

# symmetry

A joint Fermilab/SLAC publication

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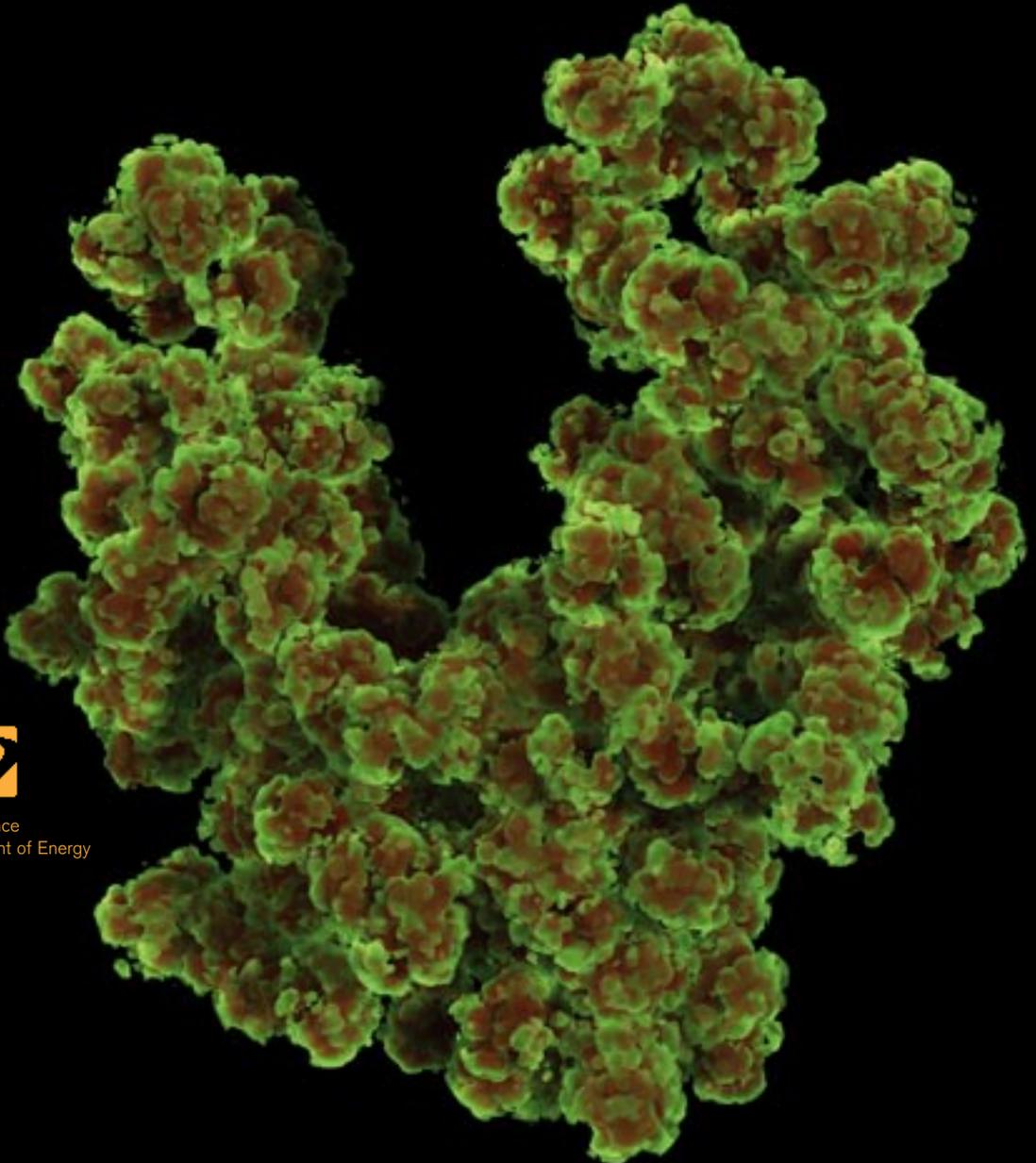


### On the Cover

You're not a trained scientist, but you think you have a great idea that will turn established physics on its head—if only you can get the right people to listen. What to do? Researchers who get these pleas on a regular basis say most ignore the basic rules needed to get a proper hearing: Do your homework. Understand the language of science. Make sure your theory agrees with the results of past experiments. Use reasoned arguments. And, gosh-darn it, get the math right! See story, page 26. *Photo: Reidar Hahn, Fermilab*

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Office of Science  
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### Inside front cover

Simulated image of a molecule as it might be seen by the LCLS, in 3D and with details as small as individual atoms. Researchers are especially eager to aim the LCLS beam at proteins, workhorse molecules that carry out most of life's crucial functions. See story, page 12. *Source: SLAC InfoMedia*

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We needed formulas or calculations that could translate into the movement of bodies through space and guide the dancers as they improvised. As we toured Fermilab, learned more about the machines and the science, and brainstormed with physicists, we found what we were looking for.

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Rare particle decays could provide a unique glimpse of subatomic processes that elude the direct reach of even the most powerful particle colliders on Earth.



Photo: Reidar Hahn, Fermilab

## The balance of science

Particle physics, particle astrophysics, and cosmology are all extreme sciences. They investigate phenomena at one end or the other of various scales: the highest energies, the smallest sizes, the rarest events, the longest distances. Even though

they work at the extremes, all these sciences have close ties to the rest of physics, and to other fields of science. This issue of *symmetry* highlights a few of these connections.

One of the most important technologies to come from the development of accelerator physics is the X-ray light source. It has such a vast range of applications that it is hard to list all the contributions this technology has made toward investigating materials, proteins, energy conversion processes, archaeology, and the environment. The next step in the use of accelerator technology developed by particle physics is the creation of super-bright, ultrafast X-ray lasers. The Linac Coherent Light Source, or LCLS, under construction at Stanford Linear Accelerator Center, will be able to take freeze-frame images of chemical reactions or molecular interactions in process and then combine them into movies that will revolutionize how scientists understand the machinery that makes up the atomic-scale world.

The relationship between particle physics and other sciences is by no means one-way,

and the most common path to innovation has particle physics technologies and science combining with those from other disciplines to create something entirely new. For example, magnetic resonance imaging, or MRI, relies on principles of nuclear physics combined with superconducting wire developed for particle physics applications and magnet systems developed in atomic, molecular, and optical physics. All of these fields and others could claim responsibility for the creation of MRI in their own ways, but the truth is that the application came from the combination.

The science and technology of the LCLS come from too many areas of science to name, but include particle, atomic, molecular, and optical physics; medical, environmental, and materials research; chemistry, biology, engineering, and earth sciences.

This is true for many scientific developments, and highlights the need for scientific research programs to be well-balanced between fields. We never know where the next development will come from, but we can almost be certain that many of the technologies that end up being used by consumers will have originated in basic research done decades earlier in fields that didn't seem to have much in common at the time.

As scientists scramble for funding in difficult budget times, it is vital that they remember, and emphasize to funding agencies, that it is the balance of the research portfolio that is a driver of innovation and that will deliver benefits we can only begin to imagine.

**David Harris, Editor-in-chief**

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### A physicist's place is on the ballot



Photo courtesy of Lesley Stone

Few elected officials, from the President to members of the local school board, have strong backgrounds in science or engineering. Yet, many of the complex problems we face—in areas such as innovation and competitiveness, health care, energy, climate change, education, and even our physical infrastructure—have policy solutions that

depend on an understanding of the sciences.

It's time more scientists got involved in politics. Scientists have a contribution to make to public life. They have a way of thinking that is transferable to the policy realm; problem-solving, evidence-based thinking and testing hypotheses are all likely to generate good policy.

Just as important, scientists have specific knowledge that policymakers from other disciplines lack. Training in law (the background of many of our legislators) is useful for thinking rationally and weighing evidence, but it does not enhance understanding of the importance of nanotechnology, public health strategies, or the processes at work in climate change. These are all areas of knowledge critical to finding solutions to the obstacles we face. Further, the more diverse the expertise and experience a legislature has to draw on, the more likely it is to come up with innovative solutions that will keep us on the right track.

Eight members of the US House of Representatives hold doctoral degrees in science, including the newest addition, Bill Foster of Illinois, who is the third physicist. These scientists have contributed to law and policy in important ways, as have many who serve in state and local government. They are proof that it is possible to serve one's community not only in the lab, but also in civic life.

It's easier than you think to get involved. The local school board is a great place to start. There are about 15,000 school boards in the United States, the vast majority of them elected. Most campaigns cost less than \$1000—though in bigger cities the cost is closer to \$10,000—and serving may mean a commitment of about five hours a week. Yet this commitment is minor

considering the important contributions a scientist can make.

Who better than a scientist to evaluate science, technology, engineering, and mathematics curricula? In some parts of the country, people are searching for innovative ways to insert creationism into science classes. A scientist can keep this from happening by explaining the difference between a scientific theory and an untestable hypothesis. Even in localities where intelligent design is not an issue, we are struggling to find effective ways to help our students learn cutting-edge material so they are prepared for an increasingly competitive world. Study after study shows children in the United States are falling behind in critical areas of math and science; publicizing this issue has not made it go away. But, serving on a school board where you can help evaluate your community's educational programs and options could be a step in the right direction.

For those interested in learning more about running for office, Scientists and Engineers for America, along with a group of scientific societies, scheduled a May 10th workshop in Washington, DC, to teach scientists and engineers the nuts and bolts of running a campaign.

Even if running for office is not on your horizon, it is important to take action. Most scientists believe science should have a place at the table when important policy decisions are made; scientific advisory boards should include the best scientists available; scientists working for the government should be free to discuss their research, regardless of the political implications; and when science is misrepresented by the government, people who speak out should not fear retribution. Yet, well-documented breaches of these principles have become all too common. To ensure that our government values science, we must demonstrate that we value it, both by asking candidates for office hard questions and through the ballot box.

If scientists invest time and energy in politics, whether by running for office or by making sure that potential representatives know what their constituents value, policy will change for the better. Not getting involved means accepting the status quo.

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*Lesley Stone is executive director of Scientists and Engineers for America.*

## signal to background

Tesla coils sing electrifying duets; printers crank out 3D prototypes; breadsick souls hold tastings in Tsukuba; geeks cruise the Caribbean; Congress gains a physicist; *Numb3rs* character joins the DZero experiment



Photo: Jeff Larson, Fermilab

### Now *that's* serious metal music

Tesla coils always draw crowds, and the DucKon science fiction convention in Naperville, Illinois, was no exception. People gathered around the seven-foot-tall metal transformer tower and awaited its monotone crackle, purple sparks, and thrilling flashes of artificial lightning.

But this coil had other plans.

As it fired up, the pitch of its crackle began to rise and fall. A tune emerged. People in the crowd started to cheer and clap. They began to dance. Someone held up a lighter.

A listener shouted a request: "Free Bird" by Lynyrd Skynyrd.

Thanks to Steve Ward, electricity lovers had a soundtrack.

Tesla coils were invented about 100 years ago in a quest

to transfer electricity wirelessly. Today they're known mostly for their entertainment value, used in science projects, haunted houses, and conventions, as well as for movie props.

Ward studies electrical engineering at the University of Illinois at Urbana-Champaign. A YouTube video of his coil's June DucKon performance has received more than a million hits. And a friend of his, Jeff Larson, a senior technician at Fermi National Accelerator Laboratory in Illinois, has built another singing coil so they could perform duets.

Larson estimates that fewer than a few dozen Tesla coils make music. "Our setup got so much attention because it was so big," he says. "Most musical Tesla coils are only a

few feet high and shoot sparks that are a couple of feet long. We can produce 13 feet of spark with ours."

The music starts when a laptop computer signals the coil to emit a spark. The spark heats the air, making a popping noise; when sparks are emitted in rapid succession their sound merges into a musical note. The faster the sparks emerge, the higher-pitched the note.

Ward has written music for this bizarre new instrument. Together, the Tesla twins can be heard humming anything from the theme of the *Mario Bros.* video game to "Dance of the Sugar Plum Fairy" from the *Nutcracker* ballet.

**Haley Bridger**



Photo: SLAC

## Taking prototypes to the next dimension

As popular as the snack vending machine it resembles, a new 3D printer has been busy dispensing plastic-wrapped treats for designers and engineers.

Since the Dimension Elite printer arrived at Stanford Linear Accelerator Center in early January, its tea-box-sized printing head has been on the move day and night, whirring and clicking like a home inkjet printer while it automatically builds up models by depositing many thin layers of melted plastic.

The lightweight models that emerge are more tangible than a set of design drawings and more totable than a 35-pound metal model, easily carried to meetings to show colleagues how a design for an accelerator component would work.

