symmetry

dimensions of particle physics

A joint Fermilab/SLAC publication

volume 06

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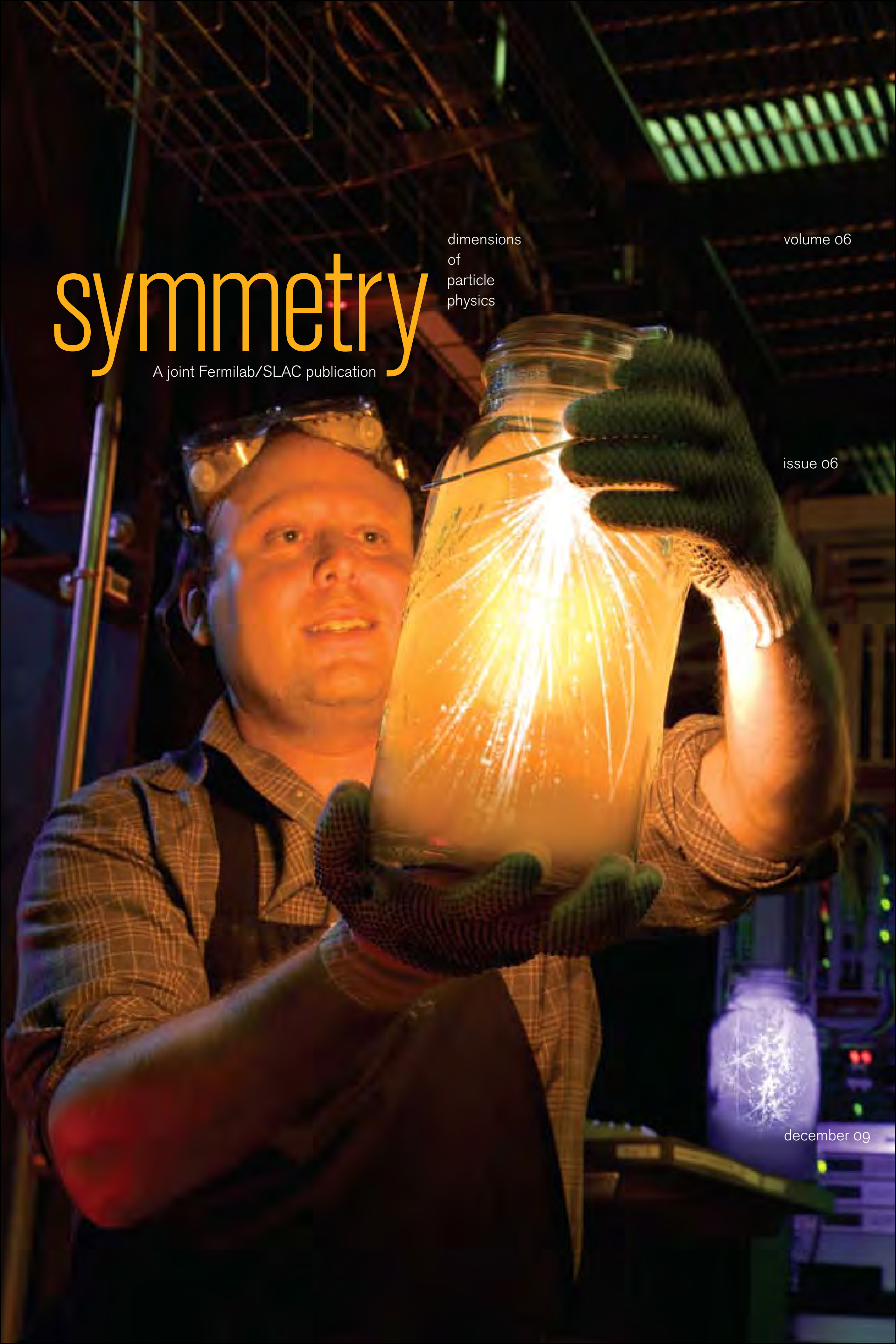
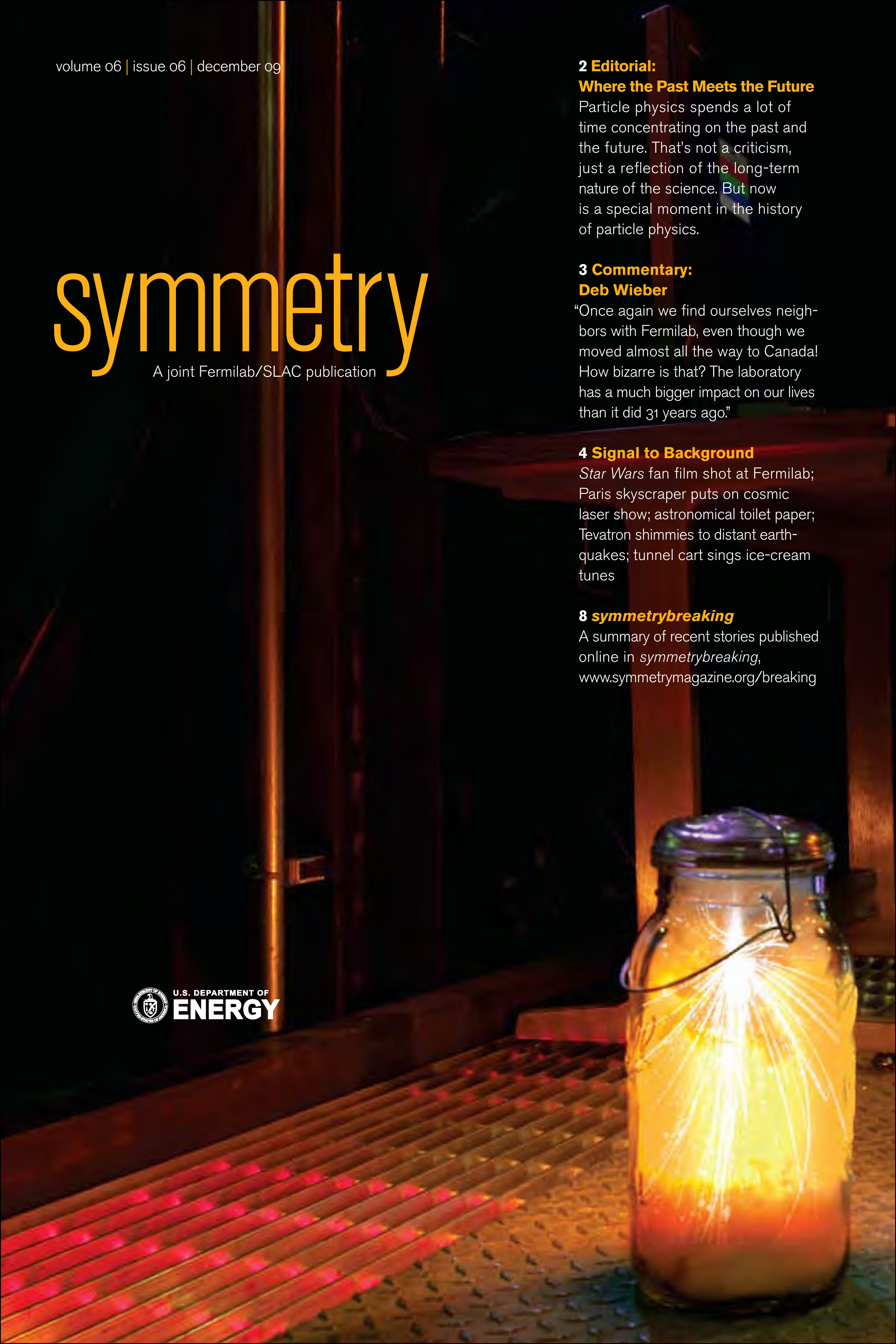
december 09





