of Technology

The Walter Burke Institute for Theoretical Physics at the California Institute of Technology (Caltech) solicits applications for its Fellowship program. The Prize Fellowships at the Burke Institute offers an opportunity for outstanding recent and new Ph.D. recipients to perform research at Caltech for three years. They are selected by a faculty committee representing all areas of theoretical physics and astrophysics at Caltech and are provided with:

- flexibility, support, and freedom in choosing research direction within theoretical physics and astrophysics (including but not limited to theoretical astrophysics/cosmology, condensed matter theory, general relativity, particle/string theory, physical mathematics, and quantum information),
- an inclusive environment with faculty mentorship and activities organized by the Burke Institute to promote scientific exchanges and professional growth, and
- an annual stipend/salary and an annual research fund that are comparable to those of other prestigious fellowships.

The Burke Fellowship program significantly expands and strengthens the existing Prize Fellowship program at Caltech. The Prize Fellowship program has been successful with over 95 percent of the more than 120 former fellows holding distinguished academic positions, as shown here http://burkeinstitute.caltech.edu/CurrentFellows. We encourage all candidates to apply by **November 15, 2016**. Applicants should submit curriculum vitae (with email address and citizenship), a statement of research interests, and a list of publications at this application website https://applications.caltech.edu/job/burke. Applicants should also ensure that at least three letters of reference are submitted on their behalf to this website. *EOE of Minorities / Females / Protected Vets / Disability.*

Faculty Position in Experimental Condensed Matter Physics
University of Minnesota

The School of Physics and Astronomy at the University of Minnesota, Twin Cities, invites applications for a tenure-track position in the area of Experimental Condensed Matter Physics. The appointment is expected to be at the Assistant Professor level, although a more senior appointment will be considered for a candidate with exceptional qualifications. Candidates are expected to hold a Ph.D. in physics and should have demonstrated the potential to conduct a vigorous and significant research program as evidenced by their publication record and supporting letters from recognized leaders in the field. The ability to teach physics effectively at both the graduate and undergraduate levels is required. Condensed matter physics is a major research area at the University of Minnesota that involves 19 faculty members, including the recent addition of one experimentalist and four theorists. In 2014, the experimental condensed matter group moved into a new building with state-of the-art laboratory space. The new building is part of an institutional commitment to physics and nanoscience by the university, and the successful candidate will have the opportunity to customize their dedicated laboratory space in this building as well as have access to the facilities in the Minnesota Nanofabrication Center. The start date for this position is negotiable and could be as early as July 1, 2017. Candidates for this position (Job ID **312051**) must go to http://z.umn.edu/cmexpfaculty2016 and submit an application online. Application materials, which must be submitted as a single PDF file, should include a cover letter, a current C.V. with a list of publications, a statement of research interests, a statement of teaching interests, and the names of at least three references with complete address and contact information. Candidates should arrange to have letters of reference (signed and on official letterhead) sent directly to faculty-hiring@physics.umn.edu as PDF files no later than **November 28, 2016**. Alternatively, letters of reference may be sent to **Professor Ronald Poling, School of Physics and Astronomy, University of Minnesota, 116 Church St. SE, Minneapolis, MN 5545**5. Review of applications will begin on **November 28, 2016**, and continue until the position is filled. *The University of Minnesota shall provide equal access to and opportunity in its programs, facilities, and employment without regard to race, color, creed, religion, national origin, gender, age, marital status, disability, public assistance status, veteran status, sexual orientation, gender identity, or gender expression.*

Faculty Opening, Biological/Biomedical Physics
Washington University in St. Louis

The Department of Physics in the School of Arts and Sciences announces a tenure-track faculty opening at the Assistant Professor level in the Biophysics sub-discipline. We are searching for an experimentalist, but applications from data-driven theorists will also be favorably considered. We are seeking a candidate who will enhance activities within the Physics Department and develop connections with other Arts and Sciences, Engineering School, and Medical School Departments. The duties of the position will include, but are not limited to, teaching and advising students, conducting original research and publishing the results, and participating in departmental and university service. A PhD in Physics or a closely related field is required, along with the ability to teach a range of traditional undergraduate physics courses in addition to specialized courses. Candidates are sought who have highly visible research achievements and who have a strong aptitude for teaching and mentoring students at the undergraduate and graduate levels. The appointment will begin Fall 2017. Information on our department can be found at http://www.physics.wustl.edu. Applications should consist of the following: cover letter, current resume including publication record, statement of research interests and plans (up to 4 pages), statement of teaching interests and approach (up to 2 pages), and names and complete contact information (including email addresses) of three references. Application materials must be submitted electronically by email as a single file in editable (e.g. not password protected) PDF format to biophysicssearch@physics.wustl.edu. For full consideration applications should be submitted on or before **November 1, 2016**. *Washington University is an Equal Opportunity Employer. All qualified applicants will receive consideration for employment without regard to race, color, religion, age, sex, sexual orientation, gender identity or expression, national origin, genetic information, disability, or protected veteran status.*

Tenure Track Faculty Position - Assistant Professor
University of Maryland, Baltimore County

The University of Maryland, Baltimore County (UMBC) Department of Physics invites applications for a tenure-track assistant professor position with a research focus in computational condensed-matter or materials physics to begin in August 2017. Exceptionally qualified candidates may also be considered at a higher level of appointment. Candidates are expected to contribute to the diversity and excellence of the academic community through research, teaching and service. We seek candidates who have the capacity to establish a vigorous, externally funded research program that complements existing faculty research interests, and who are able to teach effectively both the undergraduate and graduate physics curricula. A PhD in Physics or in a closely related field is required, and postdoctoral experience is preferred. Start-up funds are available. UMBC is a dynamic public research university integrating teaching, research and service. It is located in the Baltimore suburbs, 15 minutes from Baltimore's Inner Harbor and 30 minutes from Washington D.C., in an area with a high concentration of federal and private research laboratories and research universities. The Department of Physics currently consists of 21 tenure-track and 16 research faculty, 46 graduate students and 160 undergraduate majors. The department offers a BS and BA in Physics, and both MS and PhD degrees in Physics and in Atmospheric Physics. Research expenditures currently exceed $6M per year. For more information, see http://physics.umbc.edu. *UMBC is an affirmative action / equal opportunity employer. Candidates from diverse backgrounds, including women and under-represented minorities, are particularly encouraged to apply. Interest and experience in working with a diverse student and faculty population is valued. UMBC and the Department of Physics are dedicated to creating an inclusive, collegial environment where all faculty members can achieve excellence.* Information on faculty diversity initiatives and faculty groups is available at http://facultydiversity.umbc.edu, and information on the resources provided to help balance work and personal priorities are available at http://hr.umbc.edu/work-life-balance/. Interested candidates should upload an application letter, a CV, detailed research and teaching plans, and the names and addresses of at least three references on the Interfolio website at http://apply.interfolio.com/36609. For best consideration, submit applications by **November 1, 2016**.

Associate Professor in Experimental Condensed Matter Physics
Georgetown University

The Georgetown University Department of Physics invites applications for a faculty position in experimental hard condensed matter physics at the rank of Associate Professor with tenure. Targeted areas include nanoscience, biomedical nanotechnology, photonics, electronic materials and devices, and MEMS/NEMS. We seek candidates with strong potential for synergy with ongoing experimental and theoretical research efforts on campus, both within the Department of Physics and in other departments, including those in the Georgetown University Medical Center. The successful candidate will have laboratory space in a recently constructed state-of-the art integrated science building and will benefit from the Georgetown Nanoscience and Microtechnology Laboratory clean room. Further, the university's location in Washington, DC, provides many opportunities for building strong collaborative ties with researchers in nearby government laboratories and other research institutions. The successful candidate will have a Ph.D. degree in physics or a closely related field and will be an outstanding scientist with a strong track record of research funding and success in leading a productive cutting-edge research program. In addition, the successful candidate will have demonstrated a commitment to excellence in teaching at both the undergraduate and graduate levels, and an enthusiasm for contributing to development and implementation of innovative curricula and pedagogies. Applicants should submit a single pdf file containing a curriculum vitae with a complete publication list, a statement of current research activities and future research plans, a statement of teaching experience and interests, and contact information for at least three references, to search@physics.georgetown.edu. Review of applications will begin on **Nov. 1, 2016** and continue until the position is filled. For further information, contact **Paola Barbara, Search Committee Chair,** at paola.barbara@georgetown.edu. *Georgetown University is an Equal Opportunity, Affirmative Action employer fully dedicated to achieving a diverse faculty and staff. All qualified candidates are encouraged to apply and will receive consideration for employment without regard to race, sex, sexual orientation, religion, national origin, marital status, veteran status, disability or other categories protected by law.*

Portland State UNIVERSITY

Maseeh College of Engineering & Computer Science
Department of Electrical & Computer Engineering
Two Tenure-track Assistant Professor Positions

The Electrical and Computer Engineering (ECE) Department at Portland State University seeks outstanding candidates for two tenure-track assistant professor positions in the area of underwater sensing. We are especially interested in applicants with research agendas that are internationally recognized, regionally relevant and complement our existing research programs. The positions are part of a hiring initiative to grow our group of research faculty in sensing and monitoring of coastal and freshwater hazards and habitats. This group of faculty will collaborate closely to attract and execute funded research for the development of sensing systems, signal processing algorithms, and unmanned sensing systems for coastal and riverine environments. Outstanding candidates may be considered at the associate professor level. A Ph.D. in Electrical Engineering, or a closely related field, is required. Candidates who are ABD will be considered, but must have completed their degree prior to the start date of employment. The Electrical and Computer Engineering Department is committed to excellence in education and the best practices of pedagogy. Duties include instruction at the undergraduate and graduate levels. The Department has ABET-accredited B.S. degree programs in Electrical Engineering and Computer Engineering, as well as M.S. and Ph.D. programs. Applications must be submitted online at https://jobs.hrc.pdx.edu/ for positions D91781 and D91784. Applications must include a cover letter, curriculum vitae, a teaching agenda, a research agenda and at least three references. Application reviews will begin immediately and continue until finalists are identified. *Portland State University is an Affirmative Action, Equal Opportunity institution and welcomes applications from all diverse candidates, including, among others, protected veterans and individuals with disabilities.*

FACULTY POSITIONS IN HARD CONDENSED MATTER, QUANTUM INFORMATION AND ATOMIC MOLECULAR AND OPTICAL PHYSICS

Department of Physics

ARTS AND SCIENCE

The Department of Physics at New York University invites applications for two faculty positions in the general areas of hard condensed matter, quantum information and atomic molecular and optical physics. These positions are part of an initiative for further significant growth in this area and establishment of a Center for Quantum Phenomena in the department. One of the positions will be in quantum material thin film synthesis and characterization, a focus of one of the research themes in the Center.

The openings are for experimental physicists at the tenure track Assistant Professor level, but more senior candidates in both theory and experiment may also be considered under exceptional circumstances. A successful candidate will have a Ph.D. and is expected to establish a leading research program in his/her field, as well as teach at the undergraduate and graduate levels. The positions can begin as early as September 1, 2017, pending administrative and budgetary approval.

Interested candidates should apply online at **http://physics.as.nyu.edu/object/physics.facultypositions**, with a letter describing current and planned research and teaching activities, a curriculum vitae, list of publications, and the names of three references. **Review of applications will begin on November 14, 2016.** More information about department's research programs can be found at **http://physics.as.nyu.edu**.

The Faculty of Arts and Science at NYU is at the heart of a leading research university that spans the globe. We seek scholars of the highest caliber, who embody the diversity of the United States as well as the global society in which we live. We strongly encourage applications from women, racial and ethnic minorities, and other individuals who are under-represented in the profession, across color, creed, race, ethnic and national origin, physical ability, gender and sexual identity, or any other legally protected basis. NYU affirms the value of differing perspectives on the world as we strive to build the strongest possible university with the widest reach. To learn more about the FAS commitment to diversity, equality and inclusion, please read **http://as.nyu.edu/page/diversityinitiative.**

NEW YORK UNIVERSITY

EOE/Affirmative Action/Minorities/Females/Vet/Disabled/Sexual Orientation/Gender Identity

THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

Department of Physics

Faculty Positions

The Department of Physics invites applications for substantiation-track faculty positions at the Assistant Professor level. Ranks at Associate Professor or above will also be considered for candidates with exceptional record of research excellence and academic leadership. Applicants must possess a PhD degree in physics or related fields and have evidence of strong research productivity. We seek

> **Theorists and experimentalists** in the area of condensed matter physics. Preference will be given to candidates in the area of low dimensional and highly correlated materials, and novel wavefunctional materials for manipulating light and sound.

Appointees are expected to assume teaching responsibilities for undergraduate and graduate courses, and to conduct vigorous research programs. Further information about the Department is available at **http://physics.ust.hk**.

Starting salary will be highly competitive and commensurate with qualifications and experience. Fringe benefits including annual leave and medical/dental benefits will be provided. Housing benefits will also be provided where applicable. A contract-end gratuity will be payable upon successful completion of contract.

Applicants should send their curriculum vitae, together with a list of publications, a brief statement of current interests, a plan for future research program, and the names and addresses of three referees, **by email to physjobs@ust.hk and address to Chairman of Search and Appointments Committee, Department of Physics, HKUST, Clear Water Bay, Hong Kong**. Screening of applications will begin as soon as possible, and will continue until the positions are filled.

Los Alamos NATIONAL LABORATORY

EST.1943

Los Alamos National Laboratory (LANL), a multidisciplinary research institution engaged in science on behalf of national security, has an opportunity available for a T-1 Group Leader.

T-1 GROUP LEADER (R&D MANAGER 4)

(JOB IRC51375)

The Theoretical Division at Los Alamos National Laboratory invites applications for the Physics and Chemistry of Materials (T-1) Group Leader position. The Group Leader will report to the Division Leader, will serve on the broader Theoretical Division management team, and will hold primary responsibilities for group management, administration, and scientific leadership.

The Physics and Chemistry of Materials (T-1) Group provides scientific and technical leadership in fundamental and applied theoretical research on the physics and chemistry of materials. The position is funded with the expectation that the successful candidate will lead the group while engaging personally in active and funded programmatic technical research at approximately 50% of the time.

Ph.D. or equivalent independent research experience in Material Science, Chemistry, Physics, Mathematics, or a related field required. Must possess relevant research experience, be able to develop technical programs, and assess the technical work of scientific researchers.

To view the official job ad, and for complete application instructions and more information, visit:

http://www.lanl.gov/careers

EOE

Tenure-line Faculty Position in Astronomy and Astrophysics
Northwestern University

The Department of Physics and Astronomy at Northwestern University invites applications for a new full time faculty position in astronomy and astrophysics, as part of a major expansion in this area over the coming years. We seek outstanding individuals who will complement and expand the current activities of the department in astronomy and astrophysics (www.physics.northwestern.edu) and who will become active members of CIERA, Northwestern's Center for Interdisciplinary Exploration and Research in Astrophysics (www.ciera.northwestern.edu). Candidates from all areas of observational and theoretical astrophysics are encouraged to apply. We are particularly interested in attracting astronomers with connections to major upcoming and current observational projects such as ALMA, JWST, LIGO, and LSST, and in potential interdisciplinary joint hires with planetary science, computer science, applied mathematics, statistics, and engineering. Applicants should have a strong record of achievement in astrophysics research and a commitment to excellence in undergraduate and graduate education in physics and astronomy. Appointment at the tenure-track Assistant Professor level is the target of this search. The starting date for this position is September 1, 2017. Interested applicants should send their curriculum vitae, list of publications, and research statement, and should arrange for a minimum of three reference letters to be sent in support of their application. The deadline for submission of all materials is **November 1st, 2016**. All materials should be submitted electronically; find the submission instructions at www.ciera.northwestern.edu. For questions about the application process please contact **Gretchen Oehlschlager** at CIERA@northwestern.edu. *The Department of Physics and Astronomy has a strong commitment to the achievement of excellence through diversity among its faculty and staff. Northwestern University is an Equal Opportunity, Affirmative Action Employer of all protected classes including veterans and individuals with disabilities. Women and minorities are encouraged to apply. Hiring is contingent upon eligibility to work in the United States.*

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Cambridge, MA
FACULTY POSITIONS

The Massachusetts Institute of Technology (MIT) Department of Electrical Engineering and Computer Science (EECS) seeks candidates for faculty positions starting in September 1, 2017 or on a mutually agreed date thereafter. Appointment will be at the assistant or untenured associate professor level. In special cases, a senior faculty appointment may be possible. Faculty duties include teaching at the undergraduate and graduate levels, research, and supervision of student research. Candidates should hold a Ph.D. in electrical engineering and computer science or a related field by the start of employment. We will consider candidates with research and teaching interests in any area of electrical engineering and computer science. Candidates must register with the EECS search website at https://eecs-search.eecs.mit.edu, and must submit application materials electronically to this website. Candidate applications should include a description of professional interests and goals in both teaching and research. Each application should include a curriculum vitae and the names and addresses of three or more individuals who will provide letters of recommendation. Letter writers should submit their letters directly to MIT, preferably on the website or by mailing to the address below. Complete applications should be received by **December 1, 2016**. Applications will be considered complete only when both the applicant materials and **at least three letters of recommendation are received. It is the responsibility of the candidate to arrange reference letters to be uploaded at https://eecs-search.eecs.mit.edu by December 1, 2016.** Send all materials not submitted on the website to: Professor Anantha Chandrakasan, Department Head, Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Room 38-401, 77 Massachusetts Avenue, Cambridge, MA 02139. *M.I.T. is an equal opportunity/affirmative action employer.*

Faculty Position in Theoretical Condensed Matter Physics at Rutgers, the State University of New Jersey

The Department of Physics and Astronomy at Rutgers, The State University of New Jersey, invites applicants for a tenure-track Assistant Professor position in Theoretical Condensed Matter Physics. For an exceptional candidate, appointment at a more senior level may be considered. Applicant must have a Ph.D. degree and an outstanding record of research and publication, preferably in a field related to correlated, topological, magnetic or electroactive materials; non-equilibrium systems; nanostructures; or large-scale computation or computational design. The successful candidate will be expected to establish an independent research program that will attract external funding, and should be strongly committed to teaching. A start date of 1 September 2017 is anticipated. Applicants should apply online via Interfolio athttps://apply.interfolio.com/36865, providing a cover letter, a CV including list of publications, a statement of research plans, and a teaching statement, and should follow the Interfolio instructions to arrange for three letters of recommendation. Review of applications will begin on **1 October 2016**, with those arriving by **1 November** receiving the fullest consideration. *All qualified applicants will receive consideration for employment without regard to race, color, religion, sex, sexual orientation, gender identity or expression, national origin, disability, protected veteran status or any other classification protected by law.*