"It's a service for engineers and designers across the lab to study the form, fit, and function of their designs before cutting them in metal," says engineer Kurt Vaillancourt.

Known generically as rapid prototyping machines, 3D printers and their ilk have been used in industry since the late 1980s. The one in SLAC's Mechanical Design Department can build pieces up to 8 inches square by 12 inches high, in layers as thin as 0.007 inch.

Designer Gene Anzalone and his colleagues have eagerly taken advantage of the printer to build models of a collimator that could be used to upgrade the Large Hadron Collider, which is scheduled to start operating this year in Geneva, Switzerland. Collimators block

stray particles inside a pipe carrying particle beams. This one is designed to rotate when damaged, presenting a fresh face of metal so the collider can keep working without interruption.

It took about five days to make the 3D plastic model, which showed that the design worked well. Since the printer works unattended, it saves money on labor as well as materials.

"The model is accurate enough to gain an understanding of how well the parts fit together into a working assemblage," says engineer Steve Lundgren, "and it gives us tangible results at an early phase of the project."

### Heather Rock Woods

## A yen for dough like mom made

Many high-energy physics laboratories have athletic clubs, music clubs, or chess clubs, but a bread-tasting club? Only in Japan. And only at Koo Energy Ken, KEK, outside of Tsukuba.

Bread Tasters of Tsukuba, or BRET, formed in late 2005 in response to some foreign scientists' distaste for Japanese bread.

"It tastes like five-day-old Wonder Bread," says Tokio Ohska, referring to the soft, white sandwich bread that took on an iconic status in the United States as far back as the 1930s.

To be fair, bread is not a staple of the Japanese diet. What Europeans and Americans would eat with bread, the Japanese eat with rice.

Still, food reminds people of the comforts of home, and some foreign scientists and their families were getting a little homesick, not to mention hungry. That presented a problem for Ohska, who as head of the KEK research services office is charged with making foreign scientists feel comfortable at the lab.

Nearby bakeries initially turned down requests to make Western-style bread, citing a lack of imported flour and yeast as well as a lack of demand from Asian customers. So scientists took things into their own hands—literally.

One French scientist started importing ingredients and making his own bread. Ohska tried a different tack. He gathered 15 KEK members, mostly physicists from Europe, America, and Brazil, and started BRET.

Although members have not met recently, at their most active the bread tasters gathered roughly twice a year to sample 30 breads from area bakeries. They sniffed, pinched, and eyed the doughy specimens as if they were the finest glasses of wine. Each piece was rated on its texture, taste, crust, interior, and fragrance.

To keep their palates untainted by foreign flavors, eaters could consume only water, plain tea, olive oil, and unsalted butter with the breads. "Nothing else is provided to the judges, who have to eat through some 30 baguettes," Ohska says. "It is a kind of torture, but they endure it faithfully."

Five Japanese newspapers have run articles on the bread club and published the results of tastings. "This made the bakeries in this town sort of worried," Ohska says. "Now, one of the bakeries is bringing its bread especially in to KEK. It is sold in the restaurant and at the grocery store on site."

And so Ohska's food dreams came true: Taste it, and they will come.

### Tona Kunz



## Geek Cruise

For most people, a Caribbean cruise is an opportunity for sun-splashed daydreaming, guiltless beach reading, and lackadaisical dips in warm, shimmering waters—in other words, complete mental repose. But when Stanford Linear Accelerator Center's Bebo White and Tom Abel boarded the MS Veendam in January, they and their ship-mates had a slightly different agenda.

With the help of four other scientists and two editors from *Scientific American*, White and Abel filled the days on board the Veendam with stimulating lectures, turning it into the challenging intellectual environment known as a Geek Cruise. The 25 lectures covered a wide range of topics, from White's computational science and Abel's astrophysics to evolution, virtual reality, and archaeology.

"It's a really fun experience," says White, who lectured on his first Geek Cruise, called Website Waves, a year and a half ago. "One of the best things about these cruises is that between lectures you talk with everyone at dinner, on deck, and during day trips, so you really become a close-knit group."

The first Geek Cruise, Perl Whirl, embarked in 2000. Most—for instance, Linux

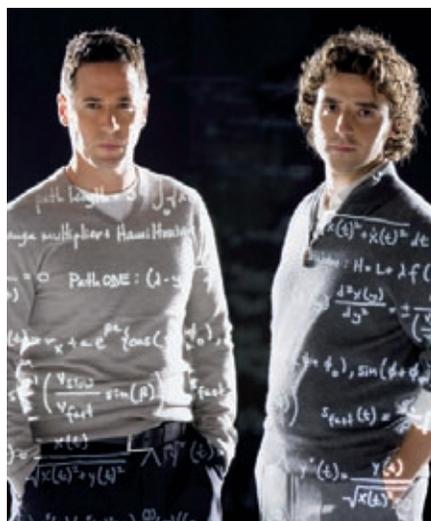
Lunacy, Mac Mania, and Chess Moves—have been quite focused. "With those cruises," says White, "you need to teach a skill. There's nothing like that on this one. We're trying to appeal to their curiosity, and make the subject interesting enough so if they want to know more they can pursue it further."

The January cruise, called Bright Horizons, was Abel's first—Geek or otherwise—and he was excited about bringing his lectures to this unique environment. "It's always great to have a chance to share the fun science you do with the public," he says.

The western Caribbean's cultural richness and tropical charm could not, of course, be ignored by even the geekiest of minds. Cruise participants enjoyed full-day excursions in Key West, Belize City, Santo Tomás de Castilla, and Cozumel, participating in activities as diverse as zip-lining through the rainforest canopy and climbing the ruins of the Mayan temples of Tikal.

"All the talks and programs are during the period at sea," says White, "so when you get to the ports, everyone can play tourist. That way, the lectures really only cut into your casino time."

**Lizzie Buchen**



## Numb3rs to DZero

On the hit television show *Numb3rs*, where crimes are solved with math and science, cosmologist and theoretical physicist Larry Fleinhardt has lived in a monastery and flown into space searching for a sense of purpose. The next step takes him to Fermilab.

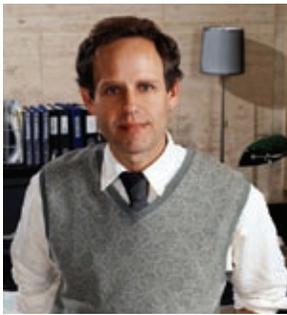
Fleinhardt, played by actor Peter MacNicol, told nine million viewers in January that he had accepted an offer to join the lab's DZero experiment, calling it "the work of a lifetime."

An earlier episode had him describing the job this way: "Can you imagine? Smashing protons at 99.99 percent of the speed of light, all to locate a single fragment which would move us one step closer to

Photo courtesy of CBS

Photo courtesy of Tom Abel, SLAC





unifying all physics, explaining how the Old One created the universe? Ah, what could be more spiritual?"

DZero is one of two experiments at the Tevatron accelerator that are racing to find the Higgs boson, a theoretical particle thought to endow other particles with mass. That search for one of the Holy Grails of particle physics attracted the attention of the show's writers.

Fleinhardt plays both sidekick and mentor to *Numb3rs* mathematician Charlie Eppes. Ever since the series started he has struggled to construct a workable 11-dimensional super-gravity theory. That quest recently led him to focus on particle physics and the search for the Higgs, according to the show's co-creator, Nick Falacci.

Scientists working on DZero love the idea and have created an office for the make-believe physicist.

For the time being, the extent of Fleinhardt's involvement with DZero is unclear, and the show's creators have not decided if he will actually visit Fermilab.

But Darien Wood, co-spokesperson for the DZero experiment, says even limited involvement would be a plus.

"The characters on the show speak with great excitement and reverence about the search for the Higgs boson at DZero, and I think it captures some of the passion that we real particle physicists have for our work," he says. "Maybe young people who watch the show will even think about pursuing physics as a career."

**Haley Bridger and  
Tona Kunz**

## One more physicist goes to Congress

Upon becoming the third physicist in the 110th US Congress, Bill Foster called his election "a pretty successful experiment"

The scientific community hopes it's a statistically significant experiment as well, signaling that the American public may want, and support, more scientists in public office. Foster's win with 53 percent of the vote, in a March special election to fill the seat of retiring Illinois Rep. Dennis Hastert, makes him one of eight people among the 535 voting members of Congress who hold science PhDs. They include physicists Rush Holt of New Jersey and Vern Ehlers of Michigan, both in the House of Representatives.

While the economy, health care, and the war in Iraq were in the forefront of Foster's House campaign, he also touted his scientific credentials in commercials and mailers and on his Web site. He was endorsed by 28 Nobel laureates and many top researchers. Foster pledged to bring the same thorough analysis to politics that he brought to his business—a company that manufactures more than half the theater lighting in the

United States—and to his 22 years as a Fermilab researcher.

While at Fermilab, Foster co-designed the Recycler, an antiproton storage ring that has increased the rate of particle collisions at the lab's Tevatron accelerator. He was one of six employees to win a federal energy award for their use of permanent magnets in the construction of a beam line, which saved water and energy and reduced waste. Foster also worked on the Collider Detector at Fermilab, which discovered the top quark, and designed a computer chip to make faster and more accurate measurements of particle collisions.

Foster says an understanding of science and technology is key to solving the economic and technological challenges of the modern age, from climate change to the feasibility of electronic border fences. "My entire career has been spent solving problems," he said in a press release.

"Washington needs more solutions and less squabbling. As a scientist and businessman, I have the right formula to bring about real change."

**Tona Kunz**

Former Fermilab physicists Bill Foster (right), now a member of the US House of Representatives, and Gerry Jackson inspect components for a new particle storage ring in 1996.



# New SLAC director grapples with change

Layoffs, budget cuts, a call for new vision in high-energy physics—in her first months as director of Stanford Linear Accelerator Center, Persis Drell had a lot to navigate. **By Glenda Chui**



Photos: Brad Plummer, SLAC

When Persis Drell became director of the Stanford Linear Accelerator Center last December, news accounts focused on her role as one of the first female directors of a US national laboratory.

But while taking note of that milestone, the high-energy physics community focused on a more pressing question: How would Drell guide SLAC through perhaps the most challenging time in its history?

The lab had already called for voluntary layoffs, part of an effort to adjust the mix of skills in its workforce to the needs of future programs; 72 people responded. Then, just 11 days after Drell took over, Congress cut funding for high-energy physics, resulting in a 20 percent reduction in SLAC's high-energy physics budget for FY08. Drell led the SLAC management team in making the wrenching decision to lay off 119 more employees and to end operations of the *B*-factory, the lab's only on-site particle physics experiment, months earlier than planned.

It wasn't long before Drell began to articulate, in unabashedly frank language, a call for vision at SLAC and in the physics community.



### **Unsettling questions**

At meetings of two influential advisory panels, best known by their acronyms, HEPAP and P5, she tackled the field's reduced budget prospects head-on. While some in the field saw Drell's words as divisive, she says they were not intended that way.

"The future of particle physics at SLAC is intimately coupled to the basic questions facing high-energy physics as a whole in the US," she told HEPAP. "I believe particle physics has fared poorly because we were perceived as not having a realistic plan for our future."

She went on to pose a series of questions the field must answer to justify the funding needed to maintain a healthy program: Does the US really need to operate its own high-energy physics accelerator? Beyond Fermilab, the designated national accelerator laboratory for high-energy physics, does it really need high-energy physics programs at other labs, such as SLAC, Lawrence Berkeley, Cornell, or Brookhaven? What role should the United States take in the international effort to push accelerator physics to ever-higher energies?

"The answers to these questions cannot be based on what we will lose if we don't get what we want," Drell told the panels. "They have to be based on what we will win."

Yes, Drell acknowledges, her questions were intentionally provocative.

"Those questions were designed to make everyone feel uncomfortable," she says. "But I think one of the most damaging things the field could do would be to marginalize the importance of dealing with the really difficult issues we are facing by saying, 'Oh, this is just one lab versus another.' We have to deal with the question of why we need to continue strong support of high-energy physics in this country when the frontier of the field is moving to Europe. My main point is if we don't ask these questions, somebody else will, and we have to be prepared to answer them."

### **Vintage Persis**

The message may have been a surprise, but not the fact that Drell delivered it.

"It's really vintage Persis," says Jim Alexander, director of Cornell University's Laboratory of Elementary-Particle Physics, who has known and worked with Drell since their postdoc days. "She's taking the long view, looking at the biggest and broadest issues, and she's quite willing to say things that are controversial. People listen very carefully to her because they respect her and they respect her judgment, but it certainly doesn't mean they're going to agree with her."