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U.S. DEPARTMENT OF ENERGY

On the cover
Particle collisions are ephemeral, occurring in the tiniest fractions of seconds. But they could be useful for decades if physicists learn how to store the data from them in a way that future generations of physicists can access and reuse.
Photos: Reidar Hahn, Fermilab

Where the past meets the future

Particle physics is a field that spends an awful lot of time concentrating on the past and the future. That's not a criticism, just a reflection of the long-term nature of the science.

Data is collected during many years of experimenting, and ideas sometimes germinate over decades before fruiting. Large collections of experimental data are some of the field's most valuable assets, but they become stale all too rapidly. Technologies change, institutional knowledge dissipates, individual recall dims. But the data could, and should, live on for a significant time, since old data can be used again, as has occurred many times in the history of physics. Storing that prized resource, however, is hard. Fortunately, many scientists are awake to the problem, and are working toward globally coordinated solutions to preserve the data and keep it available for future scientists to use as needed. (See page 18.)

Photo: Reidar Hahn, Fermilab

It's not only data that has a potential life well beyond the original goals of an experiment. The hardware of particle physics is continually being reused, repurposed, and reinvigorated. (See page 24.) It's hard to even track down how much decades-old machinery is still in use or committed to future use around the world. Sometimes magnets are simply reused in a new particle collider, and sometimes whole accelerator structures are turned into new machines, such as the 40-year-old linear accelerator that has been converted to a new X-ray laser at SLAC National Accelerator Laboratory. The reuse of particle physics equipment isn't merely about getting more from the investment in a commodity. The design and manufacturing expertise; the gathered knowledge from years of experience working with the machinery; and the very human, visceral connection to these devices are hard to quantify, but are of great value to future physicists and engineers.

Data and equipment provide a bridge from the past to the future, but we are now at a very special time in the history of particle physics. As this issue goes to press, the Large Hadron Collider is beginning operations. The LHC could provide evidence of a key missing piece of the Standard Model of particle physics, sought for decades. Finding that piece is important, but more valuable is the guidance it will provide for future explorations. Many scenarios exist for what lives beyond the Standard Model, but nobody has any compelling evidence that would allow us to choose between those scenarios. However, physicists are almost unanimously sure that there are great discoveries imminent and that the LHC's results will revolutionize particle physics. Those results will take a few years to obtain, and getting to that future will rely on reusing data and equipment from the past, fueled by the energy and excitement of the physics community right now.

David Harris, *Editor-in-Chief*

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Two times a neighbor: reconnecting with Fermilab

I am not a physicist, scientist, or any other "ist" that I can think of, but Fermilab has been a recurring theme in my life. It began as an interesting footnote back when my husband and I became a couple, and unexpectedly jumped back into our lives 31 years later.