Assistant Professor of Astronomy, Cornell University

The Cornell University Astronomy Department invites applications for a tenure-track assistant professor appointment to begin July 1, 2017. We will consider applications from observers, experimentalists and theorists working in any area of astronomy, but particular areas of interest are cosmology, extragalactic astronomy, extrasolar and solar system planetary science, and relativistic astrophysics, including gravitational wave astronomy and astrophysics. Applicants should upload their applications, including a CV, list of publications, statement of research interests, and statement on teaching plans and philosophy to https://academicjobsonline.org/ajo/jobs/7615. Applicants should also arrange to have three letters of recommendation submitted to **Academic Jobs Online.** Inquiries may be sent to **Ira Wasserman** (ira@astro.cornell.edu), chair of the department. We will begin reviewing applications **November 1, 2016**. *Cornell University is an Equal Opportunity/Affirmative Action Employer and Educator. Women and underrepresented minorities are strongly encouraged to apply.*

KAVLI INSTITUTE FOR THEORETICAL PHYSICS
Deputy Director
Job #JPF00805

The Kavli Institute for Theoretical Physics at UC Santa Barbara seeks applications for a Researcher to serve as Deputy Director with a start date as early as September 1, 2017. The Institute is supported principally by the National Science Foundation and has the responsibility of contributing to progress in all areas of Theoretical Physics. The Institute seeks a person with a proven research record and administrative capabilities. The Deputy Directors work closely with the Director in planning the Institute's research programs and play a prominent role in outreach planning, documentation of outcomes, and in many aspects of administering the Institute. It is expected that a Deputy Director spend one half time in scientific research. The initial term is two years, with the possibility of renewal based on the candidate's availability and performance. A Ph.D. in physics is required. Additional qualifications include outstanding research in theoretical physics, quality administrative experience, knowledge of interdisciplinary activity in physics, and a commitment to furthering diversity among participants in KITP programs. Strong interpersonal skills are required. To apply, please go to https://recruit.ap.ucsb.edu/apply/JPF00805. Applicants should submit a cover letter, curriculum vitae, contact information for three references, and a research statement. Letters of reference will be requested only for final candidates. To receive full consideration, please apply by **December 1, 2016**. The position will remain open until filled. Persons interested in the position, or wishing to nominate candidates, should contact the **Director, Professor Lars Bildsten**, at bildsten@kitp.ucsb.edu. *The KITP is especially interested in candidates who can contribute to the diversity and excellence of the academic community through research, teaching and service. The University of California is an Equal Opportunity/Affirmative Action Employer and all qualified applicants will receive consideration for employment without regard to race, color, religion, sex, sexual orientation, gender identity, national origin, disability status, protected veteran status, or any other characteristic protected by law.*

Stanford University Faculty Position
Experimental Condensed Matter Physics

The Department of Physics at Stanford University seeks applicants for a faculty position in the area of experimental condensed matter physics, broadly defined. We are seeking applicants at the tenure-track Assistant Professor level. Applicants should exhibit the potential of running a world-recognized independent research program, and should also possess good communication skills and a commitment to teaching and education. The term of appointment would begin on or around September 1, 2017. Applicants must send materials to the search committee through AcademicJobsOnline. Candidates should upload a cover letter, curriculum vitae, publication list, a research and teaching statement (maximum three pages, combined), and arrange to have four letters of reference submitted online at https://academicjobsonline.org/ajo/jobs/7744. Inquiries may be directed to **J. Tice, Dept. of Physics, 382 Via Pueblo Mall, Stanford University, Stanford, CA 94305-4060**, or to tice@stanford.edu. The due date for submission of all materials, including letters of reference, is **December 1, 2016**. *Stanford University is an equal opportunity employer and is committed to increasing the diversity of its faculty. It welcomes nominations of, and applications from, women, members of minority groups, protected veterans and individuals with disabilities, as well as others who would bring additional dimensions to the university's research, teaching and clinical missions.*

Postdoctoral Positions in Cosmic Microwave Background Cosmology
Simons Observatory

Simons Observatory (http://simonsobservatory.org/) invites applications for up to twelve postdoctoral positions at six or more institutions in cosmic microwave background (CMB) research, with start dates extending from fall 2016 through fall 2017. Full details for the positions can be found at http://simonsobservatory.org/jobs.html. Successful candidates will be involved in the design, construction, and operation of the Simons Observatory, and/or take leading roles in the data analysis and preparation of the results for publication. Opportunities for appointments across two or more institutions are available.

Assistant Professor in the Computational or Theoretical Astrophysics of Strongly Gravitating Systems
University of New Hampshire
Department of Physics and Space Science Center

The Department of Physics and Space Science Center at the University of New Hampshire (UNH) invite applications for a tenure-track position at the rank of Assistant Professor beginning August, 2017, in the area of gravitational astrophysics, with a particular emphasis on the numerical modeling of compact objects and their gravitational or electromagnetic radiation. The successful applicant can expect to interact with a number of active research groups, including: the high-energy theory group, whose interests include classical gravitational physics, quantum gravity, and string theory; the high-energy astrophysics group, which conducts experimental research in gamma-ray astronomy and is currently working on efforts to measure gamma-ray-burst polarization; and the space-plasma theory group, which is involved in theoretical studies and numerical modeling of heliospheric plasmas and magnetospheres. UNH is a research university on the beautiful New Hampshire seacoast, roughly an hour north of Boston, with significant resources for numerical scientists, including UNH's Integrated Applied Math Program and a CRAY XE6m-200 supercomputer. The successful candidate will have a strong track record of research accomplishments and outstanding potential for teaching and securing external grant funding. Applicants must have a Ph.D. in Physics, Astronomy, or a related field. Review of applications will begin on **Nov. 15, 2016**. Applicants should submit their application as a single PDF document to **Ms. Katie Makem-Boucher** at physics.search@unh.edu. This document should contain a cover letter, curriculum vitae, and brief summaries of teaching interests and future research plans. The applicant should also arrange for three letters of reference to be sent to the same address. Inquiries about the position should be directed to **Prof. Ben Chandran** at benjamin.chandran@unh.edu. *UNH is an AA/EEO Employer. UNH is committed to excellence through diversity of its faculty and staff and encourages women and minorities to apply. For a more comprehensive job description, visit* http://physics.unh.edu/jobs.

Experimental Neutrino Physics
Tufts University

The Department of Physics and Astronomy at Tufts University invites applications for a tenure-track Assistant Professor position in the field of Experimental Neutrino Physics. We seek an outstanding experimentalist to strengthen our ongoing research program, which currently involves the MINERvA, NOvA, and DUNE experiments, and the GENIE collaboration. The candidate's expertise will be sufficiently extensive to enable them to rapidly assume an important role in one or more on-going and future neutrino experiments at the Fermi National Accelerator Laboratory. We are particularly interested in candidates who can play a significant role in the Deep Underground Neutrino Experiment (DUNE) program, ideally incorporating hardware development activities. We are looking for an individual with motivation and abilities to be an excellent teacher, one who would be able to teach any of our undergraduate physics courses as well as many of our graduate-level courses, and who has the ability to effectively mentor a diverse group of students. We expect the new hire to strengthen the on-going base grant of the High Energy Physics group and to seek independent research funding after coming to Tufts. The candidate is expected to be able to supervise thesis work by graduate students and to sponsor research work by undergraduates. To qualify for the position, the candidate must have a Ph.D. in physics and several years of post-doctoral experience conducting experimental research in elementary-particle physics, with an emphasis on neutrino physics. The Department offers M.S. and Ph.D. degrees, and includes strong research programs in particle physics, theoretical physics, cosmology, condensed matter physics, physics education, and observational astronomy/astrophysics. Applicants should use the link http://apply.interfolio.com/37667 to submit a cover letter, a curriculum vitae, and separate statements of (1) research interests and plans (4 pages max) and (2) teaching experience and philosophy (2 pages max). Applicants should also ensure that three confidential letters of reference are submitted to this link. The deadline for submission of all materials is **December 1, 2016**. Review of applications will begin **December 2, 2016** and will continue until the position is filled. *Tufts University is an Affirmative Action/Equal Opportunity employer. We are committed to increasing the diversity of our faculty. Members of underrepresented groups are strongly encouraged to apply.*

Tenure Track – Theoretical High Energy Physics

The Physics Department of the **University of Massachusetts Amherst** invites applications for a tenure-track faculty position in theoretical high energy, gravitational physics and/or theoretical cosmology to start September 1, 2017. The new faculty member will be part of the Amherst Center for Fundamental Interactions, http://www.physics.umass.edu/acfi/. Further information about the Department's theoretical and experimental efforts can be found at http://www.physics.umass.edu/. The Department seeks an individual with outstanding research and a strong commitment to teaching. A PhD in areas closely related to theoretical high energy, gravitational physics and/or theoretical cosmology, and postdoctoral experience are required. To apply online, please go to http://umass.interviewexchange.com/jobofferdetails.jsp?JOBID=76611 , and submit a resume, cover letter, a detailed research plan, a teaching statement, and contact information for three professional references. Applicants should apply by the priority deadline of **November 15, 2016** in order to ensure consideration. The university is committed to active recruitment of a diverse faculty and student body. *The University of Massachusetts Amherst is an Affirmative Action/Equal Opportunity Employer of women, minorities, protected veterans, and individuals with disabilities and encourages applications from these and other protected group members. Because broad diversity is essential to an inclusive climate and critical to the University's goals of achieving excellence in all areas, we will holistically assess the many qualifications of each applicant and favorably consider an individual's record working with students and colleagues with broadly diverse perspectives, experiences, and backgrounds in educational, research or other work activities. We will also favorably consider experience overcoming or helping others overcome barriers to an academic degree and career. We are seeking talented applicants qualified for an assistant professor position. Under exceptional circumstances, highly qualified candidates at other ranks may receive consideration.*

udjobs
Employer of Choice

Faculty Position in Experimental Nanoscale Physics
Department of Physics and Astronomy

The Department of Physics and Astronomy at the University of Delaware invites application for a tenure-track Assistant Professor position in the area of experimental nanoscale physics. Areas of research interest include, but are not limited to, physics of collective excitations and emergent quantum phenomena in solids, low-dimensional electronic transport, nanophotonics, layered and topological materials and devices. The successful candidate will be a major user of the new 8,000-square-foot nanofabrication facility located within the Harker Interdisciplinary Science & Engineering Laboratory. This facility is equipped with state-of-the-art tools for electron-beam and optical lithography, deposition, etching, thermal processing, metrology and packaging. We seek creative and innovative individuals who have demonstrated excellence in research, who will engage in high-quality teaching and mentoring at both the undergraduate and graduate levels, and who are eager to work in a collaborative and interdisciplinary research environment and become leaders in their fields. Candidates conducting research that complements existing university strengths in nano-bio interfaces, optoelectronics, photonics, laser spectroscopy, renewable energy or spintronics are especially encouraged to apply.

Candidates must have a PhD degree in physics or a related discipline. Applicants should submit a curriculum vita, a 3-6-page research proposal, a one-page statement of teaching experience and interests, and a list of at least four references. Applications received by 15 November 2016 are assured of full consideration.

For additional information and application procedures about this position and all open other positions please visit the UDJOBS website at **http://apply.interfolio.com/37560**

The University of Delaware is an Equal Opportunity Employer which encourages applications from Minority Group Members, Women, Individuals with Disabilities and Veterans. The University's Notice of Non-Discrimination can be seen at: www.udel.edu/aboutus/legalnotices.html

Dare to be first.
University of Delaware

Massachusetts Institute of Technology

Come work with us!

Faculty Position – Astrophysics

The Physics Department at the Massachusetts Institute of Technology (MIT), located in Cambridge, Massachusetts, invites applications for a faculty position in Astrophysics, specializing in the study of exoplanets. The successful candidate will contribute to the scientific success of the Transiting Exoplanet Survey Satellite (TESS), which is under development at MIT for launch in late 2017.

Current MIT astrophysics faculty are active in broad areas of observational and theoretical astrophysics, including optical/IR and high-energy astrophysics, exoplanets, gravitational waves, and observational and theoretical cosmology. MIT hosts the Kavli Institute for Astrophysics and Space Research, whose faculty and research staff have a major role in instrumentation for many current and future research facilities including the TESS mission, the Magellan telescopes in Chile, the Neutron Star Interior Composition Explorer (NICER), the Chandra X-ray Observatory, and the Hydrogen Epoch of Reionization Array (HERA). Faculty members at MIT conduct research, teach undergraduate and graduate courses, and supervise graduate and undergraduate research. Candidates must show promise in teaching as well as in research. A Ph.D. in physics or physics-related discipline is required by the start of employment. Preference will be given to applicants at the Assistant Professor level.

The application deadline is October 14, 2016. Applicants should submit a curriculum vitae, publication list, and brief description of research interests (the latter not to exceed 3 pages in length) to Academic Jobs Online, https://academicjobsonline.org/ajo/jobs/7643. Applicants should also arrange for three letters of reference to be uploaded to the same site by the application deadline. Only web submissions will be accepted. Inquiries may be directed to Prof. Deepto Chakrabarty, Search Committee Chair, deepto@mit.edu.

MIT is an Affirmative Action/Equal Opportunity employer committed to diversity and inclusion.

http://web.mit.edu

Faculty Position in Physics

The Department of Physics at the **University of Richmond** invites applications for a tenure-track faculty position in physics to begin in August 2017. The search will focus on candidates at the junior level. Applications are encouraged from candidates in all sub-fields of physics, both theory and experiment, but applications from candidates whose scholarship complements existing research areas in the department (biophysics, cosmology and astrophysics, low- and medium-energy nuclear physics and nanoscale physics) may receive particular attention. The successful candidate is expected to have demonstrated a keen interest and ability in undergraduate teaching and to maintain a vigorous research program that engages undergraduates in substantive research outcomes. Candidates must possess a doctoral degree in physics or a related field. Candidates should apply online at the University of Richmond Online Employment website (https://jobs.richmond.org) using the Faculty (Instructional/Research) link. Applicants are asked to submit a cover letter, a current curriculum vitae with a list of publications, a statement of their teaching interests and philosophy, evidence of teaching effectiveness (if available), a description of current and planned research programs, and the names of three references who will receive an automated email asking them to submit their reference letters to this web site. Review of applications will commence **November 1, 2016** and continue until the position is filled. The University of Richmond is a highly selective private university with approximately 3000 undergraduates located on a beautiful campus six miles west of the heart of Richmond and in close proximity to the ocean, mountains, and Washington, DC. The Physics Department is active in research and is recognized by the AIP for consistent high production of physics bachelor's degrees. *The University of Richmond is committed to developing a diverse workforce and student body and to being an inclusive campus community. We strongly encourage applications from candidates who will contribute to these goals.* For more information please see the department's website at http://physics.richmond.edu or contact **Prof. M. L. Trawick, Chair, Department of Physics,** (email: mtrawick@richmond.edu).

Research Assistant Professor in Solar/Stellar Data Analysis
Georgia State University

The Department of Physics and Astronomy at Georgia State University (GSU) is seeking to fill a position by Fall 2017 at the assistant research professor level. The new hire will have a proven record in analyzing large amounts of solar and/or stellar data using modern methods of data analytics, and will help build an astroinformatics cluster on "The Solar/Stellar Connection" in conjunction with the Department of Computer Science and the Center for High Angular Resolution Astronomy at GSU. This position is part of a GSU Next Generation Faculty Program that will include a number of tenure- track and research faculty as well as postdoctoral hires in the above departments to work closely with current faculty, including recent senior faculty hires (Dr. Rafal Angryk, Dr. Piet Martens, and Dr. Stuart Jefferies), in the areas of solar and stellar physics, space weather, and big data mining. This position is fully supported by the university for 3 years, with an additional 2 years of university support at the 50% level possible if external funding is secured for the remaining salary. Research faculty with outstanding accomplishments may qualify for tenure-track faculty positions in the future. Applicants should have the following basic qualifications: 1) Ph.D. in astronomy, physics, or closely related field, 2) postdoctoral research experience, 3) evidence of the ability to establish and maintain a successful research program, and 4) evidence of the ability to work in a large, collaborative effort. Applications should include 1) a CV, including a publication list, 2) a statement of the candidate's research interests and how the research fits into the above program, and 3) contact information for at least three references. All materials should be sent via email to AstroSearch@astro.gsu.edu. Questions regarding the position can be addressed to **Dr. Piet Martens** at martens@astro.gsu.edu. Applications received by **December 1, 2016,** will receive full consideration. *An offer of employment will be conditional on background verification. Georgia State University, a unit of the University System of Georgia, is an equal opportunity educational institution and an EEO/AA employer. Women and minorities are strongly encouraged to apply. It is our policy to offer equal employment opportunities for all persons without regard to race, color, religion (creed), gender, gender expression, age, national origin (ancestry), disability, marital status, sexual orientation, or military status.*

The School of Natural Sciences at the **Institute for Advanced Study in Princeton, New Jersey,** will have **several openings** for members in **theoretical physics and astrophysics** for the academic year 2017-2018. The positions are at a postdoctoral or higher level in the areas of astrophysics, theoretical biology, mathematical physics, quantum field theory, particle phenomenology, string theory and quantum gravity. Postdoctoral members are selected on their ability to conduct independent research but they frequently collaborate with each other, with faculty members at the Institute or Princeton University, and with researchers at other institutions. Postdoctoral member appointments range from three to five years. Long term members have five-year appointments with a salary that is above post-doctoral level. In addition to exceptional qualifications for pursuing his or her individual research, the successful candidate for a long-term membership should be interested in mentoring, and possibly collaborating with, other post-doctoral members. Long-term members in astrophysics are designated Bahcall fellows. We will also have openings for Junior Visiting Professors. Applicants for these openings should hold a faculty or equivalent position and normally should be within ten years of receiving their Ph.D. Support will be provided to spend a period between one term and one year at the Institute while the faculty is on sabbatical or other leave from their home institution. Junior Visiting Professors are expected to conduct their own research and to help make the research environment at the IAS stimulating to the other members of the School. A small number of senior scientists can usually be accommodated on sabbatical leave. All members are normally eligible for subsidized housing on the Institute campus. All applicants must apply through AcademicJobsOnline. Three letters of recommendation are required and should be submitted directly through the AJO website. Applications must be received by **November 15**. For more information write to michelle@ias.edu or **Michelle Sage, School Administrative Officer, School of Natural Sciences, Institute for Advanced Study, Princeton, New Jersey, 08540.**

Assistant Professor in Experimental Quantum Condensed Matter Physics

The Department of Physics and Astronomy at the **University of Pennsylvania** seeks applications from outstanding candidates for an appointment as **Assistant Professor** in **experimental quantum condensed matter physics.** Appointment at higher rank can be considered in truly exceptional cases. The successful candidate will develop an innovative research program on quantum phenomena in modern materials that attracts the participation of graduate and undergraduate students and creates collaborative links with other Penn scientists and engineers. We anticipate the candidate's program will contribute actively to the Laboratory for Research on the Structure of Matter and the newly established Singh Center for Nanotechnology. Applicants must apply online at http://facultysearches.provost.upenn.edu/postings/952. Required application materials include: curriculum vitae with a list of publications, a research statement and a teaching statement. Applicants should also submit the names and contact information for three individuals from whom we will request letters of recommendation. Review of applications will begin no later than **November 1, 2016** and will continue until the position is filled. The Department of Physics and Astronomy is strongly committed to Penn's Action Plan for Faculty Diversity and Excellence and to creating a more diverse faculty (for more information see: http://www.upenn.edu/almanac/volumes/v58/n02/diversityplan.html). *The University of Pennsylvania is an EOE. Minorities/Women/Individuals with disabilities/Protected Veterans are encouraged to apply.*

Head, Department of Physics
Carnegie Mellon University

The Department of Physics seeks a dynamic and creative leader for the position of Department Head. The successful candidate will be expected to lead and build upon the Department's strengths in Cosmology, Biological Physics, High- and Medium- Energy Particle Physics, and Condensed Matter Physics while maintaining his or her own scholarly research. The Department of Physics faculty currently includes 35 tenure-track, teaching-track, and research-track faculty members and a graduate program with more than 70 Ph.D. students. Carnegie Mellon has a long history of success in fostering interdisciplinary research collaborations. As such, the Department seeks candidates possessing excellent communication skills, interdisciplinary vision, and ambition. Working with the Assistant Department Head for Undergraduate Teaching, the Department Head oversees the educational mission of the Department, including the integration of teaching and research activities, as well as the graduate program. Carnegie Mellon University is an equal opportunity employer and is committed to increasing the diversity of its community on a range of intellectual and cultural dimensions, and we seek leaders who are committed to this goal. Carnegie Mellon welcomes applicants who will contribute to this diversity through their research, teaching and service, including women, members of minority groups, protected veterans, individuals with disabilities, and others who would contribute in different ways. Questions about the search may be addressed to the **Chair of the Search Committee: Professor Gregg Franklin**, at gbfranklin@cmu.edu. Prospective candidates should submit a cover letter, a curriculum vita, publication list, and statement of research plans; and also arrange for three letters of recommendation to be sent to Academic Jobs Online at: http://academicjobsonline.org/ajo/jobs/7967. The screening of job applications will begin **November 1, 2016** and continue until the position is filled.