Drell's roots at SLAC go deep; her father, Sid Drell, was the lab's deputy director. ("See if you can avoid mentioning my father in the first paragraph," she says, laughing. "I always resent it when women get defined by the males in their lives.") She earned a PhD in atomic physics at the University of California, Berkeley and did a postdoc at Lawrence Berkeley National Laboratory that included work on SLAC's MARK II detector.

In 1988 she joined the faculty at Cornell, where she used the CLEO II detector to study the physics of  $B$  mesons and helped that lab face its own transition.

"Persis was here when it became clear that CLEO was going to have to end as an experiment doing  $B$  physics, and she was absolutely instrumental in seeing the path beyond CLEO," says Ritchie Patterson, a Cornell professor who was Drell's first postdoc there.

Patterson says Drell was a valuable mentor, both as a scientist and as a woman working in an overwhelmingly male field.

"She didn't really hide the fact that her family life was important to her," Patterson says. "So she would move the seminar half an hour earlier so she could pick her kids up from daycare. There were plenty of fathers who needed to go pick up their kids, too, but who hadn't done anything about it or who snuck out early. I think it was probably a welcome change for an enormous number of people."

As for research, Patterson says, Drell is "wonderful at getting to the heart of a problem. So you can see a big mess in front of you and she can distill it into its essence. She has an incredible understanding of what people need to be effective and to do good science."

### **Shifting gears**

By the time Drell moved to SLAC in 2002, her interest had shifted to particle astrophysics. She chaired a task force that produced *Quantum Universe*, a report that outlined, in clear and compelling language, nine fundamental questions about the nature of the universe that particle physics is poised to address. She also served as deputy project manager of GLAST, the Gamma Ray Large Area Space Telescope.

"You know, my greatest frustration with this job I have is that GLAST is going to launch soon, and there's a big piece of me invested in that instrument, and I'm not going to get to have fun with the first data," Drell says. "When you put up a detector that's orders of magnitude better than anybody has ever put up before, even the novice can have fun."

***"The umbrella under which we see our future scientific program developing is seeking to understand the structure and dynamics of matter, from the very smallest to the very largest scales in the universe."***

In fact, Drell made the move into the directorship reluctantly. About 18 months after agreeing to serve as SLAC's deputy director in 2005, she made it clear that her intention was to step down and return to research. But when the president and provost of Stanford University asked her to take the director's seat, in the end she could not say no; the subsequent budget cuts, she says, "only made it clearer that a new person coming in would have had a very difficult time doing what we had to do."

What does the future hold for SLAC?

"The umbrella under which we see our future scientific program developing is seeking to understand the structure and dynamics of matter, from the very smallest to the very largest scales in the universe," Drell says.

"Whatever we choose to do—there is going to be a set of fields we choose to engage in—we're going to be outstanding in those fields. I don't want to be second-best. Excellence is in the tradition of this laboratory, and I don't want to change that."

### Setting a course

With the *B*-factory no longer operating, the lab's focus is shifting to photon science at the Linac Coherent Light Source, which will image processes on atomic scales of length and time with extraordinarily brilliant beams of X-ray light. It's scheduled to open in 2009.

Drell says SLAC will maintain its excellence in accelerator physics, performing research that helps define the technology frontiers for the field. It will collaborate on ATLAS, one of two major detectors at the soon-to-open Large Hadron Collider on the Swiss-French border; Drell says she hopes to create a regional center to support ATLAS scientists on the West Coast.

At the other end of the scale, she plans to maintain the lab's leadership role in particle astrophysics through the Kavli Institute for Particle Astrophysics and Cosmology, the GLAST mission, and the proposed Large Synoptic Survey Telescope, which would scan deep space for clues to dark matter and dark energy.

Drell also wants to build even stronger ties with Stanford University, which manages the lab for the Department of Energy, and with Silicon Valley—although she admits she has no clue what that might entail. "At this point, this is just a dream," she says, "but fundamental research in the photon science field can link rather directly to more mission-directed research, which can link more directly to actual deliverables. I don't want to become an applied science lab, but to the extent that we understand those couplings better, I think it'll be better for everybody."

To read a transcript of the interview, go to <http://symmetrymagazine.org/drell/>



The background features several 3D-rendered rectangular blocks in various shades of teal and blue, arranged in a way that suggests depth and perspective. The lighting creates soft shadows and highlights, giving the blocks a metallic or crystalline appearance. The overall composition is clean and modern, with a strong color palette of teal and blue against a black background.

# From atom smashers to X-ray movies

By Brad Plummer

**When particle accelerators gave birth to the powerful X-ray microscopes known as synchrotrons, they revolutionized the study of virtually every field of science. Now the Linac Coherent Light Source promises to make an equally big leap, making movies of atoms and molecules in action and changing the way we think about matter.**

In this artist's conception, a pulse of electrons travels a wiggling path through an undulator, an array of magnets, in the LCLS. This causes the electrons to give off intense X-ray light—shown here as a white glow—which can be used to study structures as small as atoms and molecules.  
*Image: SLAC InfoMedia*

**P**article physics has done far more than deepen our understanding of the fundamental make-up of matter; it has forced researchers to invent the very tools with which to conduct their work.

First came the cyclotron, a circular accelerator for smashing subatomic particles together. The cyclotron spawned generations of ever-bigger accelerators, from one that would fit in your hand to the Large Hadron Collider, soon to open on the Swiss-French border, which spans several postal codes and requires teams of thousands to operate.

As it evolved, accelerator technology unexpectedly gave rise to a whole new field called photon science. It sprang from a major hassle confronting high-energy physicists—the fact that electrons racing around in circles give off radiation in the form of X-ray light. Researchers found a way to put this “synchrotron radiation” to work; the result was a billion-fold increase in the brightness of X-rays available for probing processes at very small scales, and a new generation of machines known as light sources.

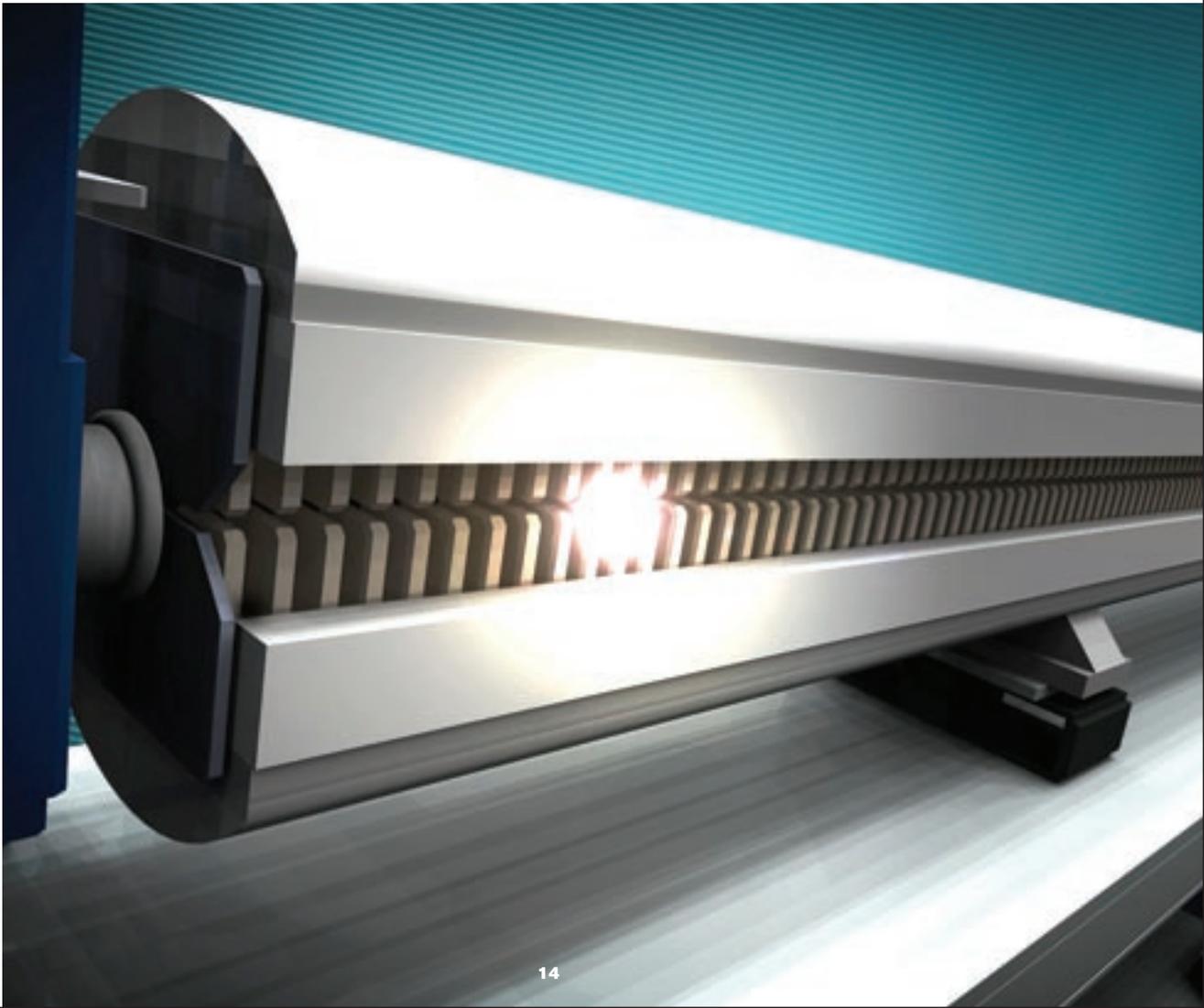
“Light-source science was born from the table scraps and headaches of physics research,” says Claudio Pelligrini, a physicist at the University of California, Los Angeles. “This is a case of using negative or unwanted phenomena, in which nature is helping us do what we want.”

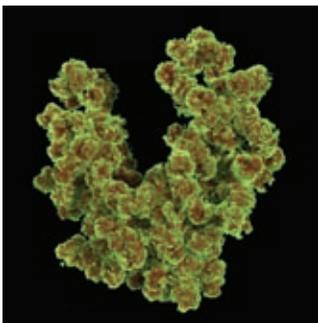
Photon science is one of the most revolutionary spin-offs of high-energy physics, with practical impacts in fields ranging from medicine and archaeology to materials and environmental science.

Now, thanks to further advances in accelerator technology, photon science is poised to take another major leap at the Linac Coherent Light Source, or LCLS, scheduled to open next year at the Stanford Linear Accelerator Center. The LCLS will produce X-ray beams that are a billion times brighter still, paving the way for an entirely new way of understanding the chemistry of life and the physics of condensed matter.

**One of the undulators within the LCLS. Each one weighs a ton and is about two meters long. The “teeth” in this rendering are actually alternating pairs of north-south magnetic poles. As pulses of electrons wiggle their way through the magnet array, they generate bright X-ray light.**

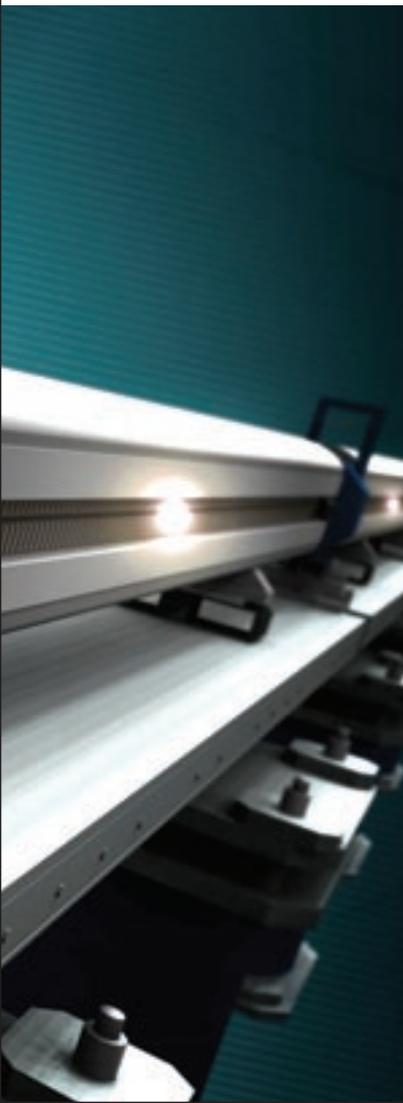
*Image: SLAC InfoMedia*





**Simulated image of a molecule as it might be seen by the LCLS, in 3D and with details as small as individual atoms. Researchers are especially eager to aim the LCLS beam at proteins, workhorse molecules that carry out most of life's crucial functions.**

*Image: SLAC InfoMedia*



For the first time, scientists could make 3D images of individual molecules, as well as 3D movies of chemical reactions and other dynamic processes never before seen by human eyes. Today's light sources can determine the structures of proteins; the LCLS will film them as they fold and unfold and interact with other molecules.