Let me explain. In 1978, a soon-to-be married young couple buys a house off Batavia Road in Warrenville, Ill. They drive every day by this huge facility surrounded by lush green lawns and landscaping on their way to and from their jobs in the Chicago area. They can't see the actual facility, but they know that inside it, some pretty smart folks are performing studies incomprehensible to the average person. They hear that physicists are shooting energy around a huge, underground circle four miles in diameter.

Yep, that was pretty much the non-scientific explanation for Fermilab back in our earlier days, one we pondered with our neighbors during our Friday night happy hours. Fermilab research was way beyond our scope of understanding, but it was fun to talk about after a few cocktails, when we got so much smarter.

When my husband and I were transferred in 1980 to downstate Illinois, we thought our connection to Fermilab had ended.

Now fast-forward 22 years. The young couple is still a young couple at heart. In 2000, they exit their corporate careers and relocate to northern Minnesota to start a new life as resort owners. Living on the Ash River Trail near the entrance to Voyageurs National Park and hosting anglers, hunters, and snowmobilers seems much more fun than holding down corporate careers.

We are so remote in our part of northern Minnesota that cell phones don't work; high-speed DSL lines don't exist; and the local phone company tells me we're darned lucky to have phone service at all.

A few years into the new millenium, we heard that the University of Minnesota and Fermilab might want to expand their neutrino search to the Ash River Trail. Scientists with the NOνA experiment hope to study the behavior of neutrinos generated at Fermilab in Illinois and sent through the ground to a detector here.

Wow, pretty cool. Once again, the local bars were buzzing with lively discussion about particle physics. No one could describe exactly what the scientists would be doing (most of us still can't), but we had lots of positive reactions to the new development coming to the Ash River and what it would mean to the local economy. (By local, I mean maybe 7000 folks, most employed in tourism or logging.) We were thrilled when in 2009 the NOνA project got its funding and we had a groundbreaking date of May 1.

Once again we find ourselves neighbors with Fermilab, even though we moved almost all the way to Canada! How bizarre is that? The laboratory has a much bigger impact on our lives than it did 31 years ago. As resort owners, we have housed or fed University of Minnesota scientists, Fermilab scientists and employees, staff from the nearby Soudan Underground Laboratory, and construction workers developing the NOνA site. These folks are far removed from the typical angler or snowmobiler we have seen in the past 10 years and have created new business opportunities (and revenue) for us and for other businesses on the Ash River Trail. In October our community typically gets very quiet until the November deer-hunting season. Not this year: We are lucky to be housing several construction workers, hosting project meetings in our dining room, serving spaghetti suppers to visiting dignitaries, and hosting celebratory pizza parties. We are discussing how to meet the NOνA project's lodging needs over the next three years and beyond, when visiting scientists will come to Ash River from all over the world.

Our bar conversations take a more intellectual bent when we have scientists and other staff around. Some of us can now even describe what a neutrino is and why we care about them. We are thinking of putting in our cabins a short description of neutrinos and the NOνA project to address the frequently asked question, "What is going on down the road?" A year ago, we never dreamt we would be brainstorming business opportunities related to the project. Thank you, Fermilab! You make great neighbors, once again.

Deb and Steve Wieber and their son, Tom, are owners of Ash Trail Lodge in Ash River, Minn. In their pre-resort life, Steve was in sales for Hewlett-Packard and Deb was a corporate training and development consultant.

Photos courtesy of Deb Wieber

Star Wars fan film shot at Fermilab; astronomical toilet paper; Paris skyscraper puts on cosmic laser show; tunnel cart sings ice-cream tunes; Tevatron shimmies to distant earthquakes.

May the fundamental forces be with you

A long time ago in a national laboratory far, far away… some physicists looked around their workplace and thought of dark forces. Not dark matter; not dark energy; but the ultimate force from the dark side: Darth Vader.

Now, nearly five years later, they are preparing to air the first feature-length Star Wars fan movie—and most likely the first ever filmed at a national high-energy physics laboratory. Called *Star Wars: Forgotten Realm*, the two-hour film was shot at Fermilab under the direction of Darren Crawford, the lab's accelerator operations crew chief.

The actors include fellow Fermilab workers and their friends and relatives. Grade-school children played diminutive Jawa creatures; they were the only ones who fit the costumes. Physicists and engineers brought science-related gadgets, such as Tesla coils and Lichtenberg figures, to add a 1970-style sci-fi feel to the cantina scene. A local artist provided an adult-sized, moving robot.

"This film is going to blow away all other fan films," says Mark Van Slyke, a member of the Midwest Garrison of the 501st Legion: Vader's Fist, a worldwide organization of Star Wars costuming enthusiasts. The garrison supplied several actors, as well as costumes and props.

Crawford capitalized on the laboratory's concrete-walled, industrial-looking experimental tunnels and its natural prairies to create the stark, wild look of a futuristic world. Computer-aided special effects, generated with the help of co-workers, promise to give the film a polished, if not Hollywood, look.

While Lucas Productions does not endorse the film, it does allow fans to make and show films so long as they don't charge admission.