Tenure-Track Assistant Professor in Theoretical Nuclear Physics

The Department of Physics and Astronomy at the **University of North Carolina at Chapel Hill** seeks candidates with a Ph.D. in physics or a related area, a record of strong postdoctoral research in theoretical nuclear physics, and a commitment to teaching for appointment as a tenure-track assistant professor. The successful candidate will be expected to contribute for the first four years of employment to the Department of Energy Topical Nuclear Theory Collaboration for Double Beta Decay and Fundamental Symmetries. The collaboration currently includes experts in lattice QCD, nuclear structure, and physics at the interface of nuclear theory, particle theory, and cosmology. The nuclear-theory group at UNC has expertise in nuclear structure, quantum Monte Carlo methods, cold atoms, neutrino physics, nuclear astrophysics, and fundamental symmetries. At http://unc.peopleadmin.com/postings/105659 applicants should specify Physics and Astronomy in the Department drop-down list box, then upload PDF versions of their cover letter, CV, publication list, and separate research and teaching/mentoring statements by **December 16, 2016**, when application review will begin. Applicants should submit the names, titles, email addresses, and telephone numbers of a minimum of four (4), and a maximum of four (4), reference letter writers. *EEO Statement: The University of North Carolina at Chapel Hill is an equal opportunity employer that welcomes all to apply, including protected veterans and individuals with disabilities.*

Research Scientist for Imaging Science - Georgia State University
Georgia State University

Applications are invited for appointment as Research Scientist in the Department of Physics and Astronomy, to commence as soon as possible. The appointee will be expected to conduct basic research into novel methods for high-resolution imaging through strong atmospheric turbulence. Applicants should posses a Ph.D. in a relevant field (e.g., physics, astronomy) and have direct experience in imaging through turbulent media, or are able to demonstrate how their experience will have application for the target research. They must also have excellent interpersonal skills, a consistent record of research publications, and a desire to pursue competitively funded research grants and contracts as a Principal Investigator. Applicants should also be U.S. Citizens or Permanent Residents. Applications should be submitted and questions addressed to **Dr. Stuart Jefferies** at smj@astro.gsu.edu. Applications received by **December 1, 2016**, will receive full consideration. Information about the Department of Physics and Astronomy at Georgia State University can be found at http://www.phy-astr.gsu.edu . An offer of employment will be conditional on background verification. *Georgia State University, a unit of the University System of Georgia, is an equal opportunity educational institution and an EEO/AA employer. Women and minorities are strongly encouraged to apply. It is our policy to offer equal employment opportunities for all persons without regard to race, color, religion (creed), gender, gender expression, age, national origin (ancestry), disability, marital status, sexual orientation, or military status.*

PHYSICS & ENGINEERING PHYSICS: ASSISTANT PROFESSOR
Central Connecticut State University

CCSU invites applications for a full time tenure track Assistant Professor starting in the Fall of 2017. The department offers comprehensive programs in physics leading to a B.S. in Physics with optional concentrations. Required Qualifications: Ph.D. in Experimental Physics or Engineering Physics, with research interests appropriate for student participation, experience in involving undergraduates in research, and commitment to serving culturally, ethnically and linguistically diverse communities. Preferred Qualifications: research experience in energy storage systems, biophysics, materials physics and/or engineering physics; experience teaching undergraduate Electronics, and Nanostructure Science and Technology; and experience in successful research grant writing. For full consideration, applications must be received by **November 7, 2016**. For more information and application instructions, go to https://hrat.ccsu.edu/default.php. *CCSU is an affirmative action and equal opportunity employer.*

SENIOR FACULTY POSITION IN
Experimental Nanoscale Science

THE DEPARTMENT OF PHYSICS within the Division of Physical Sciences at UC San Diego (http://physics.ucsd.edu) invites applications for a senior (tenured) faculty position in Experimental Nanoscale Science. We seek outstanding candidates who work in the broad general area of Nanoscience, including Mesoscopic Physics. Applicants should have a Ph.D. in physics or a closely related field, an outstanding record of research accomplishment and professional activity, and demonstrated ability and strong interest in undergraduate and graduate instruction, including the education of underrepresented populations. The successful candidate is expected to establish a world-class research program and to participate in the educational programs and other activities of the Department. All positions are subject to budget approval. The department is committed to academic excellence and diversity within the faculty, staff, and student body. A successful candidate will be judged on research and teaching accomplishments, as well as on demonstrated leadership in areas contributing to diversity, equity and inclusion in higher education. Applications are to be submitted online at: https://apol-recruit.ucsd.edu/apply/JPF01212. Please select the following open position: PHYSICS Tenured Full Professor - Experimental Nanoscale Science. All candidates should submit: a curriculum vitae, list of publications, summary of research interests, future research plan, and a separate statement describing past and/or potential contributions to and leadership in promoting equity, inclusion, and diversity (see http://facultyexcellence.ucsd.edu/c2d/index.html for further information). Candidates should also arrange to have three letters of reference addressing research, teaching and professional service posted to the above website. Information about spousal/partner employment is available on the Partner Opportunities Program website: http://academicaffairs.ucsd.edu/aps/partneropp/index.html. Salary is commensurate with qualifications and based on University of California pay scale. Review of applications will begin **October 24, 2016** and continue until the position is filled. *UC San Diego is an equal opportunity/affirmative action employer with a strong institutional commitment to excellence and diversity (http://diversity.ucsd.edu/).*

The University of Virginia Department of Physics invites applicants for a **tenure-track Assistant Professor position**. We seek a theoretical physicist with a strong record of research in the area of general relativity, gravitational waves, cosmology, and/or the nature of dark matter/dark energy. In addition to their primary role in the Physics department, it is highly desirable that the successful candidate can engage with the Department of Astronomy and the National Radio Astronomy Observatory, whose headquarters are located on the grounds of the University of Virginia. We seek candidates who are dedicated to our educational mission and are passionate about teaching at a world-class, international university. Upon joining the faculty at the University of Virginia, the new faculty member will be expected to establish a vibrant and successful research program in physics; obtain external funding; teach at the undergraduate and graduate levels; provide service to the University, Department, and professional organizations; and mentor doctoral students. Review of applications will begin **November 1, 2016**; however, the position will remain open until filled. The appointment begins with the fall term of 2017, with an anticipated start date of July 25, 2017. Applicants must have earned a Ph.D. in physics or a related field at the time of application. To apply, candidates must submit a Candidate Profile through Jobs@UVa (https://jobs.virginia.edu), search on posting number **0619296** and electronically attach the following: a cover letter of interest describing research agenda and teaching experience, a curriculum vitae, a publication list, and contact information for three references. Please have the reference letter writers email letters directly to phys-astro-job@virginia.edu. Questions regarding the application process in Jobs@UVa should be directed to: **Tammie Shifflett, 434-924-6565,** tms4t@virginia.edu. The University will perform background checks on all new faculty hires prior to making a final offer of employment. The University of Virginia assists UVA faculty spouses and partners seeking employment in the Charlottesville area. To learn more about these services, please see http://provost.virginia.edu/dual-career. *The University of Virginia is an equal opportunity/affirmative action employer. Women, minorities, veterans and persons with disabilities are encouraged to apply.*

Tenure-track or Tenured Faculty Position in Instrumentation/Astrophysics
Tsinghua Center for Astrophysics, Department of Physics, Tsinghua University

The Tsinghua Center for Astrophysics (THCA) in the Department of Physics at Tsinghua University invites applications for a tenure-track or tenured faculty position in experimental astrophysics. The successful candidate is expected to establish a dynamic research program that is complementary to the existing R&D efforts on instrumentation, which are focused on high energy astrophysics (see http://astro.tsinghua.edu.cn). All qualified candidates are encouraged to apply. English is a working language at THCA. A complete application, including a curriculum vita, a list of publications, and a statement of previous research and future plan should be sent, in one PDF file, by **November 30, 2016**. The applicant should also arrange for three letters of recommendation (or five, if applying for a tenured position) to be sent prior to the deadline. The successful candidate will be offered a competitive salary, startup funding, affordable housing, and modern lab space. The starting date is September 1, 2017 (although it can be negotiated).

The **Heidelberg Graduate School of Fundamental Physics (HGSFP)** at the **Department of Physics and Astronomy** at **Heidelberg University**, a School funded by the German Excellence Initiative, invites applications for

Doctoral Fellowships

in the following areas of modern fundamental physics: (a) Astronomy and Cosmic Physics, (b) Quantum Dynamics and Complex Quantum Systems, (c) Fundamental Interactions and Cosmology, (d) Complex Classical Systems, (e) Mathematical Physics, and (f) Environmental Physics. Thesis research topics cover areas such as experimental and theoretical astrophysics, cosmology, accelerator based particle physics, precision measurements in physics, study of quantum systems – many body as well as small systems, low as well as high temperature physics, atomic, molecular and optical physics, mathematical physics and string theory. In addition, fundamental problems in biophysics, e.g. in materials science aspects of cell biology, and in environmental physics are studied. The HGSFP combines doctoral projects at the forefront of international research in the areas mentioned above with a rich and thorough teaching programme. Further information can be found on the School's web site: http://www.fundamental-physics.uni-hd.de.

The branch Astronomy & Cosmic Physics is the International Max Planck Research School (IMPRS) for Astronomy and Cosmic Physics at the University of Heidelberg (http://www.mpia.de/imprs-hd). Students accepted into the Graduate School will automatically be members of the IMPRS-HD and conversely. Admission to the IMPRS for Precision Tests of Fundamental Symmetries (www.mpi-hd.mpg.de/imprs-ptfs), to the IMPRS for Quantum Dynamics in Physics, Chemistry and Biology (http://www.mpi-hd.mpg.de/imprs-qd), to the RTG Particle Physics Beyond the Standard Model (http://www.thphys.uni-heidelberg.de/~gk_ppbsm) or the RTG HighRR (High Resolution and High Rate Detectors in Nuclear and Particle Physics) is also possible. The IMPRS and RTGs offer doctoral positions and fellowships as well, and are combined efforts of Heidelberg University with the Max Planck Institutes for Astronomy and Nuclear Physics, which form an integral part of the exciting and broad research environment in Heidelberg.

Highly qualified and motivated national and international students are invited to apply. Applicants should preferably hold a Master of Science or equivalent degree in physics. Excellent candidates holding a four year bachelor degree and proof of research experience may also be considered. At equal level of qualification, preference will be given to disabled candidates. Female students are particularly encouraged to apply.

Applicants have to initiate their application registering via a web form available at http://www.fundamental-physics.uni-hd.de/fellowships. Applications should be completed by **November 22, 2016**.

Boston College Physics
Experimental Condensed Matter

The Department of Physics at Boston College invites applications for a **tenure-track Assistant Professor** position in experimental condensed matter. All areas of condensed matter/materials physics will be considered, with particular interest in optics/photonics, energy and quantum matter. Applicants should have a Ph.D. in physics or a closely related field, with a proven track record of scientific and professional accomplishment. Boston College Physics is undergoing a dynamic expansion. It is projected that up to five new faculty will be hired in the coming years, all in condensed matter/materials physics. We particularly seek future faculty members interested in broad collaborations, with a vision for growth of the department and the integrated and applied sciences overlapping with cognate disciplines. Successful candidates will be expected to develop world-class research programs and contribute significantly to service and educational activities of the department and University, including participation in a new Institute for Integrated Science and Society currently being planned at BC. BC Physics offers a rich condensed matter research environment, with strengths in applied and fundamental areas of correlated matter, nanophotonics, plasmonics, photovoltaics, thermoelectrics, topological matter, superconductivity, and physics at the bio-neuro-nano interface (visit physics.bc.edu for more information). Candidates will be judged on their research, potential for becoming an excellent teacher, and commitment to interdisciplinary science and education in the service of society, including diversity and equity. The successful candidates will be supported by nationally-competitive start-up packages. Applicants should submit a detailed curriculum vitae, a statement of teaching interests, and a research plan to apply.interfolio.com/36517. Applicants should also have 3 letters of reference submitted via Interfolio. Review of applications will begin in **November, 2016** and continue until the position is filled. *Boston College is an Affirmative Action/Equal Opportunity Employer, committed to the policies, principles and practices of equal opportunity, affirmative action and nondiscrimination in all of its activities, including, but not limited to, employment. Boston College commits itself to maintaining a welcoming environment for all people and extends its welcome in particular to those who may be vulnerable to discrimination on the basis of their race, ethnic or national origin, religion, color, age, gender, marital or parental status, sexual orientation, veteran status or disabilities.*

The Department of Physics at **Oklahoma State University** invites applications for the position of **Department Head**. The position will be at the rank of **Full Professor with tenure**. The successful candidate will have a doctorate in Physics, an internationally recognized research program in any of the existing areas of physics in the Department (AMO, High Energy Physics, Biophysics, Condensed Matter Physics, and Radiation/Medical Physics), a strong record of extramural funding, and excellent teaching ability. In addition, the candidate will have outstanding leadership and communication skills, commitment to innovative teaching, and a vision for curricular reform and organizational development. The Department of Physics is expected to grow in the next few years and the Department Head will oversee the recruitment of additional faculty. Salary will be commensurate with qualifications and experience. Currently, the OSU Physics department has 21 tenured and tenure-track faculty members and 8 faculty members at other ranks (lecturers and research faculty). The graduate program has approximately 45 graduate students (M.S. and Ph.D.) and our undergraduate program more than 50 majors. The department offers B.S. degrees in physics and applied physics, M.S. degrees in physics, medical physics, and photonics, and Ph.D. degrees in Physics and Photonics. The faculty members have nationally-funded research programs in areas mentioned above, and they strongly promote involvement of undergraduate students in their research. The Department hosts weekly colloquia and research seminars in different areas, and annual workshops for high school teachers. The Department is known for its collegial and vibrant atmosphere, carrying out informal events supplementing its intellectual life. Qualified applicants should submit a letter of application, statement of research, teaching, and administrative philosophies, a curriculum vitae, and the names and contact information of 4 references who can comment on the applicant's teaching, research, leadership, and administrative skills to: **Dr. Tyrrell Conway, Chair, Department Head Search Committee, Department of Physics, 145 Physical Sciences Bldg., Oklahoma State University, Stillwater, OK 74078-3020.** E-mail: susan.cantrell@okstate.edu. Application materials can also be submitted through AcademicJobsOnline at http://academicjobsonline.org. Application review will begin **31 October, 2016** and will continue until the position is filled. The starting date is expected to be July 1, 2017, but is negotiable. This position is contingent upon available funding. For further information about the position please visit http://physics.okstate.edu. *OSU is an AA/EEO/E-verify employer committed to diversity. Women and underrepresented minorities are encouraged to apply. All qualified applicants will receive consideration for employment and will not be discriminated against based on race, color, religion, sex, ethnic and national origin, physical ability, or protected veteran status. OSU-Stillwater is a tobacco-free campus.*

Assistant Professor of Physics

The **Department of Physics** at **The University of Wisconsin-Whitewater** (https://www.uww.edu/cls/departments/physics) invites applications for a full time tenure-track Assistant Professor position in computational physics to begin Fall 2017. A Ph.D. in physics or closely related field with a demonstrated record of experience in computational physics is required; post-doctoral experience is desirable. ABD will be accepted if Ph.D. is expected by the start date. The successful candidate must have demonstrated excellence in teaching undergraduate physics and the ability to incorporate computational techniques into physics courses. The candidate is expected to acquire external funds and include undergraduate students in their research. The required elements for a complete application are described with the Job ID given below. Applicants should arrange for three letters of recommendation to be sent to physicssearch@uww.edu by the deadline: **November 25, 2016**. One of the letters must address the computational expertise of the candidate. *The University of Wisconsin-Whitewater is an Equal Opportunity and Affirmative Action Employer, and actively encourages applications from women, people of color, persons with disabilities, and all veterans.* For full position description and to apply, please visit www.uww.edu. Click on the Employment link located at the bottom of the page; then click on the UW-Whitewater Careers link at the top of the next page. The Job ID is **12248**.