Research there could reveal the way substances really behave, taking us from computer models to real life, says David Tiede, who studies molecular motion at Argonne National Laboratory; he's among those hoping to use the new machine. "It will change the way we think about molecules," he says. "This is really the start of a whole new science."

### **Brighter, tighter, faster**

Light source research facilities generate all kinds of light, from visible through ultraviolet and X-rays. It's the wavelength of that light that determines how small a structure we are able to see. The wavelength of visible light is slightly smaller than cells and bacteria, which is why we can see them under a light microscope. Hard X-rays have the very short wavelengths needed to illuminate even smaller objects, from viruses to proteins and other molecules. The LCLS will be the first machine of its type to probe matter with hard X-rays.

What's more, it aims to generate beams a billion times brighter than those at today's synchrotrons—which are, in turn, about a billion times brighter than previous laboratory sources.

Synchrotrons made that initial leap by packing a billion times more photons, or light particles, into a single pulse. This decreased the exposure time needed to look at a sample from days to minutes, giving scientists the first practical way to study very small objects.

The LCLS will achieve another billion-fold increase in brightness by compressing photons into much shorter pulses, about one-quadrillionth of a second long. Like a high-speed strobe flash, these ultra-short pulses would freeze the motions of processes that happen very fast—from electrons jumping from one energy level to another within an atom to chemicals reacting. The LCLS will reveal the first glimpses of the chemistry of life unfolding.

"The LCLS is as big a jump in peak brightness above storage rings as storage rings were above laboratory X-ray machines," says John Galayda, director of construction for the project.

One downside to that kind of power is that it can blow a sample to bits. But because the LCLS's pulses are so fast, an image can be collected in the fraction of an instant before the sample blows apart.

The LCLS "will be a world-leading machine. It's an exciting machine. It will be a hard machine to make work," says William Barletta, director of the US Particle Accelerator School, who is based at the Massachusetts Institute of Technology. "I don't think the people building it have any illusions that it will be easy. But SLAC has a long history of being able to tackle those kinds of technical challenges successfully."

### **The first of its kind**

Light from the LCLS will also be coherent, or laser-like, with its waves lined up like the tracks of snow skiers carving downhill in unison. Coherent beams give scientists the power to do a whole different class of experiments, including making 3D images of very tiny things.

The LCLS is a free-electron laser, or FEL—the most powerful one in the world for some time to come. Free-electron lasers were developed in the 1970s by John Madey at Stanford University. Unlike traditional optical lasers, which generate light from excited atoms, FELs exploit unbound or "free" electrons moving through a vacuum chamber at nearly the speed of light to create their beams.

The key to achieving these coherent beams is an undulator—a set of magnets—that forces the electrons to wiggle back and forth. This causes them to give off X-rays, which in turn act back on the electrons, gradually nudging them into tighter and tighter bunches. The result is an electron

"crystal"—sheets of electrons, precisely layered, that produce intense, coherent laser radiation. If the magnet array is long enough, the electron pulse can achieve this state during a single pass. This feature is what permits an FEL to work in the hard X-ray region of the spectrum, according to Pellegrini, one of the developers of the theory behind the single-pass FEL.

To build the LCLS, crews are modifying SLAC's two-mile-long linear accelerator, adding half a mile of tunnels chewed into the California sandstone.

With the recent end of data collection at the SLAC *B*-factory, the lab's only on-site particle physics experiment, the LCLS also marks a shift in SLAC's scientific emphasis from high-energy physics to photon science.

Five institutions—UCLA and Argonne, Brookhaven, Lawrence Berkeley and Lawrence Livermore national laboratories—are collaborating with SLAC to build the LCLS, which is scheduled to start operations in 2009, at a total project cost of \$420 million.

Though the LCLS will be the first of its kind, a number of similar machines are soon to follow. Japan is scheduled to open the SCSS, or SPring-8 Compact SASE Source, in 2012, and Hamburg's DESY lab plans to open the European XFEL in 2013. Like the LCLS, both will generate short-wavelength X-rays. How short? A hydrogen atom is about one ångström, or one ten-billionth of a meter, in diameter; the typical distance between atoms in a molecule is also one ångström. LCLS will generate X-rays as short as 1.5 ångströms; the European XFEL, down to 0.8 ångström; and SCSS, one ångström.

"There's a big class of experiments that's just waiting for FELs to be available," Barletta says. "There are many, many more potential users than there will be beam time to go around."

Future possible upgrades to the LCLS include installing additional undulators to create softer or harder X-rays. The machine now uses just one-third of the two-mile-long linear accelerator to rev up electrons; eventually it could use the entire linac to drive multiple experiments at various wavelengths.



**SLAC's Burton Richter analyzing data from the SPEAR storage ring, which opened in 1972. He shared the 1976 Nobel Prize in Physics for the discovery of  $J/\psi$  particle there.**

*Photo: Vera Luth, SLAC*

### Turning trash into treasure

Even though the LCLS became a technical possibility only within the last 15 years, it has a long pedigree that begins with the birth of high-energy physics.

The early decades of accelerator research centered on firing beams of particles at fixed targets to probe the inner workings of atoms. But in the 1970s, a group of physicists at SLAC, led by Burton Richter, proposed a project to store accelerated particles in a ring-shaped vacuum chamber lined with magnets. Within this ring, opposing beams of positrons and electrons could circulate for hours at a time, colliding many times a second; in the debris, scientists looked for clues about the behavior and identity of subatomic particles, deepening our understanding of the fundamental laws of physics.

However, researchers paid a price for the efficiency of storage rings. Electrons, positrons, and other charged particles dislike being forced to travel in a circle, and they express their displeasure by radiating waves of electromagnetic energy. That energy was a downright nuisance for early particle physicists, who had to shield themselves and their sensitive equipment from this synchrotron radiation.

As colliding-beam storage rings became increasingly powerful, the synchrotron radiation became more intense, to the point where X-ray physicists began to take notice. When operated at energies of a few billion electron volts, or GeV, colliding-beam rings produced synchrotron radiation in the form of very bright hard X-rays.

Richter went on to share the 1976 Nobel Prize in physics for the discovery of the  $J/\psi$  particle with SLAC's colliding-beam storage ring, and later became director of SLAC. From the earliest days, he and a handful of other researchers had agreed that perhaps those X-rays could be put to good use.

The process of making a 3D image of a single molecule starts with very short, bright pulses of X-ray laser light. These pulses carry so much energy that they destroy the molecule—but not before producing a diffraction pattern in a detector. By stringing together data from about 10,000 pulses hitting 10,000 molecules at a rate of 120 per second, researchers could reconstruct the 3D structure of a complex molecule, such as a protein. The technique can also be used to make stop-action movies of chemical reactions and other ultra-fast processes.

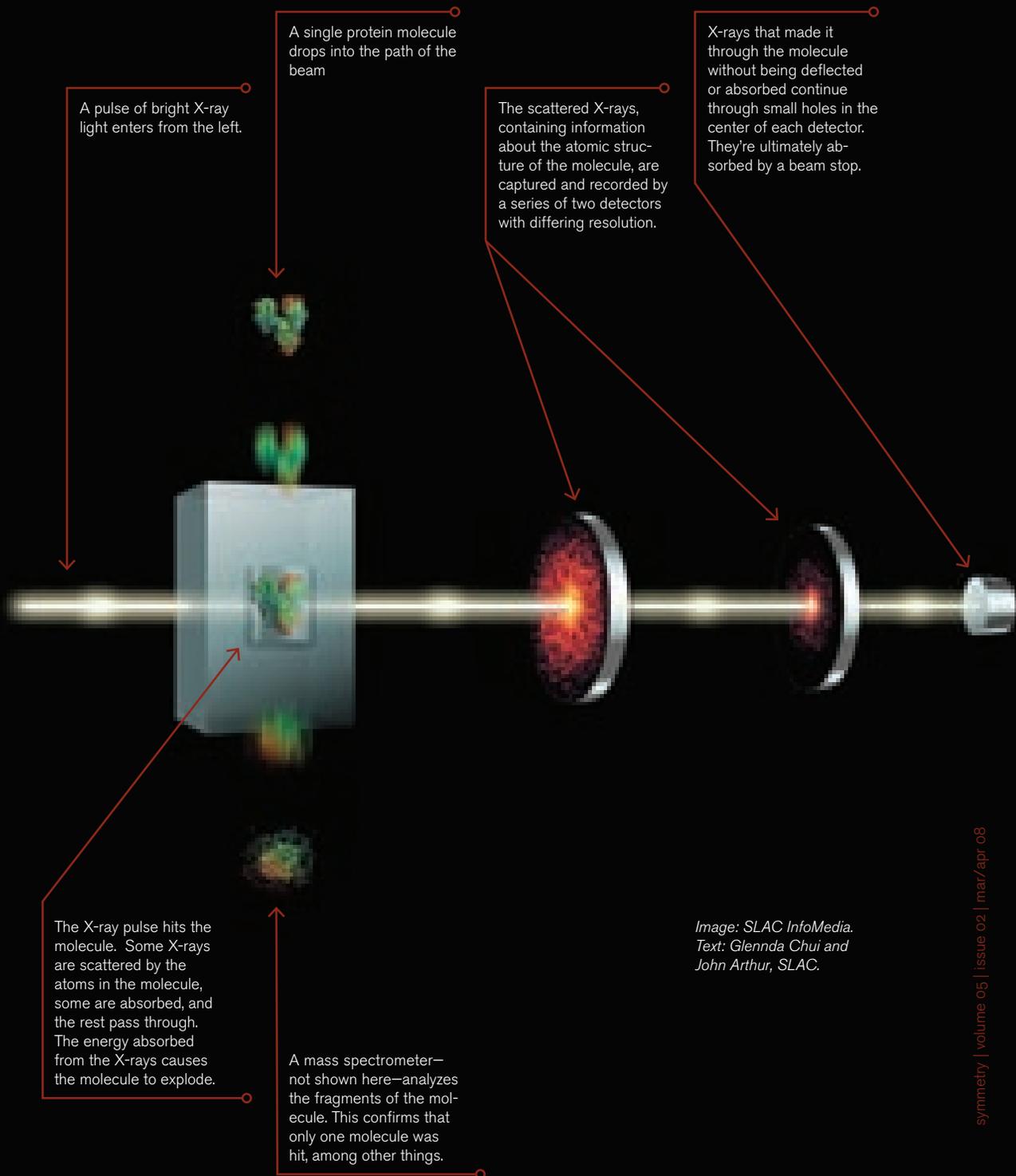




Photo: SLAC

"Sebastian Doniach and William Spicer came to me and said that if we could let the X-rays out, they could revolutionize condensed matter physics," says Richter. The two men, he says, delivered on that promise.

Thirty years later, more than 60 light sources around the world generate intense beams of synchrotron light, mostly in the form of X-rays and ultraviolet light.

Almost all branches of science have benefited from "letting the X-rays out." Synchrotron users are developing better ways to capture solar energy and store and use hydrogen as an energy supply. Projects are under way to map the structures of all the proteins in our bodies. And environmental scientists use synchrotrons to understand how pollutants move through the environment, resulting in better methods for cleaning up toxic waste.

### Straightening the circle

As photon science continued to mature, high-energy physics reached a roadblock in the effort to push electron accelerators to higher energies. The circular design had reached its limit of practicality; studying physics phenomena with electron beams at energies greater than a couple of hundred GeV would require an entirely new kind of machine.

Enter the linear collider, a machine conceptualized around the straight design of the original fixed-target accelerators. Because it has no curves, it generates a minimum of unwanted synchrotron radiation. And in principle it could achieve much higher energies than a circular collider of the same length.

The Stanford Linear Collider, or SLC, operated from 1989 to 1998 and was the first test bed for the linear collider concept. Because it was the first of its kind, and because the technical requirements for producing collisions at the interaction point were so stringent, getting the SLC to work tested the abilities and patience of physicists.

"The initial problem was reliability," says Nan Phinney of SLAC, the accelerator systems project leader for the SLC. "If a machine's not very well understood, and it breaks and you put it back together again, it takes a long time to recover. If it breaks enough, you might never recover."

It took five years to bring the SLC to the point where it could start collecting data. But once it got there, it turned in a stellar performance, collecting precise measurements associated with the Z boson and helping to further elucidate the link between the electromagnetic and weak forces.