Granted, filming at Fermilab did present unusual challenges: getting security clearances, complying with safety rules, shooting on weekends and during off-hours, descending 350 feet into the NuMI experiment tunnel, and working around "Caution: Strong Magnetic Field" signs. Yet below their hard hats emblazoned with "Death Star Construction Crew," the group was all smiles.

"Four years ago, when the word got out I wanted to make a Star Wars fan film, several people approached me and volunteered to be a part of the project," Crawford says. "There is a great sense of camaraderie when we are all on the set."

The film will premiere in 2010 at Fermilab.

Tona Kunz

Photos: Reidar Hahn, Fermilab

Wiping with the stars

Every so often, particle physics communicators from labs around the world gather to swap strategies for getting people interested in science. At the group's April meeting in Japan, the big hit was toilet paper.

Since 2004, more than 40,000 rolls of toilet paper with flushable facts about the life cycles of stars have found their way into Japanese society. References to Astronomical Toilet Paper litter blogs, and Web photos show the toilet paper visiting historical sites, much like the gnome in Travelocity commercials.

"People nowadays are too busy to think about the universe," says Naohiro Takanashi, a research fellow at the National Astronomical Observatory of Japan. "We hope busy people use their time in the closed rest room to think about it."

Tsuyuki Shikou, a company known for manufacturing toilet paper adorned with animals, flowers and vegetables, printed this version for the TENPLA Project, which is dedicated to popularizing astronomy. It follows in a whimsical Japanese tradition of inscribing toilet paper with comic strips, crossword puzzles, novels, and pop culture icons.

"We hope people learn that stars have a life. They are born from a molecular cloud, they become adult and finally they die; it's similar to our lives," Takanashi says. "We want people to see the similarity and feel connected to the stars and have an interest in astronomy."

You can even do a bit of astronomy with the cardboard tube at the center of the roll: Take it outside, look at the sky through the cardboard tube, count the stars in the circle and use a formula to calculate the brightness of the night sky.

That is, if you can bring yourself to use all the paper.

Fusae Miyazoe, spokeswoman for the Institute for the Physics and Mathematics of the Universe at the University of Tokyo, says many of her colleagues tell her it's a waste to read the roll only once, "so they just leave it on the shelf in the bathroom."

If the idea catches on, maybe we'll see toilet paper showing, step by step, how particles zip through a detector. Hmm. What will particle physicists do with the cardboard tube?

Tia Jones

Photos courtesy of JLR/CNRS/APC

The invisibles come to Paris

How do you make the invisible visible? Astrophysicists face this challenge daily. Unlike astronomers who view stars through telescopes, astrophysicists study cosmic particles that are too small or dark to see directly. They infer the presence of cosmic rays and neutrinos—and hunt for dark matter—by looking at how these invisible particles affect the world around them.

In October, astrophysicists used magic, public lectures, and Paris' tallest skyscraper to teach the public how to use what you can see to peer at what you can't. Thousands of people, many of whom had probably never heard of astrophysics before, met with scientists at 50 events in 10 countries during the first European Week of Astroparticle Physics.

In Spain, magicians made objects vanish and reappear to explain how cosmic particles can exist beyond our sight.

In France, the national center for scientific research, CNRS, transformed 210-meter-tall Montparnasse Tower into a cosmic-ray detector. When cosmic rays collided with a muon detector on the roof, a laser shot a beam 1.2 kilometers across the sky to the Paris Observatory.

Linking the tower with the ancient astronomical observatory was a tribute to the contributions astronomy has made to the modern-day field of astrophysics. The urban light show also was a nod to German physicist Theodore Wulf, who in 1910 mounted an electrometer atop the Eiffel Tower to measure how the number of cosmic-ray detections increases with altitude.

Spectators joined physicists atop the Montparnasse Tower to see the cosmic-ray detector in action. Questions cascaded down on the physicists as the laser beam flashed above the city's Latin Quarter, in synchronization with the invisible cosmic rays coming into the detector.

Arnaud Marsollier

Tunnel tunes rouse ice cream memories

Some of Fermilab's mechanical technicians spend a lot of time underground. In the echoing tunnels of the Tevatron collider they fix things, crawling behind equipment to replace aging nuts and bolts and repair everything from vacuum pumps to multi-ton superconducting magnets. They work six days a week at an urgent pace to get the collider back up and running as soon as possible.

"What we do is not easy," says Derek Plant, a mechanical technician for 10 years. "It takes a very special group of people with good communication and a good demeanor."

Many of the tasks facing the team require diagnostic testing, which can take hours or days.

"During the shutdown this past summer, we had to bring a third of the Tevatron to room temperature to leak-check and repair components," says Scott McCormick, who supervises the Tevatron's mechanical support group. "This meant long hours and a lot of tedious work for the team."

In this intense, hurry-up-and-wait atmosphere, it's important to keep a sense of humor. "We find ways to keep the mood upbeat," Plant says. "That is why we have the happy cart."

Plant got the idea while transporting equipment in a golf cart, one of many workers use to get around the four-mile Tevatron ring. He went home, got online, purchased the sound system from an ice cream truck and installed it on his cart.

The happy cart, as it has come to be known, still looks the same as the rest of the fleet, but now it plays sweet tunes that evoke memories of carefree childhood days spent chasing the neighborhood ice cream truck. His colleagues get a kick out of it.