THE OHIO STATE UNIVERSITY

Tenure-track Assistant Professor
Experimental Atomic, Molecular and Optical Physics

The Department of Physics in the College of Arts and Sciences at The Ohio State University seeks applications to fill a tenure-track assistant professor appointment effective Autumn Semester 2017. We seek candidates who will develop a world-class research program in experimental atomic, molecular and optical physics, broadly defined, and who will also be committed to teaching. . We are particularly interested in candidates who will complement existing strengths in ultrafast laser physics, attophysics, laser-driven plasma physics, theoretical ultra-cold atom physics, and quantum information. The department also has a several faculty using lasers in biophysics, chemical physics and condensed matter physics. The successful applicant will have the opportunity to join a newly formed interdisciplinary graduate program in Applied and Chemical Physics involving physics, chemistry and engineering.

Qualifications:

Applicants should have a Ph.D. and an outstanding post-graduate research record. A commitment to excellence in teaching at both the undergraduate and graduate levels is essential. Appointment is contingent on the university's verification of credentials and other information required by law and/or university policies, including but not limited to a criminal background check.

Application Instructions:

Apply to Academic Jobs Online at:https://academicjobsonline.org/ajo/jobs/7897. A complete application consists of a cover letter including a list of publications, curriculum vitae, description of research plans and teaching statements, and four letters of reference. Applications received prior to **December 11, 2016** will receive priority consideration. Inquiries may be directed to **Prof. Louis DiMauro** at dimauro.6@osu.edu.

The Ohio State University is committed to establishing a culturally and intellectually diverse environment, encouraging all members of our learning community to reach their full potential. We are responsive to dual-career families and strongly promote work-life balance to support our community members through a suite of institutionalized policies. We are an NSF Advance Institution and a member of the Ohio/Western Pennsylvania/West Virginia Higher Education Recruitment Consortium (HERC). The Ohio State University is an equal opportunity employer. All qualified applicants will receive consideration for employment without regard to race, color, religion, sex, sexual orientation or identity, national origin, disability status, or protected veteran status.

Tenure-Track Faculty Position in Experimental Nanoscale Science
Department of Physics, Virginia Tech

The College of Science at Virginia Tech and the Academy of Integrated Science, through its Division of Nanoscience (http://www.science.vt.edu/ais/nano), are placing strong emphasis on research in nanoscale science, quantum phenomena, complex materials, and energy through interdisciplinary faculty hires across departments. As part of this initiative, the Department of Physics (http://www.phys.vt.edu) is recruiting an experimentalist working on nanoscale science for a tenure-track faculty position, to start in fall of 2017. Appointment at the assistant professor level is anticipated but exceptional senior candidates will be considered. Current departmental strengths in condensed matter physics include molecular/organic electronics, quantum optics and transport, quantum information science, strongly correlated systems, computational materials science, and statistical and biological physics. Preference will be given to experimentalists who can expand our existing condensed matter efforts in nanoscale physics. Applicants must have a Ph.D. in physics or a closely related field and postdoctoral experience. Successful candidates will be expected to establish vigorous research programs and teach effectively at the undergraduate and graduate levels and work closely with the existing nanoscience degree program. Further information can be found at http://www.phys.vt.edu, and questions regarding the position can be directed by email to: search-nano@vt.edu. Applications must be submitted online at http://listings.jobs.vt.edu/postings/69181 and should include a cover letter, curriculum vitae, a research plan (3-5 pages), a statement of teaching philosophy that describes an integrated vision for nanoscience education, and contact information for at least three references (five for senior candidates). The references will be notified by email to upload their letters using the online system. Review of applications will begin on December 1, 2016 and continue until the position is filled; to ensure full consideration, complete application packages and reference letters should be received by **December 1, 2016**. *Virginia Tech is an EO/AA institution, and offers a wide range of networking and development opportunities to women and minorities in science and engineering. Virginia Tech is a recipient of the National Science Foundation ADVANCE Institutional Transformation Award to increase the participation of women in academic science and engineering careers* (www.advance.vt.edu). Individuals with disabilities desiring accommodations in the application process should please notify **Ms. Jacqueline Woodyard, Department of Physics, (540) 231-7566**, or call **TTY 1-800-828-1120** prior to the application deadline.

Position in Experimental Physics of Quantum Materials
and/or Quantum Devices

École Polytechnique considers hiring an outstanding scientist in the field of Experimental Physics of Quantum Materials and/or Quantum Devices, broadly defined. The successful candidate will join the Physics Department and create an independent research program in one of the nine physics research laboratories established on campus. The position will be at the tenured Associate Professor or Full Professor level, depending on seniority. Generous startup funds will be provided, as well as laboratory and office space.Applicants should submit a cv, a publication list with a brief comment about each of the five most significant ones, and a statement of research and teaching interests including a vision about the projects to be developed on campus. They should provide the names of three references. Applications (preferably a single pdf file) should be sent to: secretariat-depphys@polytechnique.fr by **December 1st 2016**. École Polytechnique is a leading higher education and research institution in France within the recently created Université Paris-Saclay. A number of research institutions and facilities related to the field of this opening are located in its immediate vicinity.

Post-Doctoral Position in Theoretical Condensed Matter Physics
National High Magnetic Field Laboratory at Florida State University

The National High Magnetic Field Laboratory (NHMFL) at Florida State University has an opening for a post-doctoral position in Condensed Matter Theory, beginning September 1, 2017. The successful candidate will have opportunities to collaborate with all faculty members of the theory group, including N. Bonesteel, V. Dobrosavljevic, L. Gor'kov, E. Manousakis, O. Vafek, and K. Yang. Current areas of active research within the group include (but are not limited to): Quantum Hall Effect, Graphene and Topological Insulators, Topological Quantum Computation, Unconventional Superconductivity, Quantum Criticality,Theory of Metal-Insulator Transitions, Complex Behavior of Correlated Electrons, Many-body Physics in Cold Atom Systems. More detailed information about the NHMFL Condensed Matter Science program can be found at: http://cms.magnet.fsu.edu. This position will remain available until filled. Applicants should provide a Curriculum Vita that includes a list of publications, a statement of research interest, and have at least three reference letters provided separately. The application materials should be submitted in electronic (PDF) format through email, to **Mr. Arshad Javed**, Coordinator Research Program Services at ajaved@magnet.fsu.edu. Inquiries should be addressed to **Prof. Oskar Vafek** at vafek@magnet.fsu.edu. Screening of application will start as they arrive, so early applications are encouraged. Criminal Background Check - This position requires successful completion of a criminal history background check. Tobacco Free Campus - Effective January 1, 2014, tobacco use, including simulated tobacco use, is prohibited on property, interior and exterior owned or managed by Florida State University. This policy applies to all Florida State University students, employees, consultants, contractors, visitors, and external individuals. *Equal Employment Opportunity - An Equal Opportunity/Access/Affirmative Action/Pro Disabled & Veteran Employer.* FSU's Equal Opportunity Statement can be viewed at: http://www.hr.fsu.edu/PDF/Publications/diversity/EEO_Statement.pdf.

Faculty Opening
Georgia Institute of Technology

The School of Materials Science and Engineering (MSE) at the Georgia Institute of Technology (GT) seeks to add tenure-track faculty who have an established record of nationally and internationally recognized excellence in research and leadership. Outstanding candidates with demonstrated expertise in materials science and engineering featuring some combination of synthesis, processing, theory, computations, data analytics, and/or high-throughput experimentation are sought. Exceptional candidates may also be considered for the College of Engineering interdisciplinary hire in Data-enabled Design and Manufacturing. These positions are designed to enhance the broad research portfolio of MSE at Georgia Tech that spans all forms and classes of materials. Qualified candidates must possess a Ph.D. in Materials Science and Engineering or a closely related discipline. Successful candidates will be expected to provide leadership in research programs that cut across several academic programs. The ideal candidate will champion independent and collaborative research at the cutting edge of his/her field and be able to attract external funding to build strong sponsored-research activities. The top candidate will also be expected to successfully mentor graduate students, and develop and teach fundamental courses at the undergraduate and graduate levels in materials science and engineering. Interested applicants must submit an online application, which includes a cover letter, curriculum vitae, statements of research interest and teaching philosophy, and the names (and contact information) of at least five references, at: http://www.mse.gatech.edu/content/faculty?positions. Applicants are strongly encouraged to submit their completed application package by **December 2, 2016** to ensure full consideration. The selection process will include passing a pre-employment background screening. *The Georgia Institute of Technology is an Affirmative Action/Equal Opportunity Employer.*

STANFORD UNIVERSITY
Postdoctoral Research Scholar

The Department of Applied Physics invites applications for the 2017 Karel Urbanek Postdoctoral Fellowship. We seek early-career scientists of exceptional ability with the potential to do outstanding research in our department. The initial appointment includes 2 years of support with an annual salary of $67,000, benefits, and $5,000 to cover research expenses. Applications and supporting credentials must be submitted through:

https://academicjobsonline.org/ajo/jobs/7862

Candidates should upload their curriculum vitae, publication list, and two-page essay detailing proposed research with faculty collaborator(s). Applicants are encouraged to discuss their proposed research plan with potential faculty collaborator(s) in preparing their application. They should arrange to have three letters of reference submitted online. For queries, please contact the **Department Manager, Paula Perron** (pperron@stanford.edu). Review of applications will begin immediately and continue until the position is filled, but candidates are strongly encouraged to submit applications by **December 15, 2016**. Appointments are expected to begin during the period June - October 2017. *Stanford University is an affirmative action and equal opportunity employer, committed to increasing the diversity of its workforce. It welcomes applications from women, members of minority groups, veterans, persons with disabilities, and others who would bring additional dimensions to the University's research and teaching mission. International applications are welcome.*

Assistant Professor of Physics

The Physics Department at **California State University – East Bay**, invites applications for a full-time tenure-track position beginning September 2017. Faculty teach a full range of undergraduate physics courses for both majors and non-majors. Candidates must have a Ph.D. in Physics, a strong commitment to teaching and have a clear plan for an active research program involving undergraduate physics majors. Candidates working in astrophysics are especially encouraged to apply, although all areas of specialization will be considered. The successful candidate is also encouraged to support the university's STEM education efforts. Review of applications will begin **November 1, 2016**, and the position will remain open until filled. Please apply and submit a cover letter, a curriculum vitae, a brief statement of teaching philosophy and a description of research plans by selecting the Physics job opening at the following link: www.csueastbay.edu/oaa/jobs/csuebtt.html. *East Bay is an Equal Opportunity Employer.* **Position # 17-18 PHYS-ASTRO-TT (position #00001021).**

THE UNIVERSITY of TENNESSEE KNOXVILLE

ASSISTANT PROFESSOR POSITION IN THEORETICAL BIOPHYSICS

The Department of Physics and Astronomy at the University of Tennessee (UT) invites applications for a tenure-track faculty position at the rank of Assistant Professor in the field of Theoretical Biophysics. Candidates should have a PhD in Physics or another field closely related to Physics. The candidate is expected to have a strong research record in Theoretical Biophysics and is expected to develop a first-class, externally funded research program, to provide training for graduate students and postdoctoral researchers, and to contribute to the teaching mission of the department at both the undergraduate and graduate levels. The preferred expertise of the candidate should be in the broad area of Soft Matter Physics applied to living systems, including but not limited to non-equilibrium statistical mechanics, cellular biomechanics, multi-scale molecular dynamics and Monte Carlo simulations, and polymer physics. A strong interest in interacting with ongoing programs at UT, such as computational physics and theoretical condensed matter physics research, is highly desirable. The appointment is expected to begin August 1, 2017. The University of Tennessee, Knoxville, is Tennessee's flagship State research institution, a campus of choice for outstanding undergraduates, and a premier graduate institution. The successful candidate will benefit greatly from available computational resources, the location on campus of the National Institute for Mathematical and Biological Synthesis (NIMBioS), and by the proximity to unique research facilities at Oak Ridge National Laboratory, including the Joint Institutes for Computational Sciences, Biological Sciences, Advanced Materials, and Neutron Sciences. The campus is located in one of the most beautiful areas of the country with easy access to miles of inland waterways, pristine state and national parks, diverse cultural opportunities, and a blend of convenient urban and rural living settings. Downtown Knoxville, adjacent to campus, is a thriving neighborhood filled with restaurants, shops, and indoor and outdoor entertainment venues, and is home to the Knoxville Symphony and Knoxville Opera, as well as to the annual Big Ears Music Festival, Jazz on the Square, Shakespeare on the Square, and other events. *The University welcomes and honors people of all races, creeds, cultures, and sexual orientations, and values intellectual curiosity, pursuit of knowledge, and academic freedom and integrity. The Knoxville campus of the University of Tennessee is seeking candidates who have the ability to contribute in meaningful ways to the diversity and intercultural goals of the University.* Applicants should send a CV, list of publications, a description of research and teaching experience, a proposed research program, and also arrange for at least three letters of reference to be submitted separately. All application materials should be submitted on-line at https://apply.interfolio.com/36843. Only electronic applications will be considered and acceptable file formats are .pdf or .docx. To guarantee consideration please submit all materials by **December 1, 2016**.

ASSISTANT PROFESSOR POSITION IN EXPERIMENTAL LOW ENERGY NUCLEAR PHYSICS

The Department of Physics and Astronomy at the University of Tennessee Knoxville invites applications for a tenure-track faculty position at the rank of Assistant Professor in the field of Experimental Low Energy Nuclear Physics (LENP). The successful applicant will have a PhD in Physics or related field, several years of post-PhD experience, and a strong research record in Experimental LENP as evidenced by a publication record. The candidate is expected to define a vital program in nuclear structure, reactions, and/or nuclear astrophysics that will attract independent external research funding and provide state-of-the-art training for graduate students and postdoctoral researchers. The successful candidate will contribute to the teaching mission of the department at both the undergraduate and graduate levels. The experimental LENP group at the University of Tennessee, Knoxville (UTK) leads experiments at user facilities in the US, and worldwide, using decay and low-energy nuclear reaction techniques to study the structure of the atomic nucleus and its interactions, particularly those relevant to element production through the astrophysical r- and rp-processes. This research is strongly aligned with the program of the Facility for Rare Ion Beams (FRIB). Our group has led the development and construction of the Versatile Array for Neutron Detection at Low Energies (VANDLE) and the Hybrid Array for Gamma Ray Detection (HAGRiD) and is at the cutting-edge of developments with digital data acquisition used for decay and reaction studies. UTK is a key member of the Center of Excellence for Radioactive Ion Beam Studies for Stewardship Science, funded by the National Nuclear Security Agency, and maintains significant funding from the Department of Energy, Office of Science. UTK has an established partnership with Oak Ridge National Laboratory through the Joint Institute for Nuclear Physics and Applications. Our group collaborates closely with local theory groups at UTK and Oak Ridge National Laboratory (ORNL). The successful candidate is expected to strengthen the UTK LENP group program and will be encouraged to explore research opportunities at the future FRIB facility. The University of Tennessee, Knoxville, is Tennessee's flagship research institution, a campus of choice for outstanding undergraduates, and a premier graduate institution. It benefits greatly from close proximity to the unique research environment at ORNL. The campus is located in one of the most beautiful areas of the country with easy access to miles of inland waterways, pristine state and national parks, diverse cultural opportunities, and a unique blend of convenient urban and rural living settings. This appointment is expected to begin August 1, 2017. *The University welcomes and honors people of all races, creeds, cultures, and sexual orientations, and values intellectual curiosity, pursuit of knowledge, and academic freedom and integrity. The Knoxville campus of the University of Tennessee is seeking candidates who have the ability to contribute in meaningful ways to the diversity and intercultural goals of the University.* Applicants should send a cover letter, CV, list of publications, a description of teaching and research experience, and their proposed research program, and also arrange for at least three letters of reference to be submitted separately. All application materials should be submitted on-line at https://apply.interfolio.com/36687. Only electronic applications will be considered, and acceptable file formats are .pdf or .doc. Review of applications will begin on **November 15, 2016** and continue until the position is filled.

PHYSICS TODAY Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page PHYSICS TODAY

THE UNIVERSITY OF CHICAGO

INSTITUTE FOR MOLECULAR ENGINEERING (IME)

The Institute for Molecular Engineering (IME) is a unique interdisciplinary institute launched by the **University of Chicago** in 2011 with the aim of translating molecular-level science into technological solutions with potential societal impact in health care, energy, environmental sustainability and information technology. An independent unit within the university, IME is also affiliated with Argonne National Laboratory (ANL) and joint appointment is encouraged when appropriate. IME invites applications from outstanding candidates for the following tenure-track or tenured faculty and lecturer positions. Faculty candidates must have a doctoral degree in a relevant field of study and an outstanding research record. Successful faculty candidates will be expected to establish and maintain a strong research program and teach at the graduate and undergraduate levels. Applicants are required to upload a cover letter, curriculum vitae, a list of publications, and a statement of research interests. In addition, candidates are requested to provide the names and contact information for three references, who will be contacted separately for letters of recommendation.

Quantum Information Engineering

IME invites applications for tenure-track and tenured faculty positions at the ranks of Assistant Professor, Associate Professor and Professor in the area of Quantum Information Engineering. Areas of interest include, but are not limited to quantum coherent devices and systems, optics and nanophotonics, optomechanics, quantum measurement, quantum materials, quantum information and communication. The appointment will be at IME with positions available both in experiment and theory. To apply, please visit the University of Chicago's Academic Career Opportunities website, https://academiccareers.uchicago.edu/. The review of the applications will start on **October 15, 2016** and continue until the position is filled. To be considered for a position at the rank of Assistant Professor, please apply to Requisition **#03104**. To be considered for a position at the rank of Associate Professor, please apply to Requisition **#03105**. To be considered for a position at the rank of Professor, please apply to Requisition **#03106**.

Materials Synthesis and Engineering

IME invites applications for tenure-track and tenured faculty positions at the ranks of Assistant Professor, Associate Professor and Professor in the area of experimental materials synthesis and integration. Areas of interest include, but are not limited to, materials and systems for new computing approaches, quantum materials, sensing, energy conversion, additive materials and additive manufacturing, engineered low-dimensional materials with novel properties, and biologically inspired materials. The candidate will be expected to establish a strong independent research program and be interested in a multidisciplinary, system level approach to materials science and engineering. The IME also has close ties with Argonne National Laboratory (several faculty members have joint appointments) and the position will enable close interaction with Argonne scientists. While we will consider exceptional candidates from all fields of materials science, we seek in particular expertise in inorganic materials based approaches to the areas noted above. To apply, please visit the University of Chicago's Academic Career Opportunities website, https://academiccareers.uchicago.edu/. The review of the applications will start on **October 15, 2016** and continue until the position is filled. To be considered for a position at the rank of Assistant Professor, please apply to Requisition **#03110**. To be considered for a position at the rank of Associate Professor, please apply to Requisition **#03111**. To be considered for a position at the rank of Professor, please apply to Requisition **#03112**.