The expertise gained at the SLC gave photon scientists a new range of possibilities to consider. Once again, they put those lessons to use in creating the next-generation light source—the LCLS.

"No one would have proposed the LCLS if the SLC hadn't happened," says Phinney. "It would have been unthinkable."

### Transforming research

Liberating those first hard X-rays from electron accelerators transformed how we study just about everything in science. For instance, by pinpointing the locations of tiny traces of metal in slices of brain tissue, scientists are gaining a better understanding of the mechanisms of diseases such as Parkinson's and Alzheimer's. At the Rocky Flats weapons plant in Colorado, synchrotron studies saved taxpayers billions in cleanup costs by showing how uranium binds with soil, giving specialists the key to efficiently halting its movement. Synchrotrons also played a role in discovering the structure of RNA transcriptase, a molecule responsible for telling our cells which proteins to make. That work garnered Stanford professor Roger Kornberg a Nobel Prize in Chemistry in 2006.

The study of proteins, in fact, may be the field most influenced by synchrotron science. Proteins are the workhorse molecules that carry out most of the functions in our bodies, and their structures give clues to how living things work at the most fundamental levels. To work out a protein's structure, researchers first grow a purified sample into a crystal, usually no bigger than a grain of salt, and expose it to a needle-thin beam of X-rays,

which diffract and interfere with each other and register a distinctive pattern on a detector. Researchers use that pattern to work out the structures of individual molecules.

Synchrotrons have made it possible to conduct such studies in volume, creating a growing library of protein structures that are invaluable for research in biology and medicine. However, some proteins refuse to be crystallized, leaving no way to study their structures in detail.

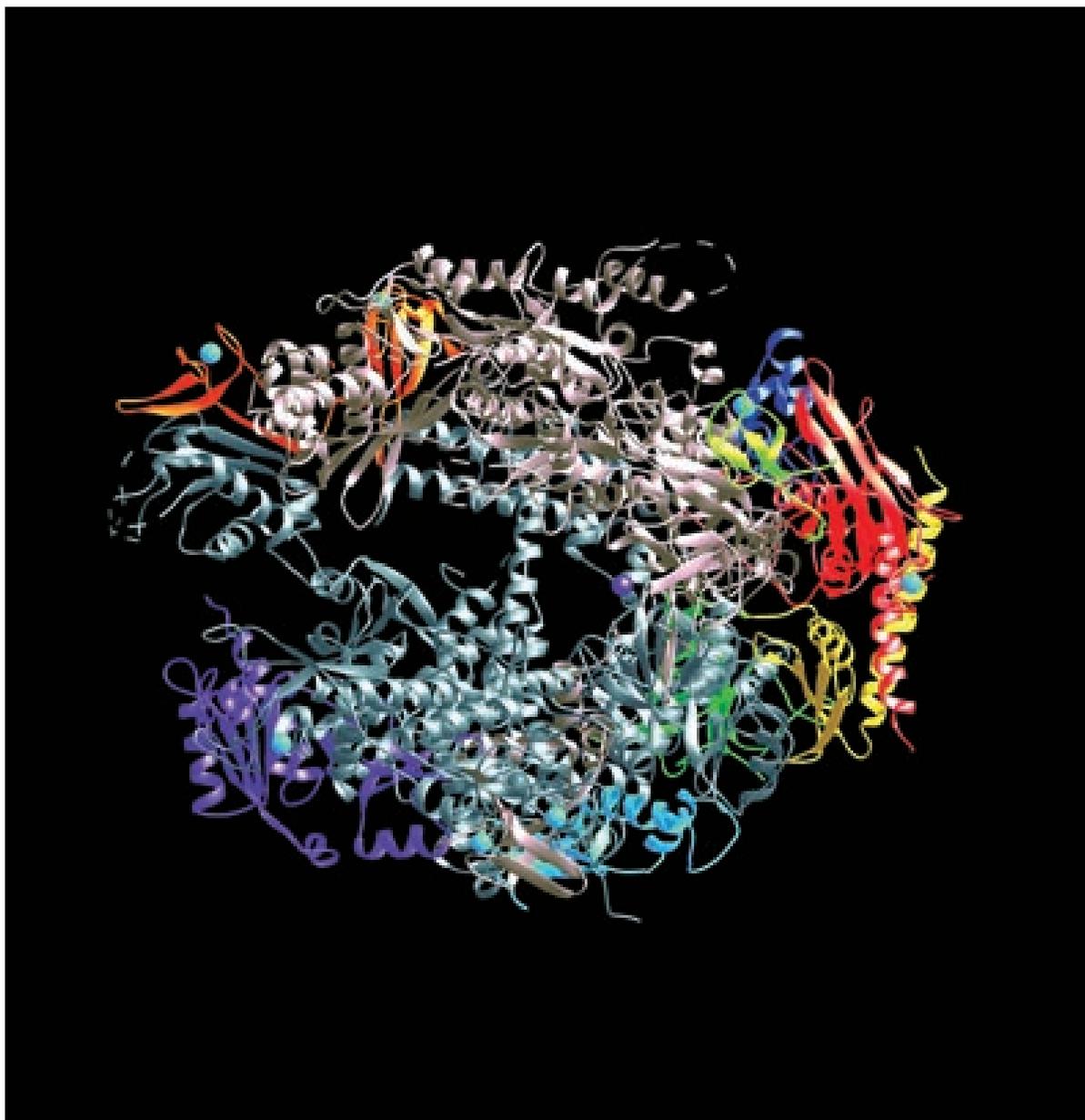
The LCLS removes this obstacle; it can make 3D images and movies of samples that have not been crystallized. This will allow scientists to study processes they can't reach in any other way. They might create and probe new states of matter, including ultra-high-temperature plasmas like those at the center of the sun. Researchers could also selectively remove electrons from an atom—up to an entire orbital shell at once—to create "hollow atoms" that tell us about the behavior of matter that doesn't exist in nature.

"The first science from the LCLS will be very exciting," says SLAC Director Persis Drell. "But the LCLS is such a revolutionary tool that I believe the greatest experiments that will be done are the ones we haven't even thought up yet."

**This protein molecule, called RNA polymerase, contains more than 30,000 individual atoms. It plays a vital role in copying the genetic information contained in DNA and translating it into the chemical processes that are the foundation for life. Scientists worked out its structure using diffracted beams of X-rays generated by a synchrotron.**

*Image: SLAC*

**An animation showing how the LCLS will work is at <http://symmetrymagazine.org/LCLS/>**





# SECRET OF THE PYRAMIDS

In a boon for archaeology, particle physicists plan to probe ancient structures for tombs and other hidden chambers. The key to the technology is the muon, a cousin of the electron that rains harmlessly from the sky. By Haley Bridger

*Illustrations: Sandbox Studio*



the dense jungles of northwestern Belize, the sound of metal hitting rock startles flocks of tropical birds and troops of black howler monkeys. Archaeologist Norman Hammond and his team stop digging. They have hit a stone wall 10 feet below ground; inside is a royal tomb. After almost one hundred test excavations at La Milpa, an ancient Mayan city of 50,000 people, Hammond has unearthed something big.

Within the tomb lie the remains of a man wearing a jade pendant in the form of a vulture's head. He is thought to be either Bird Jaguar, the fifth-century ruler of La Milpa, or one of Bird Jaguar's successors.

And finding him was an incredible stroke of luck.

Hammond made his famous discovery more than 10 years ago, but repeated efforts to find other tombs at the site have come up empty-handed. Lacking an ancient map of La Milpa or blueprints for its five pyramid mounds and buried plaza, archaeologists rely mostly on instinct. They run the risk of piercing priceless relics with their shovels or digging fruitlessly for years.

The ground beneath the site "could be Swiss cheese, for all we know," riddled with burial chambers, tunnels, and hidden entrances, says Hammond, who is based at Boston University.

Now researchers hope to find those hidden spaces with the help of particle physics.

### A cosmic X-ray machine

The key to the new approach is the muon, a heavy cousin of the electron that's created when cosmic rays hit the atmosphere. Muons pass harmlessly through people and buildings; in fact, nearly 600 of them fly through your body each minute. They fascinate scientists because they're one of the few high-energy particles raining down from the sky that can be examined for clues to the nature of the cosmos. Particle physicists started building muon detectors in the 1940s and they're still at it today; the most advanced particle detectors in the world, at the Large Hadron Collider in Geneva, Switzerland, have components that record muons created in particle collisions. But it's the ability of the muon to penetrate deep into rock and water that has archaeologists excited.

Muons traveling through rock or other dense material will slow and eventually stop, while those flying through empty spaces keep going full-speed. The idea is to catch the muons after they've passed through an archaeological site and measure their energies and trajectories. With this information, researchers can reconstruct their paths and compile a 3D image that reveals hidden chambers or other voids.

### La Milpa

Scientists at the University of Texas at Austin plan to place two muon detectors on either side of a pyramid at La Milpa in Belize. This arrangement gives them a stereo view of the site, making it easier to compile a 3D image.

*Photo: Norman Hammond, La Milpa Archaeological Project*

*Schematic: Sandbox Studio*



If archaeologists are like surgeons probing a patient, physicists are the radiologists whose X-rays show where to cut and how to do it safely. Just as X-rays leave patients unscarred, muons offer a way to explore ancient ruins without disturbing them.

This fall, a team led by Arturo Menchaca-Rocha of the National Autonomous University of Mexico, or UNAM, plans to place a muon detector beneath the Pyramid of the Sun in Teotihuacán, northwest of Mexico City. Meanwhile, Roy Schwitters of the University of Texas at Austin is making plans to install muon detectors in wells dug on opposite sides of a mound at La Milpa.

The detectors will gather muons for about a year, slowly building a picture of the interior of each pyramid.

### First stop: Egypt

Muon detectors have a rich history of revealing the unusual and the unseen. Sixty years ago, scientists in Australia used them to measure layers of mountain snow. Today, Japanese scientists are testing the technology as a way to track magma rising within volcanoes, a possible sign of impending eruption. Border patrol agencies in the United States see muon detectors as a potential way to uncover radioactive materials shielded and hidden inside cargo containers and trucks.

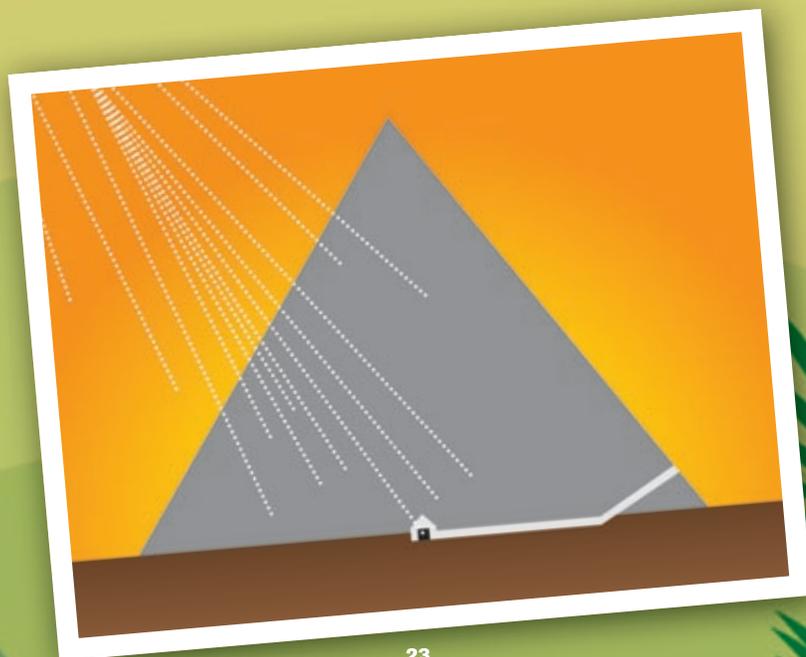
It was about 40 years ago that archaeologists tapped muons for the first time. Luis Alvarez, a Nobel Prize-winning physicist at the University of California, Berkeley, wondered if muons might reveal chambers in the Second Pyramid of Chephren, one of the three great pyramids of Egypt, that had somehow escaped the notice of archaeologists and looters for 4500 years.

Alvarez and his team put a detector in the Belzoni Chamber, near the center of the pyramid's base, and left it to collect muons for two years. They concluded that no additional chambers were hidden in the limestone above, although the scan was able to distinguish the four edges of the pyramid and what little remained of its smooth limestone facing. While it would have been more exciting to discover a new chamber, this information was nonetheless valuable for Egyptologists and archaeologists studying the pyramid—and it showed that the technique worked.