"After many hours underground," Plant says, "the sound of an ice cream truck coming from around the bend is enough to get a chuckle out of almost anyone."

Rhianna Wisniewski

Was that a quake? Ask the Tevatron

Long after the hard shaking stops, an earthquake's seismic waves reverberate around the world, imperceptibly rocking the ground. As one seismologist puts it, a great earthquake causes every grain of sand on Earth to dance.

And big particle accelerators dance along.

Fermilab's Duane Plant found this out one Sunday afternoon when he logged on to his home computer to check the performance of the Tevatron, an underground ring four miles in diameter where subatomic particles collide. It was November 3rd, 2002.

He noticed the particle beams had suddenly stopped circulating. Then, on a TV playing in the background, a newscaster announced that a 7.9-magnitude earthquake had just struck thousands of miles away in south-central Alaska.

"And it slowly seeps into his brain," recalls a colleague, Todd Johnson, "and he called me up and said, 'Is this crazy?'"

Johnson and Plant, who has since retired, checked sensors installed on a dozen of the Tevatron's magnets to detect slow ground movements that can throw the beam off kilter. "The readings for these tiltmeters were all over the place," Johnson says, "and just when they peaked is when the beam went away."

The two accelerator operations specialists figured out when the first surface waves from the earthquake would have arrived at the collider in Illinois. "The timing was perfect," Johnson says.

The quake watch was on.

Since then the Tevatron has recorded about 20 more earthquakes from all over the globe, including this year's deadly shocks in Sumatra and Samoa. Only one, a moderate local quake on June 28, 2004, shut the collider down. The tiltmeter recordings look a lot like seismogram squiggles—which makes sense, says US Geological Survey seismologist William Ellsworth, because these sensors are essentially low-resolution seismometers.

Seismic waves are a problem for other large structures, too, including LIGO, the Laser Interferometer Gravitational-Wave Observatory, which operates enormous detectors in Louisiana and Washington. Joe Giaime, head of the Louisiana observatory, says seismic waves sometimes push finely tuned pieces of equipment out of alignment, and account for about 10 percent of downtime there.

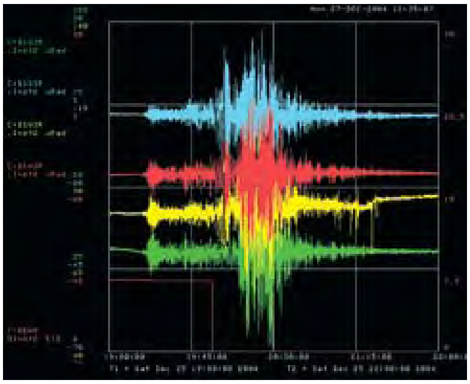


Image courtesy of Fermilab

Johnson says he doesn't see the Tevatron quake watch as a way of alerting accelerator operators to turn the beam off; the accelerator does that automatically when needed. "We would just let the machine do what it wants," he says. But it does give them one more way to quickly identify the cause of a beam loss, "rather than waste a lot of time trying to diagnose some phantom in the machine that isn't really there. Also, I find it really interesting."

Glennda Chui

letters

Dear editors:

Could someone please explain to me the vertical scale on the Livingston plot on page 30 of the October 2009 issue? I can't make any sense out of it at all. Where was the 2-TeV storage ring in 1970? Or the 300-TeV machine in the years before 1990? Don't we wish there were a 100,000-TeV machine scheduled to come on line by 2010.

Matt Moulson, INFN/Laboratori Nazionali di Frascati

Dear editors:

You might want to re-check the vertical scale on the Livingston plot on page 30 of the October 2009 issue.

Jim Brau, University of Oregon

The editors respond:

We adapted the Livingston plot from the 2001 Snowmass Accelerator R&D report. Although we kept the scale the same, we unfortunately omitted the text from the Snowmass report that explains the units: "Energy of colliders is plotted in terms of the laboratory energy of particles colliding with a proton at rest to reach the same center of mass energy." Using these units, the energy of collisions at the Large Hadron Collider is nearly 100,000 TeV.

Highlights from our blog

Not available at Hallmark: Nobel thanks
November 17, 2009

When Leon Lederman won the Nobel Prize in physics in 1988, he composed a cheeky form letter to thank hundreds of well-wishers. It starts with a check-off list of possible recipients: Dear cousin, best friend, old flame, occupant, member of the Swedish Academy.

Starting up the world's largest particle accelerator
November 10, 2009

The LHC is 17 miles around, more than 300 feet underground, and contains more than 9000 magnets. Making particles collide in this massive machine is no easy feat. Read on for an overview of the LHC's start-up checklist, which takes months to complete and tests every system in the accelerator.

Antimatter from lightning flashes the Fermi space telescope
November 6, 2009

Fermi recently turned its eyes back to Earth to watch terrestrial gamma-ray flashes, which are believed to originate at the tops of thunderstorm clouds. Fermi researchers announced the first detection of positrons from these flashes, a major clue about what actually causes them.

NO*ν*A neutrino detector gets full construction approval
November 4, 2009

The NO*ν*A neutrino experiment will beam neutrinos from Fermilab to two massive underground detectors in Illinois and Minnesota to learn more about these ghostly particles that stream from the sun and helped shape the evolution of the cosmos.