Lecturer – Experimental Quantum Laboratory

The University of Chicago's Institute for Molecular Engineering is seeking a creative, highly motivated laboratory instructor for its Experimental Quantum Laboratory. The successful applicant will lead an effort to design, assemble, and teach a set of advanced laboratories focused on experimental quantum science, in conjunction with related lecture classes. These laboratories will be taken by University of Chicago undergraduates enrolled in the IME's undergraduate B.S. program. Topics will include optics; microwave engineering; semiconductor devices; advanced instrumentation; and of labs covering fundamental quantum science experiments and including numerical modeling. The successful candidate will be able to design and construct compelling instructional experimental setups; generate clear and compelling teaching materials; work effectively with faculty, staff and students from a variety of diverse backgrounds; and plan and pursue expansion of the lab facilities. The initial appointment will be for one year, renewable pending satisfactory performance, with longer contract periods available in subsequent years. Minimum qualifications include a PhD in physics, electrical engineering, a related field, or in science education; experience with scientific instrumentation; evidence of strong communication skills. Applicants must submit a cover letter, curriculum vitae, names of three professional references to be contacted separately for letters and a 3-5 page writing sample describing three distinct quantum science experiments that could be taught as part of the lab. Each topic covered in the writing sample should include: details of the experimental setup; learning goals; measurements to be performed; how results will be reported.

To apply, please visit the University of Chicago's Academic Career Opportunities website, https//academiccareers.uchicago.edu/ and requisition **# 03097**. The review of the applications will start on **October 16, 2016** and continue until the position is filled.

The University of Chicago is an Affirmative Action/Equal Opportunity/Disabled/Veterans Employer and does not discriminate on the basis of race, color, religion, sex, sexual orientation, gender identity, national or ethnic origin, age, status as an individual with a disability, protected veteran status, genetic information, or other protected classes under the law. For additional information please see the University's Notice of Nondiscrimination at http://www.uchicago.edu/about/non_discrimination_statement/. *Job seekers in need of a reasonable accommodation to complete the application process should call* **773-702-5671** *or email* ACOppAdministrator@uchicago.edu *with their request.*

Physics Teaching Laboratory Manager
Department of Physics, University of Connecticut

The Department of Physics seeks qualified applicants for a manager of high-enrollment laboratory courses in physics and astronomy. The successful candidate will be responsible for all aspects of teaching lab management (lower and upper division. The successful applicant must interact positively with a large and diverse group of faculty, staff assistants, teaching assistants, undergraduate students, and University administrative personnel. Along with interested faculty, the lab manager is expected to seek federal grant funding for research related to undergraduate education and to assist faculty in the design and operations of the advanced physics teaching labs. For more details and to apply visit https://academicjobsonline.org/ajo/jobs/7637/ online. *EOE.*

Assistant Professor - Computational Materials Physics
Colorado State University

The Department of Physics at Colorado State University, located in Fort Collins, seeks to hire a tenure-track faculty member at the rank of Assistant Professor in computational materials physics. This will be a joint appointment with the School of Advanced Materials Discovery. Candidates must hold a Ph.D. or an equivalent degree in physics or a related field and have a documented potential for outstanding teaching, scholarship, and research. Postdoctoral and/or other relevant experience beyond the Ph.D. is expected. Complete applications must include a detailed CV, descriptions of research plans and teaching interests, and three letters of reference. Applications should be submitted online. For more information, including application instructions, see http://jobs.colostate.edu/postings/37121. Applications completed by **December 1, 2016** will receive full consideration, but applications will be accepted until the position is filled. *CSU is an EO/EA/AA employer and conducts background checks on all final candidates.*

Assistant / Associate Professor, Physics
(High Energy Density Physics (HEDP))
University of Nevada, Reno

The University of Nevada, Reno invites applications for a full-time tenure-track faculty position with the Department of Physics. The selected candidate may be hired at either the Assistant or Associate Professor level. The level is to be determined by the department and will be comparable to their experience, knowledge, skills and abilities. Candidates must have a Ph.D. in Physics or related field by the time of appointment and post-doctoral research experience. The duties of this position will include teaching physics at the graduate and undergraduate levels and establishing a vigorous research program in the area of theory, modeling and numerical simulation of high-energy density plasma physics. Synergy with research activities at the Nevada Terawatt Facility would be advantageous. Start-up funds will be provided. *The University of Nevada, Reno recognizes that diversity promotes excellence in education and research. We are an inclusive and engaged community and recognize the added value that students, faculty, and staff from different backgrounds bring to the educational experience* Applications will be accepted through **December 12, 2016**.For more information about the position, and to apply, please visit https://www.unrsearch.com/postings/21960. *EEO/AA. Women, under-represented groups, individuals with disabilities, and veterans are encouraged to apply.*

UNIVERSITY OF TORONTO
DEPARTMENT OF PHYSICS
Faculty Position in Theoretical High Energy Physics

The Department of Physics at the University of Toronto invites applications for a tenure-stream appointment at the rank of Assistant Professor in the area of Theoretical High Energy Physics. This appointment will begin on July 1, 2017. We seek candidates with a Ph.D. in Physics, and with evidence of excellence in both research and teaching. Outstanding candidates in any field of theoretical particle physics and string theory are encouraged to apply. Evidence of excellence in teaching is demonstrated through teaching accomplishments, letters of reference and teaching materials submitted with the application. Excellence in research is demonstrated by publications in top-ranked and field-relevant academic journals, presentations at major conferences, awards and accolades, and strong endorsements by referees of high international standing. The successful candidate will have the opportunity to interact with existing groups in theoretical and experimental high energy physics at the University of Toronto as well as with researchers in related fields in the Department of Physics, the Department of Mathematics and the Canadian Institute for Theoretical Astrophysics. For more information about the Department of Physics, please visit us at http://www.physics.utoronto.ca/. Information about the theoretical and experimental high energy research in the Department of Physics can be found at:

http://www.physics.utoronto.ca/research/theoretical-high-energy-physics/, and
http://www.physics.utoronto.ca/research/experimental-particle-physics.

Salary will be commensurate with qualifications and experience. All qualified candidates are invited to apply by clicking on the following link:

https://academicjobsonline.org/ajo/jobs/7764.

Applications should include a cover letter, curriculum vitae including a list of publications, a teaching statement describing teaching philosophy and experience, and a statement of research interests. Applicants should also ask three referees to send letters (on letterhead and signed) directly to the department via e-mail to academicjobsonline@physics.utoronto.ca by the closing date. The closing date for applications is **November 15, 2016**. If you have questions about this position, please contact chairsec@physics.utoronto.ca.

The University of Toronto is strongly committed to diversity within its community and especially welcomes applications from racialized persons / persons of colour, women, Indigenous / Aboriginal People of North America, persons with disabilities, LGBTQ persons, and others who may contribute to the further diversification of ideas. As part of your application, you will be asked to complete a brief Diversity Survey. This survey is voluntary. Any information directly related to you is confidential and cannot be accessed by search committees or human resources staff. Results will be aggregated for institutional planning purposes. For more information, please see http://uoft.me/UP. *All qualified candidates are encouraged to apply; however, Canadians and permanent residents will be given priority.*

TENURE-TRACK ASSISTANT PROFESSOR IN THEORETICAL AND COMPUTATIONAL PLASMA PHYSICS
Department of Physics and Astronomy, Dartmouth College

Applications are invited for a faculty position in Theoretical and Computational Plasma Physics, with a preferred starting date of Fall 2017. Consideration will be given to applicants at the assistant professor level, as well as to more senior exceptionally qualified candidates for appointment at higher ranks. We are interested in a broad spectrum of computational plasma physics areas, including fundamental plasma physics, geospace, solar, heliospheric and astrophysical plasma physics, plasma fusion, and plasma device modeling. Candidates are sought who combine an outstanding research record with a strong commitment to undergraduate and graduate teaching and mentoring. The successful candidate is expected to complement and expand existing theoretical and experimental efforts; in particular the ideal candidate will have research interests that overlap with both space and laboratory plasmas and demonstrate an exceptional computational and theoretical background. Please visit http://www.physics.dartmouth.edu for additional information. A Ph.D. in Physics is expected. Application material (including: cover letter; current CV with publication record; statement of research interests and plans; statement of teaching interests; complete contact information of at least three professional references) should be submitted electronically to http://apply.interfolio.com/37045. Application review will begin on **January 4, 2017**, and continue until the position is filled. *Dartmouth College is an equal opportunity/affirmative action employer with a strong commitment to diversity and inclusion. We prohibit discrimination on the basis of race, color, religion, sex, age, national origin, sexual orientation, gender identity or expression, disability, veteran status, marital status, or any other legally protected status. Applications by members of all underrepresented groups are encouraged.*

THE UNIVERSITY OF KANSAS
J.D. STRANATHAN ASSISTANT PROFESSOR
in Experimental High-Energy Physics

The Department of Physics and Astronomy at the University of Kansas (KU) seeks outstanding applicants for the J.D. Stranathan Assistant Professorship in Experimental Physics (tenure track position) in the area of high-energy physics (HEP) to begin as early as August 18, 2017. The primary focus of the KU HEP group presently is on the Compact Muon Solenoid (CMS) experiment at CERN's Large Hadron Collider (LHC) where they have significant responsibilities with the detector development, software and computing, in addition to a strong participation in a variety of physics analyses. The group also is working to develop future detectors and is very active in various outreach projects. The qualifying candidates must have a Ph.D. in Physics or a closely related field and relevant postdoctoral experience. A strong record of research and commitment to excellence in teaching are required. Candidates with research interests compatible with the existing experimental high-energy program are particularly encouraged to apply. The University of Kansas is especially interested in hiring faculty members who can contribute to the climate of diversity in the College of Liberal Arts and Sciences and to four key campus-wide strategic initiatives: (1) Sustaining the Planet, Powering the World; (2) Promoting Well-Being, Finding Cures; (3) Building Communities, Expanding Opportunities; and (4) Harnessing Information, Multiplying Knowledge. For more information, see http://www.provost.ku.edu/strategic-plan/initiatives. For a complete announcement and to apply online, go to: https://employment.ku.edu/academic/7120BR. A complete online application includes the following materials: cover letter, curriculum vitae, a research statement, a teaching statement, and three professional letters of reference. The letters of reference should be sent from the referees directly to kuhepexprof@ku.edu. For additional information about the position, please contact: **Professor Alice Bean, Search Committee Chair, Department of Physics & Astronomy, University of Kansas,** kuhepexprof@ku.edu. Initial review of applications will begin **October 31, 2016** and will continue as long as needed to identify a qualified pool. *KU is an EO/AAE, full policy* http://policy.ku.edu/IOA/nondiscrimination.

Assistant Professor Experimental High-energy physics
Colorado State University

The Department of Physics, Colorado State University, seeks to hire a tenure-track faculty member at the rank of Assistant Professor in experimental high-energy physics. Exceptional candidates from all areas of high-energy physics are encouraged to apply. Candidates must hold a Ph.D. in physics or an equivalent degree and have a documented potential for truly outstanding teaching, scholarship, and research. Postdoctoral and/or other substantial experience beyond the Ph.D. is expected. Complete applications must include a detailed CV, descriptions of research plans and teaching interests, and at least three letters of reference. Applications should be submitted online. To apply, please see http://jobs.colostate.edu/postings/36937. Applications completed by **November 15, 2016** will receive full consideration, but applications will be accepted until the position is filled. *Colorado State University is an EO/EA/AA employer and will conduct background checks on all final candidates.*

The Department of Physics at **Georgia Southern University** invites applications for a **tenure-track assistant professor** in **Experimental or Theoretical Physics**. The position requires teaching, research, and service responsibilities as well as a terminal degree. Applicants should submit a cover letter (including the names, addresses, telephone numbers, and e-mail addresses of at least three professional references), a curriculum vitae (including a list of publications), a statement of teaching philosophy, and a description of current and future research, to: **Dr Xiaojun Wang, Search Chair, Search # 67401, Department of Physics, Georgia Southern University, P. O. Box 8031, Statesboro, GA 30460-8031 Electronic mail:** aklingel@georgiasouthern.edu, **Telephone: 912-478-5292.** Screening of applications begins **November 1, 2016**, and continues until the position is filled. The preferred position starting date is August 1, 2017. Only complete applications and applications submitted electronically will be considered. Finalists will be required to submit to a background investigation. The full text advertisement, including information about the department, faculty, and the complete position announcement with all qualifications and application instructions, is available at http://cosm.georgiasouthern.edu/physics/employment-opportunities/. *Georgia is an open records state. Georgia Southern is an AA/EO institution. Individuals who need reasonable accommodations under the ADA to participate in the search process should contact the Associate Provost.*

LEHIGH UNIVERSITY

Assistant Professor of Physics
Lehigh University

The Department of Physics at Lehigh University invites applications for a tenure track position at the Assistant Professor level beginning in August 2017. We are seeking a theorist, computational physicist, or experimentalist working on Atomic and Molecular Physics, Cosmology, Plasma Physics, or Quantum Computing/Information. Successful candidates will have a PhD or equivalent and a strong interest in an academic career combining research and teaching Physics at both the undergraduate and graduate levels. The department has strong research programs in Astrophysics, Biophysics, Condensed Matter and Nanophysics, High Energy and Nuclear Physics, Nonlinear Optics and Photonics, Plasma Physics, Statistical Physics, and String Theory. The current search is part of an effort to broaden the department's research portfolio. In addition to interactions within the Physics Department, many opportunities exist for interdisciplinary collaborations, for example in Computer Science and Engineering, Biological Sciences, Bioengineering, Chemistry, Materials Science, Chemical Engineering, and Mechanical Engineering. Located in Pennsylvania's scenic Lehigh Valley, the campus is situated on 1,600 acres in close proximity to both New York City and Philadelphia. Lehigh is a premier residential research university, ranked in the top tier of national research universities each year. Lehigh University is a coeducational, nondenominational, private university that offers a distinct academic environment of undergraduate and graduate students from across the globe. Lehigh University and the Physics Department have a strong commitment to our growing population of culturally diverse students. Therefore, we seek candidates who will successfully serve as mentors and role models for students belonging to groups that are currently underrepresented in STEM. Lehigh provides a wide range of networking, mentoring and development opportunities for early-career faculty, and is a leader in promoting work-life balance (see http://www.lehigh.edu/~inprv/faculty/worklifebalance.html). Lehigh is a recipient of the 2006 Alfred P. Sloan Award for Faculty Career Flexibility and a 2010 National Science Foundation ADVANCE Institutional Transformation Award to increase the advancement of women faculty in science, engineering, and math (see http://advance.cc.lehigh.edu). Lehigh offers excellent benefits, including domestic-partner benefits, and is a founding member of the Lehigh Valley Inter-Regional Networking & Connecting Consortium to assist highly qualified couples who face the dual career challenge. Applicants should include a cover letter describing their area of expertise and major contributions, curriculum vitae, publication list, the names and affiliations of three references, a statement of research interests, and a statement of teaching interests. All materials should be uploaded to the website https://academicjobsonline.org/ajo/jobs/7733 and must be received by **Dec. 1, 2016**. *Lehigh University is an affirmative action/equal opportunity employer.*

Faculty Positions in Biophysics
Department of Biological Sciences and Physics Department
College of Sciences and Mathematics
Auburn University

Biophysics is a new research emphasis within the College of Sciences and Mathematics and is part of a developing partnership between Biological Sciences and Physics. We are inviting applications for two tenure track faculty positions starting in Fall, 2017. The **Department of Biological Sciences** at Auburn University invites applications for the hire of a tenure-track faculty position (9-month) at the level of Assistant Professor. The successful applicant should have research focused on biological areas that significantly contribute to strengths within one of the existing core research programs in the department (http://goo.gl/VBmHo3). We are specifically interested in hiring individuals who study biophysical interactions from the cellular/molecular to organismal level. The successful applicant must establish an extramurally funded, nationally recognized research program. Instructional responsibilities include development of graduate and/or undergraduate course in biological-oriented biophysics or cell & molecular biology. Applicants must have a Ph.D. in life science or a related discipline. Qualifications include significant postdoctoral or professional experience, a strong record of publication and potential for funding. The Physics Department at Auburn University is seeking a highly qualified individual for a tenure-track faculty position in the area of biophysics; candidates at all faculty ranks (i.e., Assistant, Associate and full Professor) will be considered. Applications from both experimental and theoretical/computational physicists are encouraged. Research subspecialties within biophysics that are of interest include (but are not restricted to) soft matter and biological materials, statistical physics of living systems, complexity in biological systems, modeling of cellular processes from molecular to intracellular processes, and the interface between biological and physical systems. Post-doctoral research experience is highly desirable. The successful candidate will be expected to: (1) demonstrate strong leadership potential in the area of biophysics, (2) establish a new research group in the area of biophysics at Auburn University, (3) provide direction to undergraduate, graduate students and postdoctoral researchers in biophysics, and (4) conduct excellent instruction at the undergraduate and graduate level in the Physics curriculum. Applicants must possess a Ph.D. or equivalent degree in Physics or a related field.

Applicants to the position in the **Department of Biological Sciences** must apply online at: http://aufacultypositions.peopleadmin.com/postings/1878.

Applicants to the position in the **Department of Physics** must apply online at: http://aufacultypositions.peopleadmin.com/postings/1872.