There are other high-tech ways to explore a ruin. Ground-penetrating radar reflects off buried features, while electrical-resistivity probes measure the increased resistance to electrical flow due to the presence of stone and brick. Though useful, neither of them probes as deeply or takes as wide a view as the muon detector does.

#### Egypt

In the first experiment of its kind, a team led by Luis Alvarez placed a muon detector in a chamber of Egypt's Second Pyramid of Chephren. Although the muons revealed no hidden chambers, the experiment showed that the method had value for archaeology. Schematic: Sandbox Studio



## The Pyramid of the Sun

In the early 1970s, a pair of archaeologists cleared stone and gravel out of a well at the base of the world's third-largest pyramid, the Pyramid of the Sun at Teotihuacán. Beneath the rocks they found a stairway leading to a tunnel 100 meters long and eight meters below ground. It opened an extraordinary opportunity for the physics community, Menchaca-Rocha says: "It is the key that will allow us to carry out an experiment similar to that of Alvarez" by placing a muon detector directly below the pyramid.

Menchaca-Rocha hopes to put the detector in place this fall and begin collecting data by the end of the year.

The detector contains six gas-filled chambers. When a muon travels through one of them, it collides with particles in the gas and gives off light. By recording those light flashes and noting exactly where the muon entered and left the chamber, researchers can calculate its energy and trajectory. Menchaca-Rocha thinks the detector will reveal any cavity more than 75 centimeters—30 inches—tall.

The results could help to answer a question that has stumped archaeologists for decades: What was the purpose of the pyramid?

Linda Manzanilla, an archaeologist with UNAM, studies Teotihuacán, once a bustling center full of pyramids and temples. "It was a city that attracted many people," she says, "and it flourished for five centuries." She believes a volcanic eruption drove people from the north towards the valley where the metropolis rose; "There they built a temple to appease the fire gods."

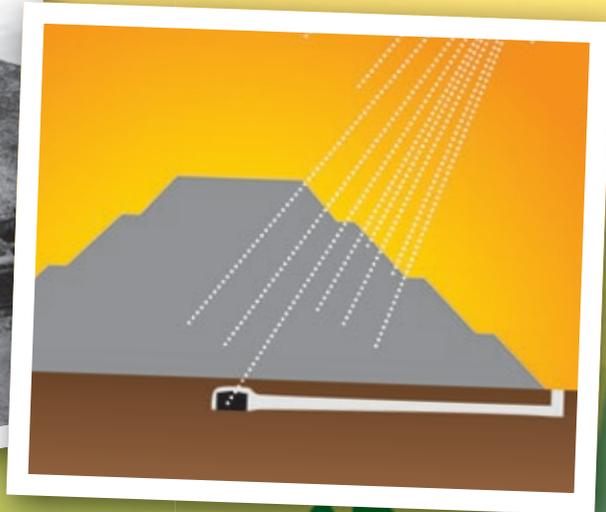
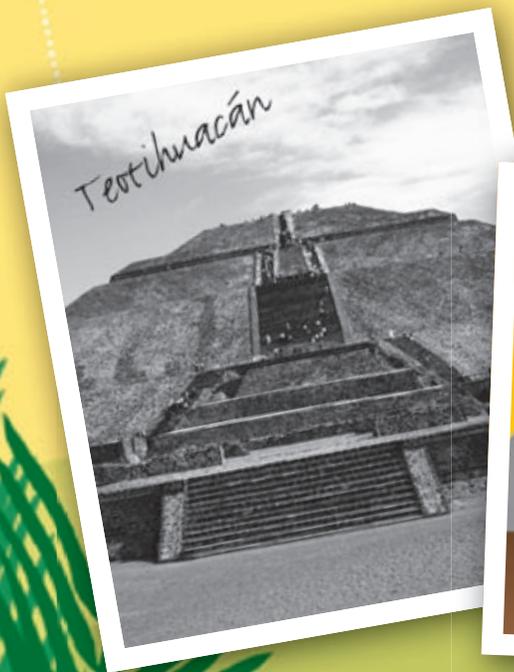
Originally devoted to agriculture, the temple became a symbol of the state and its rulers. Could one of those rulers lie in a tomb within the Pyramid of the Sun? "I don't think so. I don't believe we will find anything inside," Manzanilla says. No tombs have been found there yet, and she doesn't think that will change.

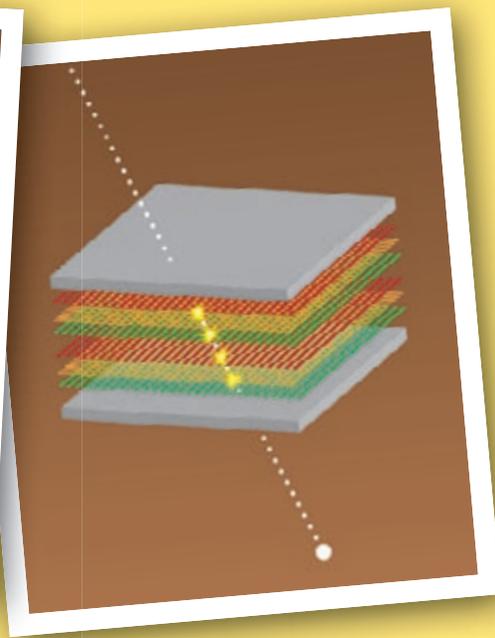
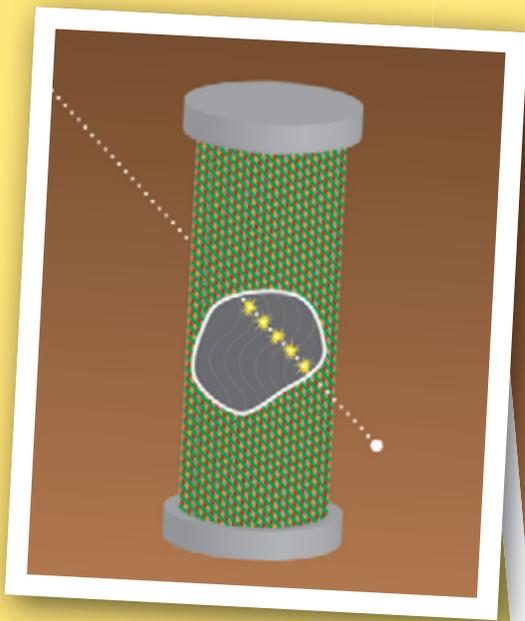
But without a muon detector, Manzanilla can't test her predictions. "The Pyramid of the Sun is so wide and so high," she says. "Ground-penetrating radar can see only a small depth and width. We can expand that view using the muon detector."

And, she hopes, put to rest speculation about what is inside.

### Teotihuacán

At the Pyramid of the Sun in Teotihuacán, scientists from UNAM will take advantage of an existing tunnel to place their muon detector. Muons traveling through its six gas-filled chambers will give off flashes of light. Schematic: Sandbox Studio





**At left**

This detector, developed for use at La Milpa in Belize, snags incoming muons in two ways. First, a muon's trajectory is recorded by three layers of material wrapped around a cylindrical chamber. Meanwhile, photo-detectors pick up flashes of light generated as muons strike molecules of gas inside the chamber.

**At right**

The detector developed by UNAM for the Pyramid of the Sun contains layers of scintillating material; they collect light produced when muons interact with gas in the detector's six chambers.

*Diagrams: Sandbox Studio*

**Mayan mysteries**

Schwitters is eager to answer similar questions at La Milpa in Belize.

The design of his detector is slightly different. It's a gas-filled cylinder wrapped with strips of material that detect muons as they enter and leave. Another detector, at the bottom of the cylinder, picks up flashes of light from muons zipping through the gas.

Rather than putting his detector directly below the pyramid, which would require digging a tunnel, Schwitters plans to place two detectors in shallow shafts on either side of the structure and 50 to 60 meters apart. This will give them a stereo view of the site, eliminate blind spots and make it easier to construct a 3D image. Only the most energetic muons will be used for the reconstruction; since they are not as easily deflected, their paths through the site are truer and more direct. Schwitters says it should take about 10 days to record and trace 1000 muon arrivals.

While waiting for the funding they need to set up a laboratory in Belize, Schwitters and his team have been testing the 16-foot-long prototype detector they built at the University of Texas at Austin. Big stacks of bricks stand in for the stony bulk of the pyramid; the team moves the bricks up onto the roof and into other difficult positions to see how the detector handles the challenge. From the data, Schwitters and his group can see not only the piles of bricks, but also the shadows of the nearby engineering and physics buildings, massive structures that impede the flow of muons. If the detector can distinguish these dense objects, Schwitters says, it can find cavities as well.

"The technology has really improved since the time of Alvarez," Schwitters says. "The detectors are simpler and more robust. We are looking to make the detector more portable and improve our software, and then we can get serious."

Designing the detector is the first of many challenges for the Schwitters team. Once they get funding and permission, they will have to transport the detectors to Belize and dig holes in which to put them. They'll also need to find a way to power the lab at the remote site. "It's a slow process and we've got a lot to do here," Schwitters says, adding that he hopes to move to Belize by the spring of 2009.

La Milpa remains shrouded in mystery. Hammond says, "Some questions we cannot yet answer are: Why was the city founded? What was its strategic or economic importance? Why did it collapse? And why was it abandoned in a time of great construction?" Muon detection may answer at least some of these questions and give archaeologists enough of an edge to unearth the next exciting discovery.

# Outsider science

**Amateur scientists make important contributions in a number of fields, from astronomy to ornithology. But very few have the background needed to succeed in high-energy physics. By Amber Dance**

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of  
Science Review





### Make sure you have

- ✓ Done your homework
- ✓ Understood the language of science
- ✓ Gotten the mathematics right
- ✓ Checked that your theory agrees with results of past experiments
- ✓ Used reasoned arguments



The Simplified Grand Unified Theory of Everything Part 1

The Simplified Grand Unified Theory of Everything Part 2

The Simplified Grand Unified Theory of Everything Part 3





**S**cience, as people often think of it, is something that happens in high-tech labs and ivory towers, where trained thinkers with strings of letters after their names apply their skills to agreed-upon problems.

But not every scientist fits that mold. Benjamin Franklin and Michael Faraday were largely self-educated. James Clerk Maxwell did much of his work at his countryside home. Albert Einstein's early "Department of Theoretical Physics," where he kept some of his greatest ideas, was the name he gave to a drawer in his desk at the patent office.

Today, citizen scientists all over the world collect important data from their backyards. A few even get their work published; a recent report in the journal *Science* of a solar system similar to ours had two amateur observers as lead authors. Could the next Einstein be out there somewhere, toiling at a menial job while developing ideas that

will revolutionize the way physicists understand the universe? Some people think so—and some even claim to be that unsung genius. Professional physicists, on the other hand, say it's unlikely solid theories will come from outside academia. While fields such as astronomy welcome amateur contributions, the expense of experimental physics is often prohibitive, and the degree of specialization needed to understand theory makes it nearly impossible for an outsider to contribute.

#### **Longing for an audience**

Outsiders want in, though, and physicists frequently get e-mails from earnest, well-meaning people who believe they have discovered new laws of conservation, or insist that a photon is shaped like a pyramid. Their ideas pop up in inboxes with the regularity of Nigerian spam; but rather than asking for money, they want help getting published.



Professional scientists don't really have the time to analyze each paper. "We certainly have a tendency not to pay attention," says Tom Rizzo, a theoretical physicist at the Stanford Linear Accelerator Center in California. "For most of them, you don't have to look for very long before you see a mistake that a physics student wouldn't make."

Rizzo recalls one thinker who sent hardbound copies of his 100-page manuscript to thousands of members of the American Physical Society. Rather than getting the scientific plaudits he desired, he became a joke.

To merit their attention, professionals say, an outsider would have to show that he's done his homework. Serious contenders have to understand the language of physics and get their math right. Most importantly, any new theory must agree with past experiments.