Imagine Science Film Festival: documentary shorts
November 2, 2009

When I left the Imagine Science Film Festival Documentary Shorts screening, it was almost impossible to wipe the grin off my face. All of the films were gorgeous and creative; nearly all of them used science in ways I'd never seen or thought of.

Gamma-ray burst restricts ways to beat Einstein's relativity
October 28, 2009

The Fermi Gamma-ray Space Telescope team has reconstructed GRB090510, which includes one of the highest-energy photons ever observed from a gamma-ray burst. This burst and photon have already received a lot of attention and will get a lot more, probably with arguments and claims about how this kills or doesn't kill various theories of quantum gravity.

America's accelerator future
October 27, 2009

The next big thing in particle accelerators may not be so big, and may not have anything to do with research into the subatomic secrets of the universe. Instead it could offer a better way to slice silicon into chips, treat cancer, or tap new sources of energy. More than 400 people met in Washington, DC, to draw up a list of possibilities.

Read the full text of these stories and more at www.symmetrymagazine.org/breaking

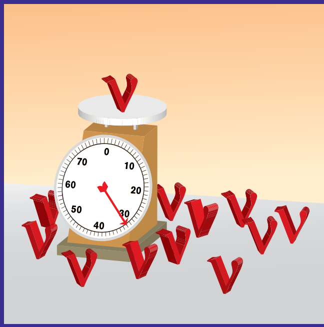
LHC's CMS collaboration submits performance results

October 27, 2009

The CMS collaboration at CERN's Large Hadron Collider has posted its first detector performance results to arXiv.org, and the paper's list of 2443 authors could run as final credits for a feature film. It takes up almost as many pages as the text of the paper.

The future of neutrino physics in Europe

October 13, 2009



For three days last week, more than 250 scientists gathered at CERN in Geneva, Switzerland, to discuss the future of European participation in the field of neutrino physics. The workshop was also a step toward increasing coordination within the European neutrino physics community and with the rest of the world.

A scientist, a humanist, and a social scientist are stuck on a desert island…

October 12, 2009

If you had a scientist, a humanist, and a social scientist stranded on a desert island, and room in a life raft for just one of them, which one would you save? Don't base it on personal affection, but on which discipline you think can most benefit the future of humanity.

Name that particle smasher. No, really, name it

October 8, 2009

Fermilab has asked the public to suggest names for its next big accelerator, currently known as Project X. Would you give it a powerful, superhero name like the Smashatron? Something poetic, like IBIS (Intense Beam InStallation, and the Egyptian god of knowledge)? Send suggestions to ykkim@fnal.gov.

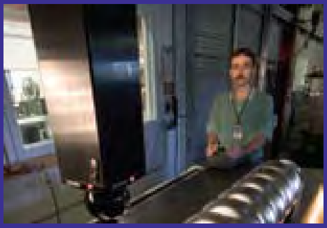
Beyond the Nobel: The largest-ever CCD digital cameras will explore the universe

October 6, 2009

Half of today's Nobel Prize in physics was awarded for the development of charge-coupled devices, or CCDs, the sensors that lie in digital cameras. The CCD at the heart of the Large Synoptic Survey Telescope will be the largest ever. It will scan the whole sky, make detailed maps of stars and galaxies, and advance understanding of dark matter and dark energy.

Tune in to the LHC

October 5, 2009



Want to keep up with the Large Hadron Collider's status, schedules, and milestones? Check out CERN's LHC News series on YouTube, which includes video, animations, interviews, and commentary.

US manufacturer passes superconducting cavity benchmark

September 30, 2009

A superconducting radio frequency cavity made by Advanced Energy Systems of Medford, NY, achieved an acceleration gradient of 41 megavolts per meter during tests at Thomas Jefferson National Accelerator Facility. It's the first time a US manufacturer has met this key requirement for the proposed International Linear Collider.

Fermi's excellent adventure

Since its launch in June 2008, the Fermi Gamma-ray Space Telescope has shed light on some of the brightest, most explosive events in the universe and opened tantalizing windows into dark matter and the nature of space-time. By Kelen Tuttle

Photo-illustration: Sandbox Studio

Three hundred and fifty miles overhead, the Fermi Gamma-ray Space Telescope silently glides through space. From this serene vantage point, the satellite's instruments watch the fiercest processes in the universe unfold. Pulsars spin up to 700 times a second, sweeping powerful beams of gamma-ray light through the cosmos. The hyperactive cores of distant galaxies spew bright jets of plasma. Far beyond, something mysterious explodes with unfathomable power, sending energy waves crashing through the universe.

This gamma-ray show is visible only from space, and Fermi, a joint mission of NASA, the US Department of Energy, and international partners, is the most advanced telescope ever to take it in. The satellite's main instrument, the Large Area Telescope, was assembled at SLAC National Accelerator Laboratory, and its advanced detectors owe much of their design to particle physics. As it orbits, slowly rocking side to side, it takes in a panoptic view of the sky every three hours, seeing gamma rays that have five million to more than 50 billion times more energy than visible light.