Candidates need to include in their application a cover letter, curriculum vitae, statement of teaching philosophy, statement of research and the names and contact information for three professional references. More information on these positions can be found at: http://www.auburn.edu/biology and http://www.physics.auburn.edu

Review of applications for both positions will begin **December 1, 2016** and will continue until the positions are filled. The desired starting date is August 16, 2017. Candidates selected for these positions must be able to meet eligibility requirements to work in the United States at the time the appointment is scheduled to begin and continue working legally for the proposed term of employment. Excellent written and interpersonal communication skills are required. *Auburn University is an EEO/Vet/Disability Employer.*

Tenure Track Position in Experimental Hadronic Nuclear Physics
Florida State University

The Florida State University Physics Department is seeking applicants for a tenure track Assistant Professor in nuclear physics to enhance our experimental hadronic physics program at Jefferson Lab. The successful applicant is expected to establish an internationally recognized research program that complements and enhances the existing efforts within the GlueX program. The starting date for this position is the beginning of the Fall semester of 2017. Applicants should send a letter of interest, a curriculum vitae, and a research plan, as well as arrange for three to six letters of recommendation to be sent to: hadronsearch@hadron.physics.fsu.edu. Review of applications will start **November 23, 2016** and continue until the position is filled. More information is available at http://physics.fsu.edu/. *Florida State University is an Equal Opportunity/Affirmative Action Employer, and it especially encourages applications from women and members of minority groups.*

Faculty Position in Nuclear Physics at
Rutgers, the State University of New Jersey

The Department of Physics and Astronomy at Rutgers, The State University of New Jersey, invites applicants for a tenure track Assistant Professor position in experimental, theoretical or computational Nuclear Physics. For an exceptional candidate, appointment at a more senior level may be considered. Applicant must have a Ph.D. degree and an outstanding record of research and publication, preferably related to current research areas in the department, including QCD studies (relativistic heavy ions, structure of hadrons, neutrino scattering, and QCD and nuclei) and nuclear structure, reactions and astrophysics. The successful candidate will be expected to establish an independent research program that will attract external funding, and should be strongly committed to teaching. A start date on or after 1 September 2017 is anticipated. Applicants should apply online via Interfolio at http://apply.interfolio.com/36532, providing a cover letter, a CV including list of publications, a statement of research plans, and a teaching statement, and should also arrange for three letters of recommendation to be requested and uploaded via Interfolio. For full consideration, applications should be received by **15 November 2016**. *All qualified applicants will receive consideration for employment without regard to race, color, religion, sex, sexual orientation, gender identity or expression, national origin, disability, protected veteran status or any other classification protected by law.*

Postdoctoral Scholars

The Kavli Institute for Theoretical Physics at the **University of California, Santa Barbara** expects to appoint Postdoctoral Scholars in theoretical physics, beginning September 1, 2017. Postdoctoral Scholar appointments are intended to provide a full-time training program of advanced academic preparation and research training under the mentorship of a faculty member. Minimum requirements: Completion of Ph.D. degree by the start date. Additional requirements: Outstanding research in theoretical physics appropriate to level of position, ability to identify and pursue research problems independently while working well in an interactive and dynamic setting. The initial appointment will be for two-years, with the possibility of renewal for a third year, contingent on continued funding and a reasonable level of research performance.

A detailed list of the KITP programs for 2017/2018 is available at:
https://www.kitp.ucsb.edu/programs

Applications for postdoctoral positions should be made electronically via the Academic Jobs Online website: https://academicjobsonline.org/ajo/jobs/7790

The application must consist of a curriculum vita, publication list, statement of research interests, and three letters of reference. Apply by **November 15, 2016** for primary consideration. Later applications will be considered only as long as openings exist. *The department is especially interested in candidates who can contribute to the diversity and excellence of the academic community through research, teaching and service.*

The University of California is an Equal Opportunity/Affirmative Action Employer and all qualified applicants will receive consideration for employment without regard to race, color, religion, sex, sexual orientation, gender identity, national origin, disability status, protected veteran status, or any other characteristic protected by law.

ASSOC/ASST PROFESSOR IN BIOPHYSICS/SOFT CONDENSED MATTER PHYSICS
UNIVERSITY OF SOUTH FLORIDA

The Department of Physics at the University of South Florida, Tampa, seeks to fill a 9-month, full-time, tenure-earning position in biophysics/soft condensed matter physics at the associate or assistant-professor level. All areas of biophysics / soft condensed matter will be considered with preference given to candidates who extend existing strengths in this area. The Physics Department has strong research programs in experimental/theoretical biophysics, condensed matter, and optics. USF also offers excellent opportunities to interact with research programs in the College of Arts and Sciences, Engineering, and Medicine, including the Moffitt Cancer Center. The National Science Foundation (NSF) ranked USF at No. 25 among public research universities for research spending. Applicants must have a doctorate in Physics or a closely related field. Applicants at the Assistant Professor level must have relevant postdoctoral experience. All candidates are expected to demonstrate a record of independent extramural funding. Salary will be commensurate with qualifications and experience. The successful candidate will establish a nationally recognized research program, teach effectively at the undergraduate and graduate level, and mentor student research at all levels. To apply, please visit http://employment.usf.edu (Position # 29548) and attach a cover letter, curriculum vita with publication record, a statement of teaching philosophy (1 page), and a research plan (2-3 pages). In addition, applicants should have three letters of recommendation sent to physearch@usf.edu. All applications completed by **November 15th, 2016** will be given full consideration, although the search will continue until the position is filled. Questions regarding this search should be directed to **Prof. Lilia Woods, Chair, Search Committee at** physearch@usf.edu. According to Florida Law, applications and meetings regarding them are open to the public. *USF is an Equal Opportunity/Equal Access Institution. For disability accommodations, contact Daisy Matos at* dmatos@usf.edu (**813-974-8415**), *a minimum of five working days in advance.*

Tenure-Track Faculty Position in Theoretical and/or Experimental Soft Matter and Biological Physics
Department of Physics, Virginia Tech

The Department of Physics at Virginia Tech invites applications for a tenure-track faculty position in the areas of experimental and/or theoretical Soft Matter and/or Biological Physics. Appointment at the Assistant Professor level is anticipated but exceptional senior candidates will also be considered. We especially encourage candidates to apply who complement, extend, or charter new directions to the department's existing strengths in complex biological systems and processes, synthetic biology, statistical and polymer physics, characterization and self-assembly of soft materials, advanced optics, and terahertz spectroscopy. Our recently chartered Center for Soft Matter and Biological Physics (www.phys.vt.edu/CSMBP) provides broad opportunities for interdisciplinary collaborations within Virginia Tech's colleges and institutes. Applicants must hold a Ph.D. or equivalent in physics or a closely related field, and have postdoctoral experience at the time of appointment. The successful candidates will be expected to establish a vigorous and externally well-funded research program; teach effectively at the undergraduate and graduate levels; continue development of scholarly activities and professional capabilities; occasionally travel, for example, to attend professional conferences and present research seminars; and actively participate in department, college, and university governance. Further information can be found at http://www.phys.vt.edu, and questions regarding the position may be directed to the chair of the Search Committee, **Uwe C. Täuber**, at smb_search@phys.vt.edu, phone: **(540) 231-8998**. Candidates should apply at http://listings.jobs.vt.edu/postings/69219. The application package must include a cover letter, curriculum vitae with publication list, a statement of ongoing and planned research, a brief description of teaching philosophy, and contact information for at least three references (five for senior candidates). The references will be notified via email to upload their recommendation letters through our online system. Review of applications will begin on **December 1, 2016**, and will continue until the position is filled; to ensure full consideration, complete application packages and reference letters should be received by **December 1, 2016**. The expected position starting date is August 10, 2017. *Virginia Tech is an EO / AA institution, and offers a wide range of networking and development opportunities to women and minorities in science and engineering.* Virginia Tech is a recipient of the National Science Foundation ADVANCE Institutional Transformation Award to increase the participation of women in academic science and engineering careers (www.advance.vt.edu). Individuals with disabilities desiring accommodations in the application process should please notify **Ms. Jacqueline Woodyard, Department of Physics, (540) 231-7566**, or call **TTY 1-800-828-1120** prior to the application deadline.

EXPERIMENTAL FACULTY POSITION IN ULTRAFAST SCIENCES AND CONDENSED MATTER PHYSICS

The Department of Physics & Astronomy invites applications from outstanding candidates for a tenure-system Assistant Professor position at **Michigan State University** in the area of experimental ultrafast sciences. Topics of interest include, but are not limited to: physics of collective excitations and emergent quantum phenomena in solids, including low-dimensional systems such as 2D materials; electron and spin quantum dynamics and control; light-induced phase transitions, and non-perturbative light-matter coupling. In the area of experimental ultrafast sciences, we are looking for candidates with demonstrated excellence in applying and developing cutting-edge instrumentation to solve forefront scientific problems on ultrafast time scales. Emphasis will be given to candidates with a strong background in probing time-dependent electronic structures and properties, and those combining electronic spectroscopy with other complementary techniques. Suitable candidates may have a partial appointment in the Department of Chemistry. This position is listed on the MSU Applicant Page (https://jobs.msu.edu), postings **#2108**. Applications should be uploaded to MSU's online job application site, https://jobs.msu.edu, and should include (1) a cover letter, (2) CV, (3) statement of research plans, (4) a one-page teaching statement, all included in a SINGLE PDF file, and have ready the names and email addresses of three references. The letters of recommendation should be submitted electronically by the recommenders through this application system. The selection process will begin on **December 5th, 2016,** and review of applications will continue until the position is filled. Questions regarding this position may be directed to: **Prof. Chong-Yu Ruan** (ruan@pa.msu.edu). *MSU is an affirmative-action, equal-opportunity employer and is committed to achieving excellence through diversity. The University actively encourages applications of women, persons of color, veterans, and persons with disabilities, and we endeavor to facilitate employment assistance to spouses or partners of candidates for faculty and academic staff positions.*

Assistant Professor
University of Colorado Denver

Faculty Position in Theoretical Condensed/Soft Matter Physics University of Colorado Denver The Department of Physics at the University of Colorado Denver (CU Denver) invites qualified candidates to apply for a tenure-track position at the level of Assistant Professor in areas of computational and/or theoretical physics that connect with ongoing interests of the department, including condensed mater/soft matter physics. The successful candidate will be expected to establish a sustainable research program, to include undergraduates in research projects, and to supervise independent student projects. The successful applicant will begin his/her appointment in the Fall Semester 2017. The Physics Department offers a B.S. degree in the College of Liberal Arts and Sciences and participates in the Master's program in Integrated Sciences. Applications must include a letter of introduction, a CV, research and teaching statements, and the names of three references to be contacted after consultation with the candidate. The full announcement and instructions for submitting applications can be found at https://www.cu.edu/cu-careers (under job posting number **06758**). Review of applications begins **December 1, 2016** and will continue until the position is filled. For more information, contact **Faculty Search Committee, Department of Physics, CB 157, University of Colorado Denver, PO Box 173364, Denver, CO, 80217-3364.** *CU Denver is dedicated to ensuring a safe and secure environment for our faculty, staff, and students. To achieve that goal, we conduct background investigations for all prospective employees. The University of Colorado is committed to diversity and equality in education and employment.*

Tenure track Assistant Professor of Physics
MTSU - Middle Tennessee State University

Physics BS program seeks faculty involved with experimental research programs in areas including (not limited to) Physics and Astronomy Education Research, Applied Optics, Nano-materials, and Experimental Biophysics. Candidates must be passionate about teaching, and provide a plan for developing an active research program that can engage undergraduates. Newly renovated building (2016) houses over 2,500 sq. ft. of dedicated research space. Department has 14 full time faculty, 100 majors, and graduates 15 majors per year with a positive growth trajectory. Information at http://www.mtsu.edu/physics/TenureTrackOpening.php. Online application required at http://mtsujobs.mtsu.edu/postings/3707.

Assistant Professor
Mississippi State University

The Department of Physics and Astronomy at Mississippi State University (MSU, http://www.msstate.edu/dept/physics) expects to fill, subject to the availability of funding, a full-time nine-month Assistant Professor starting on August 16, 2017. This tenure-track position is open to applicants who have a PhD in physics, astronomy, or a closely related field and perform research in one or more of the areas of specialization in the Department: Astronomy/Astrophysics, Atomic/Molecular/Optical/Plasma Physics (AMOP), Condensed Matter Physics, Nuclear Physics, or Computational Physics. Preference will be given to applicants in computational astrophysics, AMOP, and experimental low-energy nuclear structure, but exceptional applicants in other areas will be considered. MSU is a land-grant university with an enrollment of about 21,000 students. The Department offers BS, MS, and PhD degrees. Applicants are expected to continue the departmental tradition of excellence in sponsored research involving students, in teaching, and in service. Local resources that may be relevant include the High Performance Computing Collaboratory and the Institute for Imaging and Analytical Technologies. Phi Beta Kappa members are encouraged to apply. Applicants should submit their letter of application electronically to (physics.position@dept.msstate.edu) and/ or a hard copy to: **Faculty Search Committee, Attn: Mrs. Susan Galloway, Department of Physics and Astronomy, P.O. Box 5167, Mississippi State, MS 39762-5167,** including a cover letter, curriculum vitae, summary of research and grantsmanship plans, teaching philosophy and experience, and three letters of reference. Applicants must complete the "Personal Data Information Form" online through the MSU Human Resources website http://explore.msujobs.msstate.edu. Review of the applications will begin on **December 1, 2016**, and continue until the position is filled. *MSU is an equal opportunity employer, and all qualified applicants will receive consideration for employment without regard to race, color, religion, ethnicity, sex (including pregnancy and gender identity), national origin, disability status, age, sexual orientation, genetic information, protected veteran status, or any other characteristic protected by law. We always welcome nominations and applications from women, members of any minority group, and others who share our passion for building a diverse community that reflects the diversity in our student population.*

Cornell University
Tenure Track Assistant Professor Position
in Theoretical Physics

The Department of Physics at Cornell University expects to make a faculty appointment in theoretical physics, to begin July 1, 2017. We encourage applications in hard and soft condensed matter physics, cold atom physics, biophysics and related areas that utilize the theoretical techniques of condensed matter physics. The search will focus at the assistant professor level. Candidates must hold a doctorate in an appropriate field, must have demonstrated an ability to conduct outstanding research, and show promise for excellent teaching at both the undergraduate and graduate level. Information about the Laboratory of Atomic and Solid State Physics at Cornell can be found at www.lassp.cornell.edu. Please send the application, including a curriculum vitae, a publication list, and a statement of teaching and research interests to: https://academicjobsonline.org/ajo/jobs/7673. We actively encourage applications from diverse and historically underrepresented candidates. Applicants should arrange to have three letters of reference sent to the same website. Applications received before **December 15, 2016** will receive full consideration. *Diversity and Inclusion are a part of Cornell University's heritage. We're an employer and educator recognized for valuing AA/EEO, Protected Veterans, and Individuals with Disabilities.*

Assistant Professor in Experimental Nuclear Physics
Department of Physics, Duke University

The Department of Physics at Duke University in Durham, North Carolina invites applications and nominations for a tenure-track position at the assistant professor level in the area of experimental nuclear physics. This is a joint faculty position between Duke University and the Thomas Jefferson National Accelerator Facility (Jefferson Lab). The successful candidate is expected to lead an active research program at Jefferson Lab, and at Duke. Under a Duke/JLAB agreement this position carries 50% release time to carry out research at Jefferson Lab. Current research in the Department of Physics at Duke in the area of experimental nuclear physics includes experiments in electroweak interactions, neutrino physics, hadron structure and nuclear astrophysics. The appointment begins as early as July 2017. Applicants should have a Ph.D. in experimental nuclear or particle physics, postdoctoral experience, and show a strong commitment to research and teaching. Interested candidates should submit a cover letter, a curriculum vitae, statements of research and teaching, and arrange to have three letters of recommendation submitted through Academic Jobs Online at https://academicjobsonline.org/ajo/jobs/7762. Questions regarding the application process and the position should be submitted to npsearch2016@phy.duke.edu. Complete applications, including letters, received by **November 15, 2016** will be given full consideration, although applications will continue to be accepted until the position is filled. *Duke University is an Affirmative Action/Equal Opportunity Employer committed to providing employment opportunity without regard to an individual's age, color, disability, genetic information, gender, gender identity, national origin, race, religion, sexual orientation, or veteran status.*

U.S. NAVAL RESEARCH LABORATORY

Senior Scientist for Radiation Physics and High Energy Density Materials
ST-1310, $123,175 to $185,100* per annum
*Rate limited to the rate for level III of the Executive Schedule (5 U.S.C. 5304(g)(2))

Serves as the technical expert in the fields of radiation physics and high energy density materials including radiation atomic physics and transport, inertial confinement fusion, hydrodynamics and magnetohydrodynamics, shock waves, and hydrodynamic instabilities.

Conducts and leads a broad-based, multidisciplinary research program pushing the frontiers of plasma radiation sources and plasma discharges, with particular emphasis on applications to nuclear weapons effects simulation, thermonuclear fusion, advanced weapons, sensors and detectors, materials plasma processing, and advanced diagnostics.

As a distinguished scientist and recognized leader in his/her field the incumbent will be called upon to brief DoD senior officials regarding Laboratory research efforts in the above areas, to serve as liaison between NRL, the Navy and other national and international organizations, and to consult on important scientific and programmatic issues.

Applicants should be recognized as national/international authorities in the above areas of research, and should have demonstrated the scientific vision and organizational skills necessary to market new research proposals to obtain funding and bring long term, multifaceted research programs to successful completion. NRL is the Navy's corporate lab and operates under the Navy Working Capital Fund (NWCF).

You must apply online by logging in to **USAJOBS** at www.usajobs.gov and searching for the vacancy announcement number **NW61310-00-1757501K9453341S**. Please carefully read the announcement and follow the instructions when applying. Please contact Annemarie Slattery at annemarie.slattery@nrl.navy.mil for more information. Vacancy announcement closes on **1 November 2016**.