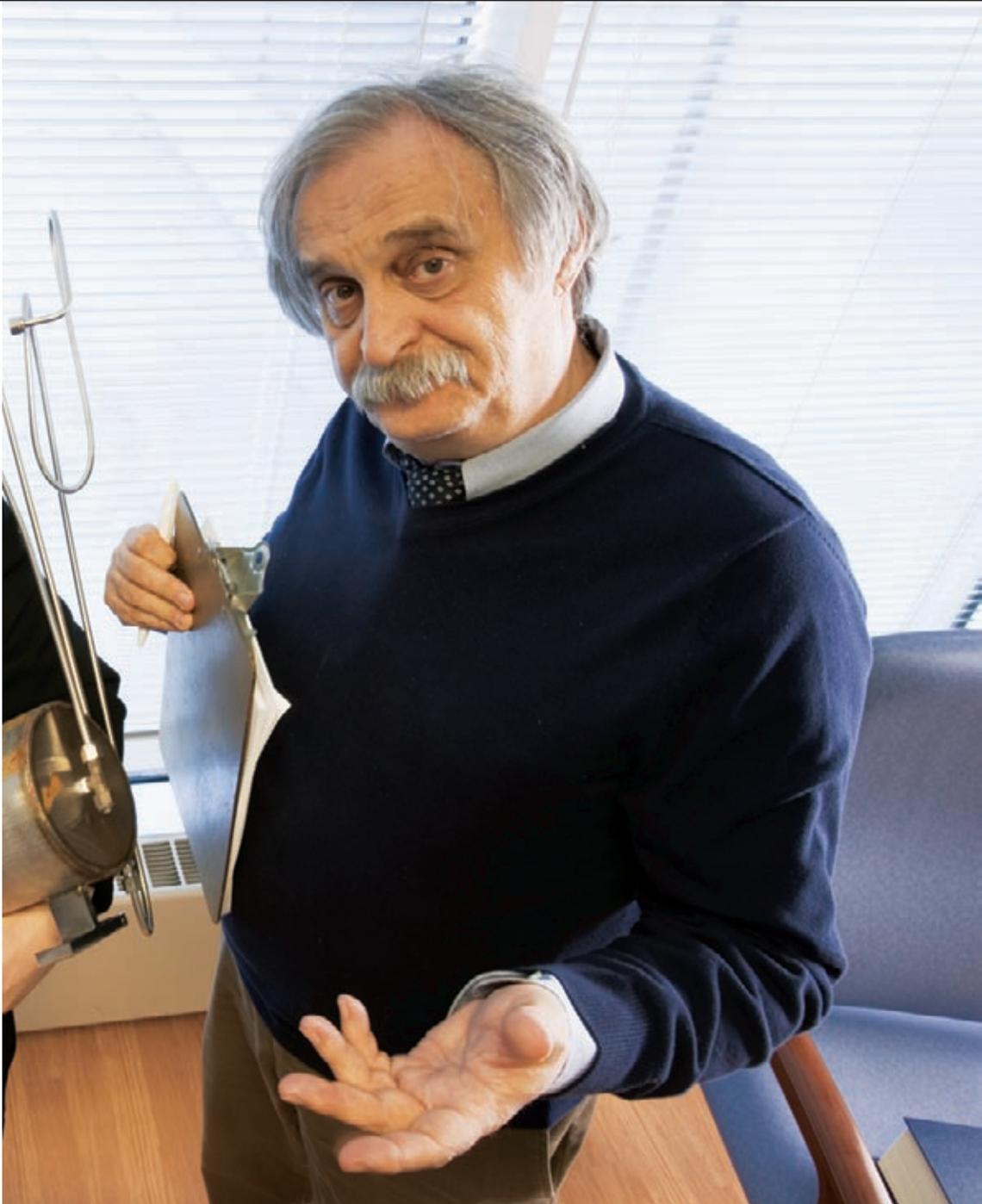
A theory could predict that hula hoops will come bouncing out of CERN's Large Hadron Collider in Switzerland, as long as it accounts for all the experimental data up to that point, Rizzo says. Too often, amateurs ignore that basic constraint.

"What the amateur has to realize is that you aren't going to be judged at the same level as the professional—you're going to be judged at a higher level," says Forrest Mims, editor of the Society for Amateur Scientists newsletter. "So far, nobody's come to me who's in that plight that I would consider worthy to be published."

### **It's wild, but could it work?**

Frustrated amateurs can be aggressive, clamoring to have their ideas heard. Not surprisingly, physicists are more receptive to polite questions than to lengthy treatises accompanied by angry rants, and if the science is solid, they may listen. Rizzo says he believes he'd referee a paper





from an outsider the same way he'd review one from a colleague.

It would be "really wonderful" if an outsider could break into physics, he says: "We could use a revolution."

Physics research tends to follow a consensus path, Rizzo says. Most of the time, of course, the herd moves in the right direction, but this standardized mode of thinking could leave exciting new ideas out in the cold.

"Professors bounce their ideas off of colleagues, and really wild ideas return a list of reasons why they won't work," wrote Garret Lisi, a self-described "freelance academic," in an e-mail. "That saves huge amounts of time. But what if one of those wild ideas would have worked?"

Lisi had several ideas he wanted to explore after earning his doctorate in theoretical physics from the University of California, San Diego, in

1999. But in considering postdoctoral offerings, he felt he would be limited to positions in string theory, which he felt was "overly speculative."

Since he had money from successful investments, Lisi decided to go it alone. He supports his research with occasional jobs, from teaching physics to teaching snowboarding, and a grant from the Foundational Questions Institute. He's still living on a grad-student budget, but he gets to live where he wants (primarily Hawaii) and he doesn't have to deal with academic chores like sitting on committees and attending seminars.

Theorizing without the regular input of critical colleagues, Lisi wrote, means he has to be conservative. "Working on my own, the only way I've been able to make progress is by being extremely cautious in my adoption of unusual hypotheses," he said. "Otherwise, my theories would crumble over shaky ground."

Being outside the ivory tower hasn't stopped Lisi from getting attention for his ideas. He recently posted a paper, "An Exceptionally Simple Theory of Everything," on the physics Web site arXiv.org; it received accolades from a few physicists amid a flurry of media coverage. It has also met with widespread skepticism, which, Lisi wrote, "every new idea should."

### Getting in the door

The arXiv site, where physicists post previews of articles before they appear in a peer-reviewed journal, has become one of the most important conduits for new ideas in physics. Lisi has the academic credibility to post there, but generally arXiv is off-limits to outsiders.

"The arXiv is a forum for professional members of the scientific community," wrote arXiv administrator Angela Zoss in an e-mail. "Thus, by and large, it is not designed for submissions from amateur scientists." Registration requires endorsement from another scientist, and a few rejected authors even claim to have been "blacklisted" by arXiv.

Some peer-reviewed journals are more open to submissions from outsiders. *Physical Review Letters*, published by the American Physical Society, receives a small number of manuscripts from authors who lack institutional affiliations.

Those papers are treated the same as the rest, wrote Daniel Kulp, editorial director of the society's publications, in an e-mail. "If the manuscript passes peer review and contains enough significant new physics with broad interest, then it will be published," he wrote. However, he cannot recall publishing anything by an amateur.

The American Physical Society itself is open to anyone willing to pay the \$115 application fee for regular membership. And any member is welcome to present their work at the Society's

annual meeting, where fringe science goes under the umbrella of "General Theory."

"There are usually a dozen or fewer of these each year out of 7000 or so papers," wrote society spokesman James Riordon in an e-mail. "It's not a burden to the society to throw open the meeting to all members."

### Citizen scientists welcome

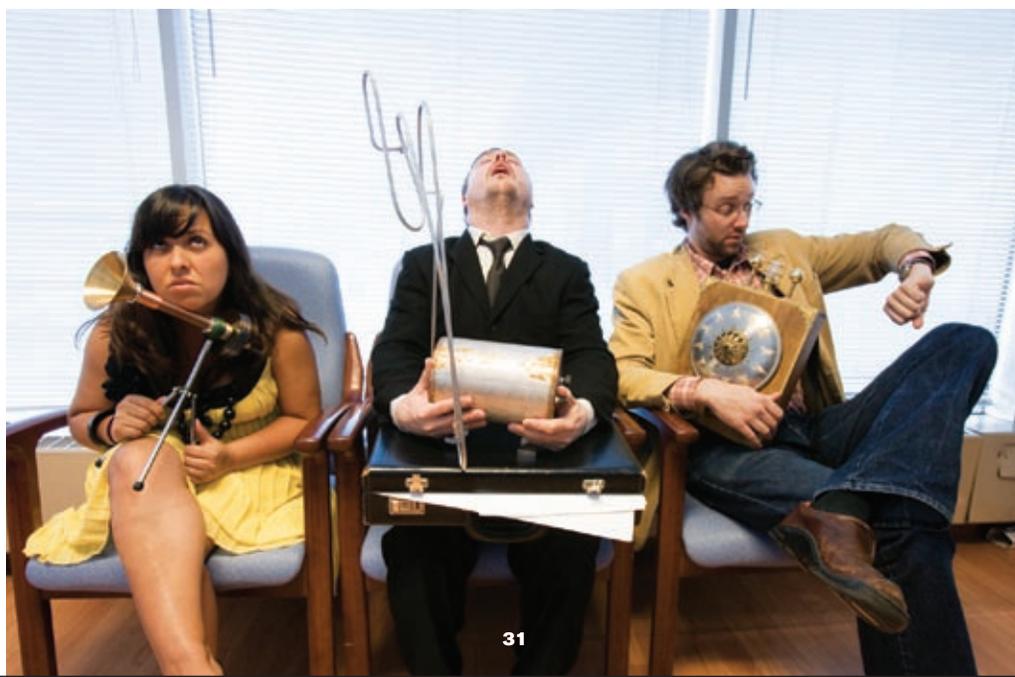
Other areas of science are more amenable to outsider contributions. There are thousands of citizen scientists out there—the Society for Amateur Scientists boasts around 2000 members—watching the skies, identifying birds, hunting for fossils. They do it not for money or scientific fame, but for fun.

"The most rewarding thing is the discovery, finding something no one else has found," says Mims, a writer specializing in science who lives in Texas. His resume would list a degree in government from Texas A&M University and several scientific publications, such as the 1993 *Nature* letter in which he described an error in a NASA satellite. NASA has since hired him as a consultant.

"My philosophy about science is to consider the contrarian view," he says. "That's where the discoveries lie." His children have taken a similar approach. One built a homemade seismometer, another detected solar flares with a Geiger counter, and the third found bacteria in smoke—all projects the experts thought weren't worthwhile.

"If I had gotten a degree in science, I wouldn't be doing what I am today," Mims says. Plus, he admits, "I nearly flunked freshman chemistry."

Mims is successful working on his own as well as with collaborators, which makes him unusual. Most amateurs hand their data to the professionals for analysis. Their observations then become part of a larger project.





Philip Unitt, curator of birds and mammals at the San Diego Natural History Museum, organized a team of skilled volunteers to census San Diego's avian population, a project they completed in 2002. He compares bird watching to solving puzzles as a hobby. "In science, there's an opportunity to make a broader contribution, rather than just entertain yourself," he says.

### **Astronomy's amateur advantage**

In astronomy, the professional must wait in line for just a few nights of telescope time. But teamed up with amateurs, the pro suddenly has access to heaps of data. Backyard astronomy has become affordable—some volunteers scan the sky with just a good pair of binoculars. Thanks to improved technology, amateurs can purchase or build equipment that rivals that of the professionals.

"Amateurs, we do a lot," says Dr. Don Parker, a retired anesthesiologist and sky watcher who lives in Florida. "Since we have no lives, we observe a lot and can detect things before the professionals have a chance." Parker, who was fascinated by space as a child, has been observing Mars for more than 50 years. He was thinking about global warming on the Red Planet before most people were thinking about it on Earth. His work has appeared in *Science* and *Nature*.

"It's a fun thing to do," he says. "It keeps me off the streets."

Organizations such as the Association of Lunar and Planetary Observers hook up professionals in need of data with amateurs who have the drive and know-how to provide it.

"It's one of those few activities where the amateurs are the equal of the PhD scientist," says Arne Hendon, director of the American



Association of Variable Star Observers, another group that matches pros with amateurs in more than 50 countries.

Joe Patterson, an astronomer at Columbia University, manages an international cadre of a few dozen volunteers who watch the skies on his behalf. By day they're accountants, engineers, or executives; by night, they're dedicated scientists whose combined technical expertise surpasses his own, Patterson says.

With his volunteers, Patterson has worldwide coverage of the objects he wants to observe—black holes and flickering white dwarfs. "When somebody in South Africa goes to bed, somebody in South America can take over," he says.

The volunteers also save Patterson from the exhaustion that set in after years of late-night observations. Now, he amasses data without losing any sleep.

"I arrive at work at 8:30 in the morning and I turn on my computer and, Bingo! Four or five of them have sent me data," he says. "I sit down and analyze it and by 10 a.m., I've discovered something."

Professional scientists such as Patterson have certainly worked hard to earn their credentials. But there's clearly space for citizen scientists too. As for that patent officer sitting on the next big idea, she'd better start reading or take some night classes to get the hard-core knowledge to back up her theory.