In its first year of operation the LAT captured more than 150 million gamma rays, 75 times more than its predecessor, EGRET, collected over a nine-year lifespan. It discovered a new class of pulsars and nabbed hundreds of blazars, revealing a variety of behaviors among these bright objects.

Meanwhile, a second instrument, the Gamma-ray Burst Monitor, has been measuring gamma rays that have lower energies, from 2000 to 10 million times those of visible light. It focuses on quick, erratic flashes called gamma-ray bursts and instantly notifies the LAT so it, too, can turn and look. It's been collecting these bursts at a rate of nearly one a day.

Together, the GBM and the LAT provide a powerful tool for studying the gamma-ray sky over a very large energy range—a range in which researchers previously had very limited data. By combining Fermi's observations with those made by other telescopes at other wavelengths, astrophysicists have a full view of the universe that may not only offer insight into astronomical objects like blazars, pulsars, and gamma-ray bursts, but also shed light on more enigmatic ideas, including dark matter and quantum gravity.

"Fermi has exceeded our expectations in terms of performance. It's performing close to perfection," says LAT Principal Investigator Peter Michelson of Stanford University. "In terms of discovery potential, we're just getting started, really. We've gotten some great first results, but there's a lot more for us to explore."

The blazar zoo

When Fermi looks past our Milky Way galaxy, its view is dominated by active galactic nuclei, compact regions in the centers of other galaxies where something—perhaps a black hole billions of times the mass of the sun—spits out a jet of plasma at nearly the speed of light. When these jets flare, they are among the brightest objects in the sky, emitting some of the highest gamma-ray energies ever detected. When these jets point toward Earth, they are called blazars.

Blazars are so bright and so prevalent that even before official observations began, Fermi identified several of them. In its first 12 months of operation, it detected about 500 sources likely to be associated with blazars, about 10 times the number discovered by EGRET.

Black hole-powered jet of electrons and other subatomic particles streams from the center of galaxy M87.
Image courtesy of NASA and the Hubble Heritage team (STScI/AURA)

These 500 likely blazars demonstrate what LAT researcher and Stanford Professor Roger Romani calls a "zoo of behavior." Some glow more than 10 times brighter than others. Some flicker like candle flames, while others hold relatively constant. And some emit polarized light, whose rays have an intrinsic extra "directionality" at right angles to the light's direction of travel. A blazar's complicated local environment seems to significantly affect how it looks—and, presumably, the details of how it works—so researchers don't yet agree on the basics of these beasts.

The more blazars the LAT records, the easier it will be to determine what makes one blazar different from the next.

"Fermi is challenging theoretical physicists to come up with models capable of producing what we observe," says astrophysicist Greg Madejski of the Kavli Institute for Particle Astrophysics and Cosmology at SLAC and Stanford.

But the LAT can't unravel the mystery of blazars on its own; it needs a whole fleet of telescopes operating in various wavelengths to get a comprehensive view. When a particularly interesting blazar lights up the sky, the collaboration sends an "Astronomer's Telegram"—nowadays, an e-mail—inviting colleagues at telescopes around the world to watch the flare in a variety of wavelengths, from radio through infrared, visible, ultraviolet, and X-ray light. Each wavelength is like a separate color, and combining them gives researchers the equivalent of a Technicolor picture of where and how a blazar creates its energetic jet.

"Because the LAT is an all-sky monitor, it can observe blazars continuously," says Gino Tosti, a researcher at the University of Perugia and INFN, the Istituto Nazionale di Fisica Nucleare in Italy. He is the co-coordinator of the active galactic nuclei group in the LAT collaboration. "This means we can study the characteristics of a large number of blazars to determine what makes them variable. But we can't do it on our own. We need multi-wavelength measurements to understand what's going on."

By combining these observations, researchers hope to infer what types of particles create blazar jets, what accelerates them to the necessary speeds, and where exactly that acceleration takes place.

"Most of us think we already know how active galactic nuclei work, but then again most of us don't agree with one another," says Roger Blandford, director of the Kavli Institute at SLAC and Stanford. "Fermi is helping us sort it all out."

Winking at Earth

Researchers don't have to look to other galaxies for gamma-ray sources; there are hundreds here in our own Milky Way.

When a collapsed star becomes so dense that a chunk the size of a sugar cube would have a mass of more than a billion tons, it's known as a neutron star. Some neutron stars have magnetic fields trillions of times stronger than Earth's, and those fields accelerate particles into fan-like beams of gamma rays. As the star spins up to 700 times per second, its beam sweeps through space like a search light and resembles a flashing strobe from Earth. These "pulsars" are one of our galaxy's chief sources of gamma rays.

Just four months after Fermi rocketed into space, the LAT collaboration announced its first major discovery: a pulsar that flashes only in gamma rays. Astronomers had discovered pulsars more than 40 years ago by detecting the radio waves they emit, and since then have observed more than 1000 of them that also beam energy in visible light, X-rays, and gamma rays. But never before had anyone discovered a radio-quiet pulsar in gamma rays.

In its first six months, the LAT collaboration observed 16 such gamma-ray-only pulsars. From this sample, researchers concluded that the gamma-ray beams from pulsars must be slightly wider than their beams of radio waves. Some pulsar beams pass over the Earth at such an angle that the wider gamma-ray part hits us, while the narrow radio-wave part misses.