Navy is an Equal Opportunity Employer

Tenure-Track Assistant Professor in Solar Physics
Georgia State University

The Department of Physics and Astronomy at Georgia State University (GSU) is seeking to fill a tenure-track faculty position by Fall 2017 at the assistant professor level with a focus on solar-stellar dynamo research. The new faculty member will help build an astroinformatics cluster on "The Solar/Stellar Connection" in conjunction with the Department of Computer Science and the Center for High Angular Resolution Astronomy at GSU. This position is part of a GSU Next Generation Faculty Program that will include a number of tenure-track, research faculty, and postdoctoral hires in the above departments to work closely with recent senior faculty hires (Dr. Rafal Angryk, Dr. Piet Martens, and Dr. Stuart Jefferies) in an interdisciplinary program of solar physics, space weather and climate, and big data mining. Our ideal candidate will have a comprehensive understanding of magnetohydrodynamics (MHD), a strong record of developing computational techniques for modeling solar and/or stellar dynamos, and a demonstrated expertise in analyzing and interpreting data relevant for guiding solar and stellar dynamo simulations. Strong candidates with related experience will be given consideration as well. Applicants should have the following basic qualifications: 1) Ph.D. in astronomy, physics, or closely related field, 2) postdoctoral research experience, 3) evidence of the ability to establish and maintain a successful research program, 4) evidence of the ability to teach at the undergraduate and graduate levels, 5) evidence of the ability to work in a large, collaborative effort. Applications should include 1) a CV, including a publication list, 2) a statement of the candidate's research interests and how the research fits into the above program, 3) a statement of teaching experience and philosophy with a focus on inclusiveness, and 4) contact information for at least three references. All materials should be sent via email to AstroSearch@astro.gsu.edu. Questions regarding the position can be addressed to **Dr. Piet Martens** at martens@astro.gsu.edu. Applications received by **December 1, 2016**, will receive full consideration. An offer of employment will be conditional on background verification. *Georgia State University, a unit of the University System of Georgia, is an equal opportunity educational institution and an EEO/AA employer. Women and minorities are strongly encouraged to apply. It is our policy to offer equal employment opportunities for all persons without regard to race, color, religion (creed), gender, gender expression, age, national origin (ancestry), disability, marital status, sexual orientation, or military status.*

Faculty Position in Observational Astronomy with a focus on relativistic objects
Montana State University

The Department of Physics at Montana State University invites applications for a tenure-track assistant professor position in observational astronomy, with a focus on, but not limited to, observations of systems with extreme gravitational fields, such as neutron stars and black holes, and cosmology. MSU hosts the recently established eXtreme Gravity Institute (www.montana.edu/xgi/), which conducts research spanning a broad range of topics, including gravitational waves and associated electromagnetic counterparts; neutron star structure; tests of general relativity; black holes and accretion disks. Faculty members in the MSU physics department conduct research, teach undergraduate and graduate courses, and supervise graduate and undergraduate research. Candidates must show promise in both teaching and research. A Ph.D in physics, astronomy, or a related discipline is required by the start of employment. Applications from qualified minorities, women, veterans, and persons with disabilities are highly encouraged. Screening of applications will start **October 24, 2016** and continue until the position is filled. For the full announcement of this position and application procedures, click on: https://jobs.montana.edu/postings/5739. *Equal Opportunity Employer, Veterans/Disabled.*

Assistant Professor in Theoretical Nuclear or Particle Physics
University of Connecticut

The University of Connecticut Department of Physics invites applications for a full-time tenure track faculty position at the rank of Assistant Professor. The successful candidate will be expected to contribute to research and scholarship through extramural funding in theoretical nuclear or particle physics, in fields compatible with the research program at the RIKEN BNL Research Center. In addition to a strong research profile, the successful candidate will share a deep commitment to effective instruction, diversity, service, and outreach. This is a full-time, 9-month, tenure track position with an anticipated start date of August 23, 2017, and will be joint with the RIKEN BNL Research Center for the first two years. For a detailed list of position qualifications and application requirements, see our complete job posting at: https://academicjobsonline.org/ajo/jobs/7788. *The University of Connecticut is an Equal Employment Opportunity/Affirmative Action employer.*

Assistant Professor-Physics and Biomedical & Translational Sciences
Rowan University

We seek outstanding candidates who will be able to contribute to the development of new interdisciplinary curricula and research initiatives. Candidates with planned research activities that apply physics to biomedical problems will be considered. Preference will be given to those with a background in biomedical applications of optics/photonics. The successful candidate also will teach undergraduate courses in both departments and train undergraduate students in research. The candidate will help define growth in biophysics and translational biomedical science programs. Search closes on **Oct 21, 2016**. Apply at **https://rowanuniversity.hodesiq.com/jobs/assistant-professor-physics-and-biomedical-translational-sciences-glassboro-new-jersey-job-5331243**.

Tenure Track – Theoretical Nuclear Physics

The **Physics Department** of the **University of Massachusetts Amherst** invites applications for a tenure-track faculty position in theoretical nuclear physics to start September 1, 2017. This position will initially be joint with the RIKEN BNL Research Center and transition after the first five years to a full-time UMass position. The successful candidate will become a member of the Amherst Center for Fundamental Interactions, http://www.physics.umass.edu/acfi/. Further information about the Department's theoretical and experimental efforts can be found at http://www.physics.umass.edu/. The Department seeks an individual with outstanding research and a strong commitment to teaching. A PhD in areas closely related to theoretical nuclear physics and postdoctoral experience are required. The successful candidate will demonstrate the ability to build a vibrant research program in fields compatible with the research program at the RIKEN BNL Research Center at Brookhaven National Laboratory (https://www.bnl.gov/riken/). To apply online, please go to http://umass.interviewexchange.com/jobofferdetails.jsp?JOBID=76613 , and submit a resume, cover letter, a detailed research plan, a teaching statement, and contact information for three professional references. Applicants should apply by the priority deadline of **11-15-2016 in** order to ensure full consideration. The university is committed to active recruitment of a diverse faculty and student body. *The University of Massachusetts Amherst is an Affirmative Action/Equal Opportunity Employer of women, minorities, protected veterans, and individuals with disabilities and encourages applications from these and other protected group members. Because broad diversity is essential to an inclusive climate and critical to the University's goals of achieving excellence in all areas, we will holistically assess the many qualifications of each applicant and favorably consider an individual's record working with students and colleagues with broadly diverse perspectives, experiences, and backgrounds in educational, research or other work activities. We will also favorably consider experience overcoming or helping others overcome barriers to an academic degree and career. We are seeking talented applicants qualified for an assistant professor position. Under exceptional circumstances, highly qualified candidates at other ranks may receive consideration.*

TENURE TRACK ASSISTANT PROFESSOR IN THEORETICAL BIOPHYSICS

The Physics and Astronomy Department at **California State Polytechnic University, Pomona** invites applications for a tenure-track Assistant Professor in theoretical biophysics, broadly construed, and including soft condensed matter if strongly overlapping biophysics, to begin in September 2017. The successful candidate will be expected to teach both introductory and advanced undergraduate courses in physics, as well as engage in publishable research involving undergraduate students. Applicants must obtain a Ph.D. in Physics, Biophysics, or a closely-related field by August 2017. Previous college teaching experience (at least at the T. A. level) and the ability to establish an independent research program are required. The successful candidates will be expected to contribute to the diversity and excellence of the academic community through research, teaching and/or service, and be committed to teaching and working in a multicultural environment. The application deadline is **November 21, 2016**. For a full position description, as well as the application procedure, please visit the Department web site at http://www.cpp.edu/~sci/physics-astronomy/. *EOE/Minorities/Females/Vet/Disability.*

Assistant Professor in High Energy Theory

The Department of Physics and Astronomy at the **University of Pennsylvania** invites applications for an **Assistant Professor** in **high energy theory**, broadly defined. Applicants from all areas of high energy physics, including particle physics, string theory, quantum field theory, particle cosmology, and the interface with mathematics are encouraged to apply. Senior appointments may be considered in exceptional cases. Applicants should have a Ph.D., an outstanding research record demonstrating independence and innovation, and strong interest in teaching and mentoring students. Interested candidates should submit materials online at http://facultysearches.provost.upenn.edu/postings/951 and include a curriculum vitae with publications, statements of research and teaching interests, and the name and contact information of at least three referees. Recommenders will be contacted by the University with instructions on how to submit a letter to the website. Review of applications will begin **November 1, 2016** and continue until the position is filled. The Department of Physics and Astronomy is strongly committed to Penn's Action Plan for Faculty Diversity and Excellence and to creating a more diverse faculty (for more information see: http://www.upenn.edu/almanac/volumes/v58/n02/diversityplan.html). *The University of Pennsylvania is an EOE. Minorities/Women/Individuals with disabilities/ Protected Veterans are encouraged to apply.*

Assistant Professor of Physics

The Physics Department at **Duquesne University** invites applications for a non-tenure-track full-time teaching faculty position beginning August 2017. Located in the heart of Pittsburgh, Duquesne University offers undergraduate physics degrees in a student-centered liberal arts environment. We seek a dynamic individual with strong communication and interpersonal skills, a genuine commitment to teaching, and the potential for achieving excellence and implementing innovations in undergraduate physics courses for science and non-science majors, with large and small enrollments. The successful candidate will demonstrate the ability to team up with other faculty in the implementation of teaching initiatives. Experience teaching undergraduate courses would be desired. A PhD in physics is required. Master-degree holders will also be considered, at the rank of Instructor. More information about the department is found at www.duq.edu/physics. Review of complete applications will begin on **November 1, 2016** and will continue until the position is filled. Motivated by its Catholic and Spiritan identity, Duquesne values equality of opportunity both as an educational institution and as an employer. Founded in 1878 by its sponsoring religious community, the Congregation of the Holy Spirit, Duquesne University is Catholic in mission and ecumenical in spirit. Its Mission Statement commits the University to "serving God by serving students - through commitment to excellence in liberal and professional education, through profound concern for moral and spiritual values, through the maintenance of an ecumenical atmosphere open to diversity, and through service to the Church, the community, the nation and the world." Applicants for this position should describe how they might support and contribute to this mission. *Duquesne University is committed to attracting, retaining and developing a diverse faculty that reflects contemporary society, serves our academic mission and enriches our campus community. As a charter member of the Ohio, Western PA and West Virginia Higher Education Recruitment Consortium (HERC), we encourage applications from members of underrepresented groups and support dual-career couples. Duquesne* University uses Interfolio to collect all faculty job applications electronically. Applicants should submit a letter of application, CV, statement of teaching interests and three letters of reference addressing teaching skills to the attention of **Dr. Simonetta Frittelli, Chair, Department of Physics,** via: http://apply.interfolio.com/37084.

Assistant Professor – Theoretical Physics

The **Physics Department** at the **University of California, Berkeley** is conducting an open search to fill a tenure-track faculty position for an Assistant Professor in Theoretical Physics with an expected start date of July 1, 2017. We welcome applications from candidates across all areas of Theoretical Physics. Preference will be given to scholars who have demonstrated excellence, originality and productivity in research, have shown promise in teaching, and have demonstrated a commitment to excellence by providing leadership towards building an equitable and diverse scholarly environment. The successful candidate will be expected to teach undergraduate and graduate courses and have a strong commitment to teaching, mentoring, and service. The basic qualification required to be considered an applicant is completion of all degree requirements for Ph.D. or equivalent degree except the dissertation at the time of application. Ph.D. or equivalent degree is required by the expected start date of the appointment. To apply, please go to the following link: https://aprecruit.berkeley.edu/apply/JPF01130. Applicants should submit a curriculum vitae, a bibliography, a statement of research, and a statement of teaching philosophy. Inclusion of a cover letter and/or a Statement of Contributions to Diversity are optional. When completing the online application, applicants should be sure to select the appropriate area(s) of specialization. Applicants should arrange to have between three to five letters of reference submitted through the online system and at least three of the letters should come from referees outside of the UC Berkeley system. All letters will be treated as confidential per University of California policy and California state law. Please refer potential referees, including when letters are provided via a third party (i.e., dossier service or career center), to the UC Berkeley statement of confidentiality: http://apo.berkeley.edu/evalltr.html, prior to submitting their letters. Applications must be received by **November 18, 2016**. Please direct questions to **Brian Underwood, brianu@berkeley.edu, (510) 642-3317**. The department is committed to addressing the family needs of faculty, including dual career couples and single parents, and is interested in candidates who will contribute to diversity and equal opportunity in higher education through their teaching, research, and service. Further information is available at http://ofew.berkeley.edu/new-faculty. *The University of California is an Equal Opportunity/Affirmative Action Employer. All qualified applicants will receive consideration for employment without regard to race, color, religion, sex, sexual orientation, gender identity, national origin, disability, age or protected veteran status. For the complete University of California nondiscrimination and affirmative action policy see:* http://policy.ucop.edu/doc/4000376/NondiscrimAffirmAct.

Tenure-Track Assistant Professor
Department of Physics at Harvard University

The Department of Physics at Harvard University invites applications for a tenure-track assistant professor position in experimental physics. The areas of interest include, but are not limited to: quantum condensed-matter physics; atomic, molecular, and optical physics; and quantum science. The appointee will teach and advise at the undergraduate and graduate levels. The appointment is expected to begin on July 1, 2017. Basic Qualifications: Doctorate or terminal degree in Physics or related discipline required by the time the appointment begins. Additional Qualifications: Demonstrated excellence in teaching and research is desired. Special Instructions: Please submit the following materials through the ARIeS portal (https://academicpositions.harvard.edu/postings/7119): 1. Cover letter, 2. Curriculum Vitae, 3. Teaching statement, 4. Research statement, 5. Names and contact information of 3-5 references. Three letters of recommendation are required, and the application is complete only when at least three letters have been submitted. Consideration of applications will begin **November 1, 2016**; applications will be reviewed until the position is filled. *Harvard is an equal opportunity employer and all qualified applicants will receive consideration for employment without regard to race, color, religion, sex, national origin, disability status, protected veteran status, or any other characteristic protected by law.* Contact Information: **c/o Jolanta Davis, Administrator to the Chair, Search Committee, Department of Physics, Harvard University, 17 Oxford Street, Cambridge, MA 02138,** email: jmdavis@fas.harvard.edu.

Faculty Position in Experimental Condensed Matter Physics OR Experimental Atomic, Molecular and Optical Physics
UC Santa Barbara, Division of Mathematical, Life and Physical Sciences

The Department of Physics at the University of California, Santa Barbara is seeking candidates for a tenure-track assistant professor position in either experimental condensed matter physics or experimental atomic, molecular and optical (AMO) physics, with an appointment to start in Fall of 2017. The department has extensive cross-disciplinary work with colleagues in the College of Engineering, Biological Sciences, and Chemistry, which is enhanced by the presence of the California NanoSystems Institute, the Materials Research Laboratory, the Institute for Terahertz Science and Technology, and the Kavli Institute for Theoretical Physics. Further information may be found at the department's website: http://www.physics.ucsb.edu. Candidates are expected to have a Ph.D. in physics or a closely related field, and will teach a range of courses in the physics department. The Department is committed to identifying excellent candidates who can contribute to the diversity of the academic community through research, teaching, and service. Applicants should submit a curriculum vitae, a statement of research interests, a statement of teaching interests, and a list of publications, and arrange for at least three letters of recommendation. Materials should be sent electronically via https://recruit.ap.ucsb.edu/apply/JPF00822. Applications received on or before **October 31, 2016** will be given full consideration. Applications will be accepted until the position is filled. *The University of California is an Equal Opportunity/Affirmative Action Employer and all qualified applicants will receive consideration for employment without regard to race, color, religion, sex, sexual orientation, gender identity, national origin, disability status, protected veteran status, or any other characteristic protected by law.*

Tenure-Track Faculty Position in Theoretical Physics
California State University Long Beach

The Department of Physics & Astronomy at California State University Long Beach invites applications for one tenure-track faculty position at the **assistant professor level** in the field of **theoretical Cosmology/Astrophysics**. Candidates must have a Ph.D. in Physics or closely related field at the time of application, a strong record of research, and commitment to excellence in teaching at undergraduate and graduate level. Full details for **position #2396** are available at http://tinyurl.com/j2c7ff5. Complete applications should be sent before **December 1st, 2016** as a single PDF file to PhysicsSearch@csulb.edu. Please ask referees to send their letter to the same email with applicant's full name in the subject. *CSULB is an Equal Opportunity Employer.*

Assistant Professor Experimental Biological Physics
University at Buffalo, SUNY

The Department of Physics invites applications for an assistant professor position in experimental biological physics starting in August 2017. We are interested in researchers using experimental approaches to study the physics of living systems including, but not limited to, cell mechanics, systems biology, or regulatory networks and nonlinear dynamics in biological systems. The successful candidate will complement existing research in nanoscience, magnetogenetics, spectroscopy, molecular and cellular biophysics, and neuroscience. Applicants should have postdoctoral experience; a strong publication record; show promise of creative research and obtaining external funding; have excellent communication skills and evidence of teaching ability. Start-up funds and laboratory space will be highly competitive and salary commensurate with experience. Please apply with cover letter, separate research and teaching statements, and a curriculum vita including list of publications to https://www.ubjobs.buffalo.edu/applicants/Central?quickFind=59213. Applicants should arrange for at least three letters of reference to be submitted online as well. Informal inquiries may be sent to the **Search Committee Chair, Professor Arnd Pralle,** apralle@buffalo.edu. Applications received by **Oct. 21 2016** will receive full consideration, and applications will continue to be reviewed until the position is filled. *We especially welcome applications from qualified members of underrepresented protected groups. The University at Buffalo is an Equal Opportunity Employer/Recruiter.*

Purdue University
Department of Physics and Astronomy
Assistant Professor in Astrophysics

The Department of Physics at Purdue University seeks applications for a tenure track faculty position in the area of astrophysics. The position is expected to be filled at the rank of Assistant Professor. We are interested in outstanding scientists with a strong research program that will augment the existing strengths of our department. The successful candidate is expected to develop a synergy with our current program while pursuing new directions. The astrophysics group at Purdue has a strong focus on high energy astrophysics, extr galactic astronomy, and dark matter experiment, with partnerships in several major facilities including the Large Synoptic Survey Telescope, VERITAS, and XENON1T. Purdue University is also a world leader in high performance scientific computing and data storage facilities. Applicants must have a Ph.D. in physics or related field with a documented record of research accomplishments. Candidates are expected to supervise graduate students, teach both undergraduate and graduate courses, and serve on departmental, college and university committees. Salary and benefits are highly competitive. Questions regarding this position and search should be directed to the **Chair of the search committee, Prof. Matt Lister** (mlister@purdue.edu). Interested candidates should submit their curriculum vitae, a list of publications to which the applicant was instrumental, a maximum 5 page description of their planned research program and of their teaching philosophy, and arrange for the delivery of 3 supporting letters of recommendation. Electronic submission at https://www.physics.purdue.edu/searches/app/ is preferred. Review of applications will begin immediately after the deadline and will continue until the position is filled. For full consideration, all application materials should be received no later than **December 9, 2016**. Purdue University requires a background check for employment in all positions. *Purdue University is an EEO/AA employer fully committed to achieving a diverse workforce. All individuals, including minorities, women, individuals with disabilities, and veterans are encouraged to apply.*

Einstein Fellowships
Smithsonian Astrophysical Observatory

On behalf of the NASA Astrophysics Division, the Chandra X-Ray Center (CXC) is pleased to announce the annual competition for the Einstein Postdoctoral Fellowship Program. Einstein Fellows hold their appointments at a Host Institution in the United States, for research broadly related to the science goals of the NASA Physics of the Cosmos program. This includes high energy astrophysics relevant to Chandra, Fermi, XMM-Newton and future NASA X-ray missions, cosmological investigations relevant to Planck, WFIRST or new Dark Energy missions, and gravitational astrophysics relevant to LISA Pathfinder and subsequent related missions. The Fellowships are tenable at any U.S. institution where research related to Physics of the Cosmos can be carried out. The Fellowship is initially for two years, with the expectation of a third year, contingent upon performance and available funding. Subject to the availability of NASA funding, 5 to 10 Einstein Fellows will be appointed this year, through grants to United States institutions. The Call for Proposals, which includes detailed Program policies and application instructions, is available at http://cxc.harvard.edu/fellows/. An application includes a cover form, a research proposal, letters of reference, a curriculum vitae, and other relevant materials as detailed in the instructions. Full instructions for submitting applications online are contained in the Call for Proposals. The application deadline is **Thursday, Nov 3 2016**. New Einstein Fellowship appointments are expected to begin on or about Sep 1, 2017. *Women and members of minority groups are strongly encouraged to apply.*