## Dance of the particles

In an empty urban lot beneath an overpass in Philadelphia, drummers beat a slow and steady rhythm. Two groups of dancers circle them in opposite directions. The drums pick up speed, pounding louder, the spaces between the beats filling with the clash of cymbals and a complex clatter of superimposed rhythms. The dancers' steps quicken. They race around the circle, faster, faster. Wham! They collide, spinning off in various directions.

Far from accidental, the choreographed collisions tell the story of science at Fermilab.

Members of Philadelphia-based Miro Dance Theatre and collaborators Nadia Hironaka and Eugene Lew conceived, choreographed, and produced the work, "Principles of Uncertainty," to show the intricate beauty of a subatomic particle collision and its aftermath. They were fascinated by the science and its parity with social life.

"Human elements collide every day, from different cultures, traditions, and backgrounds, and from these collisions new and unpredictable elements or relationships are produced," says Tobin Rothlein, producing artistic director for Miro, who is a dance, video and performance artist.

Choreographer Amanda Miller, Miro artistic director, based the dance moves on a system of structured improvisation that involved physics concepts such as velocity, trajectory, and symmetry.

"We felt this structure reflected the ever-shifting random variants of particle physics, and the freedom that exists within any set of rules," Miller says.

The group bulked up its science knowledge with a trip to Fermilab, the country's premier particle physics laboratory. They met with experimenters, theorists, and educators. As they learned more about physics and about accelerator science in particular, sketches of trajectories and choreography filled the pages of their notebooks.

In the end, each person represented one piece of the accelerator puzzle. The audience, numbering in the hundreds for each of three performances on Sept. 7, 2007, served as the detector. The drums played the part of an accelerator, the dancers were particles, and a backdrop of projected videos became a visual interpretation of monitors in Fermilab's control rooms.

The physics allusions began even before the performance started: Dancers waited in a holding chamber that represented a pre-accelerator. Once they were let into the ring, their movements reflected a detailed symbolic choreography.

"The dancers speeding one direction were supposed to represent positively charged particles, and those spinning the opposite direction, the negatively charged particles," says Hironaka, who is a video artist.

The Miro Dance Theatre artists will continue their interpretation of particle physics with a new stage show, "Spooky Action," commissioned by Indiana University of Pennsylvania Lively Arts. Set to premiere in April of 2009, this spin-off production will explore love and quantum entanglement. Miro will continue to use Fermilab as a resource, and will be working with students and community members, trying to interest them in both science and the arts. "Principles of Uncertainty" is now available for touring, with the idea of altering the work for each specific location.

"We're treating this like an experiment," Hironaka says.

**Text by Rhianna Wisniewski**

**Photos by Blaine Siegel and Aaron Iglor**







Photo courtesy of Tobin Rothlein

## Physics tour inspires dance

When I set out for Chicago with a group of artists last year, I knew almost nothing about particle physics or about Fermilab,

where we hoped to find inspiration for a singular performance project called "Principles of Uncertainty."

Choreographer Amanda Miller and I had founded the Miro Dance Theatre in Philadelphia four years ago to explore the intersections of contemporary dance, video, and visual art. When video artist Nadia Hironaka asked us to collaborate on a live performance modeled on particle acceleration, involving drummers, dancers, and video artists, we were happy to take on the project. Our other collaborator, sound experimentalist Eugene Lew, had an interest in physics; but until that point Amanda and I had little experience with the topic, and on the flight to Chicago we pored over a couple of basic physics books and some images pulled from a Web site in the hope of appearing at least minimally informed when we got there.

For our part of the project, we needed formulas or calculations that could translate into the movement of bodies through space and guide the dancers as they improvised. As we toured Fermilab, learning more about the machines and the science and brainstorming with physicists, we found what we were looking for.

We were first put in the hands of Rob Plunkett, who showed us a model of the accelerator and talked about the science behind the machine, with a joyful emphasis on smashing things apart. My imagination was sparked by his enthusiasm for the unknown, from dark matter to neutrinos. Our next host, Linda Bagby of the DZero experiment, picked up where he left off. Even with my limited scientific understanding, I soon realized what was happening here: Just as we artists continually break things down during rehearsal to reach some truth and simplicity in performance, physicists break down matter to discover simplicity and truth in the universe.

As our tour continued, we found incredible beauty in the intricacy of detector circuitry, the lines and patterns made by miles of wire trailing through the floors and ceilings, and the way light was refracted through sheets of translucent material. All the while, I must admit, I felt a

sort of overwhelming nervousness as I contemplated what was actually happening behind the aluminum foil and thick wall of concrete. The more we learned the more questions we had, and we were amused and excited when our questions elicited opposite answers from two of our hosts. The gray areas of physics fascinated us, from Schrödinger's cat and the power of the observer to the ever-changing nature of the neutrino. We were soon brainstorming with Herman White and Doug Jensen across a cafeteria table: How could we make a fat male dancer become a skinny female dancer, then turn purple, then become someone else, then go through a wall? Of course our performance would not be that literal, but this is where the conversations went.

Meeting with theorist Thomas Becher helped refine our ideas and make them more practical. We learned about the physical behaviors of each particle, about spin and trajectory. Later, in a Fermilab meeting room, we hashed out a structure and system for our experimental performance based on the information we had collected.

Our research developed into a large-scale outdoor performance at the Philadelphia Live Arts Festival involving 50 drummers, 15 dancers, two video artists, and the science of particle acceleration, all witnessed by more than 1000 people in the course of a single evening (see Gallery, page 34). Inspired by the way it turned out, Amanda and I are now creating a dance-theater piece called "Spooky Action" based on quantum entanglement. Commissioned in partnership with the Lively Arts program at Indiana University of Pennsylvania, it is scheduled to premiere in spring 2009. "Spooky Action" will explore the invisible strands that connect us across seemingly insurmountable distances. Diving into this new science-inspired performance, we look forward to continuing our relationship with Fermilab as a valuable resource for understanding physics and how it relates to the arts.

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*Tobin Rothlein is a dance, video, and performance artist whose work has been presented internationally. He produced and directed the 1997 documentary Eyes of the Storm, collaborated on the contemporary operas Adam's Apple and Cremenville, was a founding member of Phrenic New Ballet and co-founded Miro Dance Theatre in Philadelphia, where he is producing artistic director. Rothlein is also a 2006 Pew Fellow in performance art.*

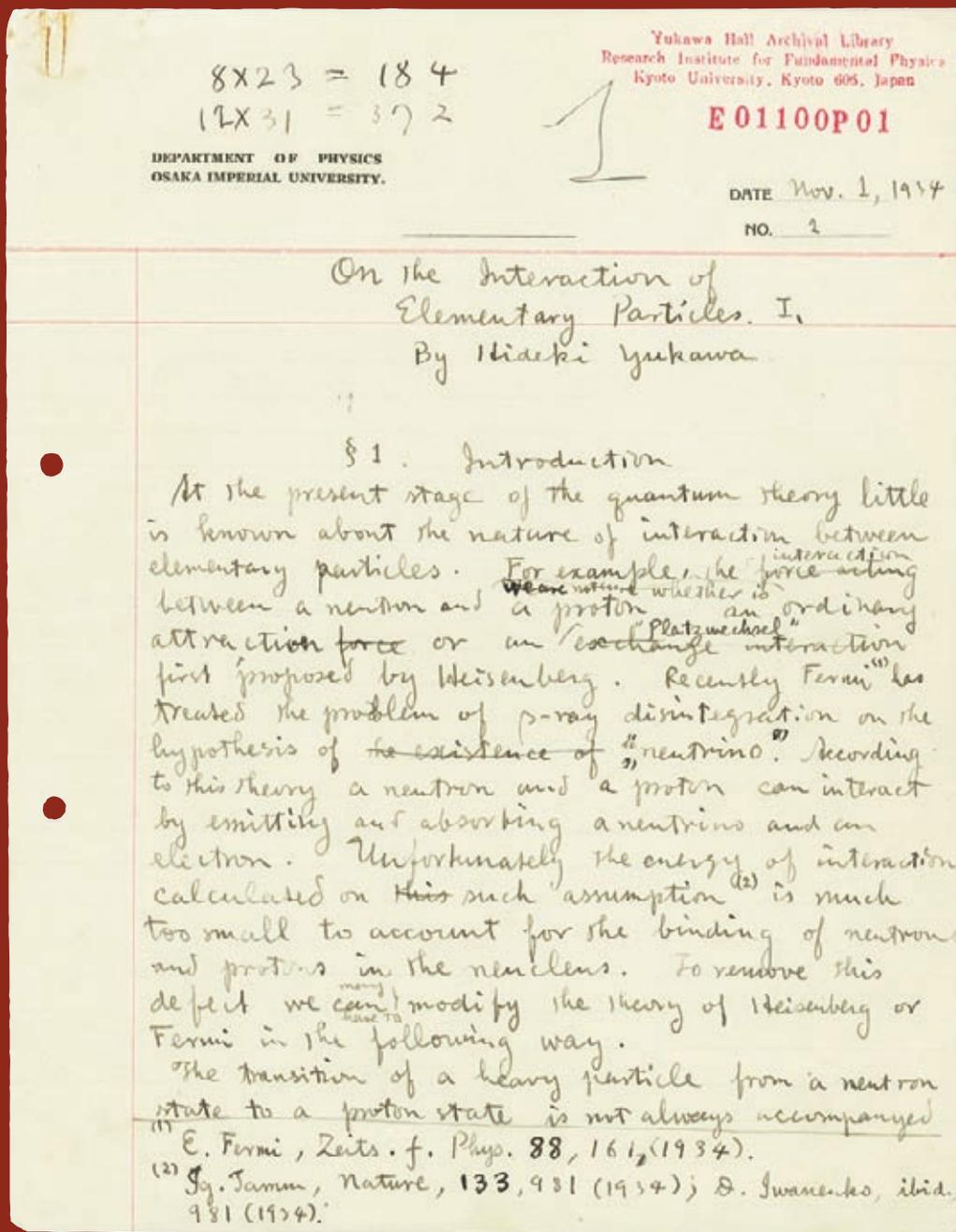


Image courtesy of the Yukawa Hall Archival Library

## On November 1, 1934,

Hideki Yukawa began to write the first draft of an article that would earn him the 1949 Nobel Prize in Physics.

Only 27 years old, Yukawa set out to explain the force that binds together protons and neutrons, forming atomic nuclei. Enrico Fermi, Werner Heisenberg, and other well-known physicists had tried to solve the problem, but their attempts had come up short. Yukawa, assistant professor at Osaka University, used the quantum field theory of electrons and photons as his starting point. He modified the theoretical description of the electromagnetic field to yield short-range forces, in agreement with nuclear experiments.

Yukawa proposed the existence of a new subatomic particle that weighs more than an electron but less than a proton. This particle, later named a meson (after the

Greek word mesos for "middle"), mediates the nuclear force among the protons and neutrons inside a nucleus. (Physicists discovered later that protons, neutrons, and mesons are made of more fundamental building blocks named quarks, held together by gluons.)

In his paper, published in the *Proceedings of the Physico-Mathematical Society of Japan*, Yukawa predicted that cosmic rays with sufficient energy could produce the new particle outside a nucleus. In 1947, Cecil Frank Powell and his group at the University of Bristol found the pi-meson, or pion, a particle about 270 times heavier than the electron. Two years later, Yukawa became the first Japanese person to receive the Nobel Prize. Powell received the award for his work in 1950.

**Michiji Konuma, Professor Emeritus, Keio University**

**Rare particle decays** could provide a unique glimpse of subatomic processes that elude the direct reach of even the most powerful particle colliders on Earth. Their observation could answer questions about the nature of matter and energy, shine light on the evolution of the early universe, and explain the subtle differences between matter and antimatter.

When an unstable particle decays to lighter particles, each possible outcome has a certain probability of occurring, similar to the chance of rolling all sixes in a dice game. A rare decay corresponds to an outcome in which one die ends up standing, unsupported, on one of its edges.

Scientists must sift through the outcomes of billions or more particle decays to find rare events that may be due to the hidden influence of new forces. They look for the die on its edge—the outcome of a process that seems impossible, such as a muon transforming directly into an electron. Theories such as supersymmetry suggest that such a transition can occur.

The search for rare decays employs high-intensity accelerators that create immense numbers of particles—the more, the better. Muons and kaons in particular have relatively long lifetimes that more likely allow hidden forces to dramatically change the outcomes of their decays. Exploring their decays, we can unveil the secrets of the quantum universe.

**Robert Tschirhart, Fermi National Accelerator Laboratory**



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