TENURE-TRACK OR TENURED FACULTY POSITION
Chemical Engineering and Materials Science
University of Minnesota
Minneapolis, MN

The Department of Chemical Engineering and Materials Science at the University of Minnesota (www.cems.umn.edu) seeks to fill a faculty position at the (tenure-track) Assistant, (tenured) Associate, or (tenured) Professor level, commensurate with experience. Outstanding candidates with a PhD degree in any area related to chemical engineering and materials science will be considered. Candidates should have a distinguished academic and research record and a commitment to teaching in a highly interdisciplinary department. Applications consisting of a cover letter, CV (including a list of publications), research statement, teaching statement, and a list of three references with contact information should be submitted online at http://z.umn.edu/cemsfaculty. Additionally, the posting can be accessed through the Department website: www.cems.umn.edu/news/faculty-search. Review of applications will begin immediately and continue until the position is filled. The successful candidate will be in place as early as Fall 2017. *The University of Minnesota is an equal opportunity educator and employer.*

Tenure-Track Assistant/Associate Professor

The **Department of Physics** at the **University of Miami** invites applications from highly qualified candidates for a faculty position in experimental optics. This appointment will be made at the Assistant or Associate Professor rank to begin fall 2017. Targeted research topics include, but are not limited to environmental optics, remote sensing, atmospheric and oceanic turbulence characterization and mitigation, free-space optical communications, and natural particle spectroscopies. Current department research strengths comprise optics in natural environments, with strong ties to the University's Rosenstiel School of Marine and Atmospheric Science. Candidates must have a Ph.D. in physics or related discipline, a demonstrated record of research achievements, and a strong commitment to teaching and mentoring students at the undergraduate and graduate levels. The physics department is located within the University's attractive Coral Gables campus in the greater Miami area, and has a wide-ranging research expertise and established Ph.D. program. Application materials, including curriculum vitae with list of publications and statement of research plans, should be sent electronically (as a single PDF) to opticssearch@physics.miami.edu or to **Optics Search Committee Chair, Department of Physics, University of Miami, Knight Physics Building, Coral Gables, FL 33124.** Applicants should arrange for three letters of recommendation to be sent to the same address. Review of applications will begin on **November 4, 2016** and continue until the position is filled. *The University of Miami is an Equal Opportunity Employer — Females/Minorities/Protected Veterans/Individuals with Disabilities are encouraged to apply. Applicants and employees are protected from discrimination based on certain categories protected by Federal law.*

Post-Doctoral Research Associate
Florida International University
COMPUTATIONAL MOLECULAR BIOPHYSICS

The Molecular Biophysics Group at Florida International University is hiring a Post-Doctoral Research Associate to carry out research in biomolecular computations. Applications are welcome from people with a Ph.D. in physics, biophysics, biochemistry, molecular biology, or related fields. Applicants are expected to have experience working with Molecular Dynamics computational simulations or computational modeling. We are also interested in someone with strong computer programming skills or a computer science background. The target date for starting in the Post-doc position is **October 20, 2016**. Further information about the research can be found at http://faculty.fiu.edu/~gerstman/ and http://faculty.fiu.edu/~chapagap/. Applicants should send their CV, including a list of publications, electronically to **Prof. Bernard Gerstman, Department of Physics, Florida International University, Miami, Florida** at gerstman@fiu.edu. The CV should include the names and contact information of three references, but letters of reference should not be sent at this time. *FIU is an Equal Opportunity/Affirmative Action employer.*

PHYSICS TODAY (ISSN 0031-9228, coden PHTOAD) volume 69, number 10. Published monthly by the American Institute of Physics, 1305 Walt Whitman Rd, Suite 300, Melville, NY 11747-4300. Periodicals postage paid at Huntington Station, NY, and at additional mailing offices. POSTMASTER: Send address changes to PHYSICS TODAY, American Institute of Physics, 1305 Walt Whitman Rd, Suite 300, Melville, NY 11747-4300. Views expressed in PHYSICS TODAY and on its website are those of the authors and not necessarily those of AIP or any of its member societies.

QUICK STUDY

Grant Deane and **Dale Stokes** are research oceanographers at the Scripps Institution of Oceanography in La Jolla, California. **Adrian Callaghan** is a project scientist at Scripps, currently on assignment at Imperial College London.

Turbulence in breaking waves

Grant B. Deane, Dale Stokes, and Adrian H. Callaghan

Laboratory experiments suggest that, on average, turbulent energy dissipation in whitecaps is the same for waves lapping on the beach and waves storming in the seas.

Ocean water covers 71% of Earth. And all of it is affected by turbulence, which mixes the ocean by transferring momentum, heat, chemicals, and organisms. Near the ocean's surface, turbulence significantly influences the exchange of gas, heat, and momentum between the ocean and the atmosphere; those exchanges, in turn, affect weather and climate. Near-surface turbulence is greatest within breaking waves, in the whitecaps formed when a brisk ocean wind drags across the sea surface. There, turbulence, as measured by the rate at which energy is dissipated in turbulent motion, can exceed oceanic background values by more than seven orders of magnitude.

Whitecaps are white because they contain bubbles of air that are entrained and fragmented by the fluid turbulence generated by surface waves as they break. Those bubbles influence many of the exchange processes that affect weather and climate. As they dissolve in a breaking wave, they enhance the transport of greenhouse gases between the atmosphere and the ocean. After the wave breaks, rising bubbles scavenge and transport organic materials that become part of the droplets formed when the bubbles burst. The droplets and their chemical and biological baggage are an important source of cloud and ice nuclei over the oceans; they also alter the radiative transfer properties of the atmosphere.

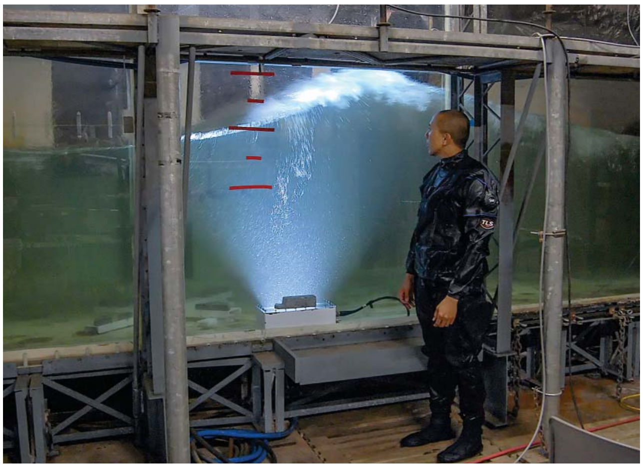


FIGURE 1. THE BREAKING LABORATORY WAVE seen here is moving from right to left and is lit from beneath. We analyzed turbulent, air-entraining flow in white, foamy wave regions like that shown just below the water surface. Electrical engineer James Uyloan helps show the scale of the experiment.

The numbers and sizes of the bubbles entrained by breaking waves influence exchange processes, and those qualities are intimately linked to the fluid turbulence in the wave crest. Pressure fluctuations driven by turbulent flow threaten to rupture the bubbles by distorting them from their spheroidal form into irregular shapes. Small bubbles are stabilized against rupture by surface tension, but large bubbles are ripped apart. The scale at which the distorting and stabilizing forces are balanced—the Hinze scale—is connected to energy dissipation rates in the upper ocean. In a plot displaying how the number of bubbles decreases as a function of bubble size, the rate of falloff would abruptly increase at the Hinze scale. Empirically, two of us (Deane and Stokes) have found the scale to be roughly 1 mm in breaking ocean waves.

Our interest in whitecap turbulence is motivated by its relationship to bubble entrainment and breakup. How do the Hinze scale and therefore the bubble-size distribution change as wind forcing increases from a gentle breeze to a tropical cyclone? Ideally, turbulence measurements would be made *in situ*, in the open ocean. However, measurements in wind-driven seas pose many challenges. For example, early in the wave-breaking process, air can make up as much as 50% of a whitecap, a fraction that makes the region effectively impenetrable to probes that use sound or light. Moreover, it's no easy task to mount instrumentation to within a few tens of centimeters of the sea surface during storms in which individual wave heights can reach beyond 10 meters.

Measuring turbulence in the lab

In view of the difficulty of field measurements, we turned to the hydraulics laboratory at the Scripps Institution of Oceanography at the University of California, San Diego. There, we could reproducibly generate breaking waves under controlled laboratory conditions; figure 1 shows an example. We used three different methods to measure the rate of turbulent energy-density dissipation during the first second or so of active wave breaking.

First, we used surface displacement measurements made upstream and downstream of the break point to calculate the total energy in the wave before and after breaking. The difference in those energies approximates the total energy lost to breaking, though the estimate needs to be refined to account

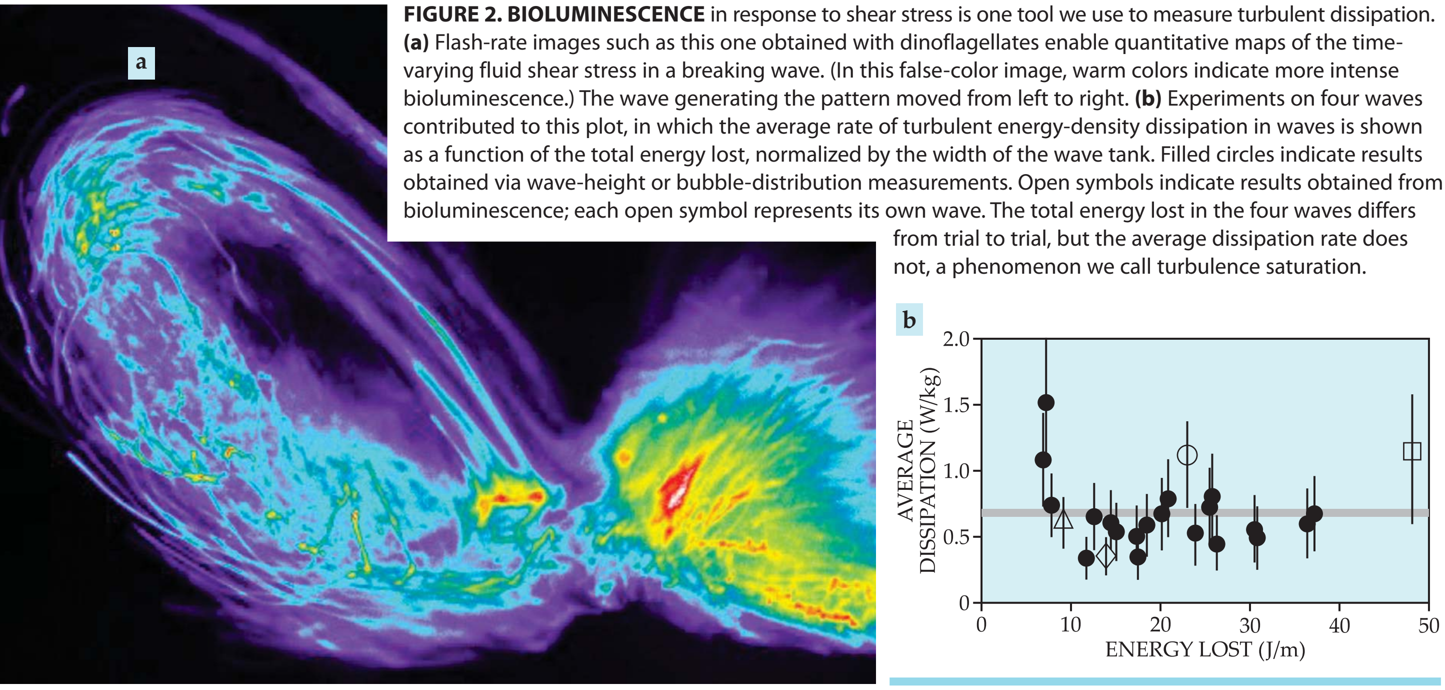


FIGURE 2. BIOLUMINESCENCE in response to shear stress is one tool we use to measure turbulent dissipation. **(a)** Flash-rate images such as this one obtained with dinoflagellates enable quantitative maps of the time-varying fluid shear stress in a breaking wave. (In this false-color image, warm colors indicate more intense bioluminescence.) The wave generating the pattern moved from left to right. **(b)** Experiments on four waves contributed to this plot, in which the average rate of turbulent energy-density dissipation in waves is shown as a function of the total energy lost, normalized by the width of the wave tank. Filled circles indicate results obtained via wave-height or bubble-distribution measurements. Open symbols indicate results obtained from bioluminescence; each open symbol represents its own wave. The total energy lost in the four waves differs from trial to trial, but the average dissipation rate does not, a phenomenon we call turbulence saturation.

for the potential energy associated with suspended bubbles. Once that correction was made, we determined the dissipation rate averaged over the volume of the whitecap and duration of the measurements. In our second approach, we estimated the Hinze scale from the break points in bubble-size distributions obtained from tedious, manual analysis of photographs taken through the glass wall of the wave tank. In conjunction with a model for bubble fragmentation, such a determination also yields a value for the average turbulent dissipation rate.

The third method relies on the probabilistic bioluminescent flash response of single-celled marine organisms called dinoflagellates as an indicator of fluid shear stress. We measured the stimulated bioluminescence in breaking crests with sensitive cameras mounted on a robotic motion system programmed to track individual breaking waves. From images such as the one shown in figure 2a, we could obtain maps of the time-varying fluid shear stress inside breaking waves, and from such maps we could determine the turbulent dissipation.

Turbulence saturation

We applied our three measurement methods to the breaking crests generated by four waves. Three of the waves had steep slopes, and they each had a different dominant wavelength. The fourth wave had a gentle slope. Figure 2b shows one of the surprising results of our study: For all four waves, the average turbulent energy-density dissipation lies in the relatively small range of 0.8 ± 0.4 W/kg. And not only is the average dissipation nearly constant, it is significantly larger than the 10^{-5} to 10^{-2} W/kg generally observed near the surface.

We use the term turbulence saturation to describe the invariance of turbulence intensity with wavelength and slope. One consequence of the saturation is that the Hinze scale is largely independent of wave slope or scale. Such invariance is observed in the laboratory bubble-size distributions, for which the Hinze scale is 1.5 ± 0.3 mm. The few determinations of the Hinze scale obtained from ocean data lie in the larger range of 0.7–1.7 mm. One possible explanation for turbulence saturation is that the bubbles themselves somehow limit the degree of turbulence intensity. Another is that, for longer or more steeply sloped waves, the breaking wave penetrates more deeply into the ocean and the large wave's greater energy is dissipated because of the increased volume of water affected rather than greater turbulence intensity.

Whatever its cause, turbulence saturation would have important implications for bubble-mediated exchange processes across the air–sea interface. A limit on fluid turbulence would mean that the laboratory breakers we studied have a two-phase flow, bubble Hinze scale, and air fraction similar to those in 10-m-high storm waves. Evidence for such scale invariance in the ocean was obtained by Zhongxiang Zhao and colleagues, who measured underwater acoustic noise in tropical cyclones having wind speeds of 10 m/s and 50 m/s. Not surprisingly, they found that the overall power of the noise increased with increasing wind speed. But the shape of the noise spectrum, which is closely related to the numbers and sizes of bubbles formed within breaking wave crests, remained relatively constant. On the other hand, observations by Johannes Gemmrich of fluid turbulence in waves breaking on a freshwater lake do not show evidence of turbulence saturation. The paucity of field observations and the differences in field and laboratory studies make the study of turbulent dissipation in wave crests an exciting and active area of research.

Additional resources

▶ G. B. Deane, M. D. Stokes, "Scale dependence of bubble creation mechanisms in breaking waves," *Nature* **418**, 839 (2002).
▶ G. B. Deane, M. D. Stokes, A. H. Callaghan, "The saturation of fluid turbulence in breaking laboratory waves and implications for whitecaps," *J. Phys. Oceanogr.* **46**, 975 (2016).
▶ J. Gemmrich, "Strong turbulence in the wave crest region," *J. Phys. Oceanogr.* **40**, 583 (2010).
▶ J. Gemmrich, "Bubble-induced turbulence suppression in Langmuir circulation," *Geophys. Res. Lett.* **39**, L10604 (2012).
▶ Z. Zhao, E. A. D'Asaro, J. A. Nystuen, "The sound of tropical cyclones," *J. Phys. Oceanogr.* **44**, 2763 (2014). PT

BACK SCATTER

Aurora in a bottle

The solar wind fuels the aurora borealis and aurora australis, also known as the northern and southern lights. The solar wind consists of plasma that is released at supersonic speed from the Sun's upper atmosphere and escapes the Sun's gravity. As the energetic particles approach Earth, some can become entrained by the planet's magnetic field. When they slam into the atmosphere, mesmerizing plasma dynamics ensue, most commonly observable at high latitudes.

One can simulate the solar wind's deflection around Earth in a tabletop lab experiment; all that's needed are a plasma source that can launch plasma packets at supersonic velocities, a dielectric sphere swathed in a magnetic field, and an enclosure that can maintain a partial vacuum. Mounir Laroussi and colleagues at Old Dominion University's Applied Plasma Technology Laboratory have carried out such experiments using a plasma pencil, a device they developed that can emit supersonic low-temperature plasma bullets. The plasma travels at velocities up to 100 km/s, usually along a narrow channel through helium or argon gas. Whereas particles in the solar wind have energies of several keV, the energies in the lab are no more than a few eV for electrons and even less for the plasma ions.

As "Earth," the researchers used a foam ball, 12 cm in diameter, with a small, 100 G bar magnet in its center; they placed the ball in the middle of a glass chamber evacuated to 30–40 torr. Just as Earth's magnetic field deflects most of the solar-wind particles, the field around the model Earth deflects the incoming plasma packets, as seen here. Although many of the specifics differ—the ball, for instance, isn't spinning—the plasma never touches the ball's surface. (M. Laroussi, M. A. Akman, *IEEE Trans. Plasma Sci.* **42**, 2662, 2014; image submitted by Mounir Laroussi.)

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

PHYSICS TODAY Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page PHYSICS TODAY