Shortly after that discovery, the LAT collaboration also uncovered the first evidence that a special class of pulsars—"millisecond" pulsars that spin almost a thousand times a second—shines in gamma rays as well as in radio waves.

This gamma-ray view is beginning to reveal the fundamental physics behind pulsars. Much of this research, Romani says, focuses on how the pulsar's extreme electric and magnetic fields, coupled with its breakneck spin, accelerate particles to nearly the speed of light.

One such revelation came from the new gamma-ray-only pulsars. Researchers discovered that gamma rays are much more likely to arise far above the neutron star, within the star's magnetic field, than from close to the star's surface as previously theorized. For the brightest pulsar in the sky, the Vela pulsar, this emission is thought to occur about 300 miles above the surface of the star, which is only 12 miles across.

"The LAT has really helped us solidify the basic story," Romani says. "Now we need to figure out the science behind it."

One-a-day zingers

Although 99 percent of the point-like sources in the gamma-ray sky are blazars and pulsars, Fermi's instruments occasionally see an overwhelmingly bright flash: a gamma-ray burst, the universe's most luminous explosion. These explosions last between a few milliseconds and a few minutes, and never occur in the same place twice.

Before Fermi's launch, gamma-ray bursts were understood to come from two distinct processes. Bursts lasting less than a second or two might be created by catastrophic collisions of neutron stars. Longer ones, lasting up to several minutes, might be released when large stars explode and send out jets of material as they collapse into black holes. Yet a

This image merges the view through Swift's Ultraviolet/Optical Telescope, which shows bright stars, and its X-ray Telescope, which captures the burst (orange and yellow).
Image courtesy of NASA/Swift/Stefan Immler

thorough understanding of these bursts remains elusive.

With its wide field of view and a detector tuned to pick up gamma-ray-burst wavelengths, the GBM instrument is well-positioned to see these events, and indeed records nearly one a day. The fact that the GBM automatically tells the LAT about the burst and reorients the spacecraft so the LAT can view it is "really exciting and really new," says Valerie Connaughton, a research scientist at the University of Alabama in Huntsville and a member of the GBM team. "The spacecraft can reorient in about 100 seconds, letting the LAT see extended emission from gamma-ray bursts."

The LAT chimed in on observations of nine gamma-ray bursts in its first year. Together, the two instruments have a very broad view of the gamma-ray-burst energy spectrum. As Blandford puts it, "The Gamma Ray Burst Monitor and the LAT are looking at something like three or four pianos worth of range, whereas our eyes can only see one octave." To extend this range even further, Fermi collaborates with other satellites to fill in even lower notes.

So far, the instruments have confirmed that the radiation from gamma-ray bursts is extremely high energy and travels very fast. Surprisingly, the LAT data shows little difference between short and long bursts, suggesting that they could come from the same type of astronomical process rather than different ones, as previous data implied.

"With Fermi's eyes, they look quite similar," Blandford says. "As we observe more gamma-ray bursts, I think that we'll start to see patterns and begin to understand them much better."

Is space-time quantumly foamy?

Fermi may also reveal important insights into the nature of space-time.

Some theorists postulate that at its smallest scale space-time is not smooth, but a turbulent, boiling froth of "quantum foam." In direct violation of Einstein's theory that all light travels at the same speed through space, some models of quantum gravity posit that the less energetic a gamma ray is, the faster it travels through the quantum foam.

A recent paper published by the GBM and LAT collaborations reported that low-energy gamma rays from one burst, known as GRB 090510, arrived at the telescope within nine-tenths of a second of the highest energy ray—which was a real whopper, a few billion times more energetic than visible light.

Some models of quantum gravity had predicted a much larger delay between gamma rays with such vastly different energies. The observation that the time delay is so small rules out those models. However, not too much can be read into the existence of some time delay. The inner workings of gamma-ray bursts could have processes that emit higher-energy gamma rays at different times or from slightly different locations, meaning that they arrive earlier or later than lower-energy gamma rays.

"From our measurements, we can't say for sure whether quantum gravity exists," says Fermi Project Scientist Julie McEnery of NASA's Goddard Space Flight Center. "But we have already been able to eliminate several particular models of quantum gravity in this way."

Stalking dark matter

Meanwhile, other Fermi observations may provide evidence for dark matter, the elusive stuff that makes up a quarter of the universe but has never been directly seen.

One possible way to do it is through cosmic rays, subatomic particles—mostly protons and electrons—that rocket through the universe with extreme energies. Cosmic rays are known to stream from the sun; but theorists also postulate that if two dark matter particles collide, they might annihilate one another, blip out of existence and leave a cosmic ray in their place. Theoretical models predict just how energetic those cosmic rays should be, and finding large numbers of them could constitute evidence for dark matter.

Other experiments, including a satellite called PAMELA and a detector called ATIC that floated above Antarctica under a huge balloon, have observed markedly more cosmic-ray electrons at certain energies than predicted by theorists. These electrons could have originated from dark matter particles crashing into one another or from a more mundane source, like a nearby pulsar. Data collected by the LAT show a much smaller excess of cosmic-ray electrons at these energies than other telescopes had reported, an excess possibly explained by nearby pulsars.

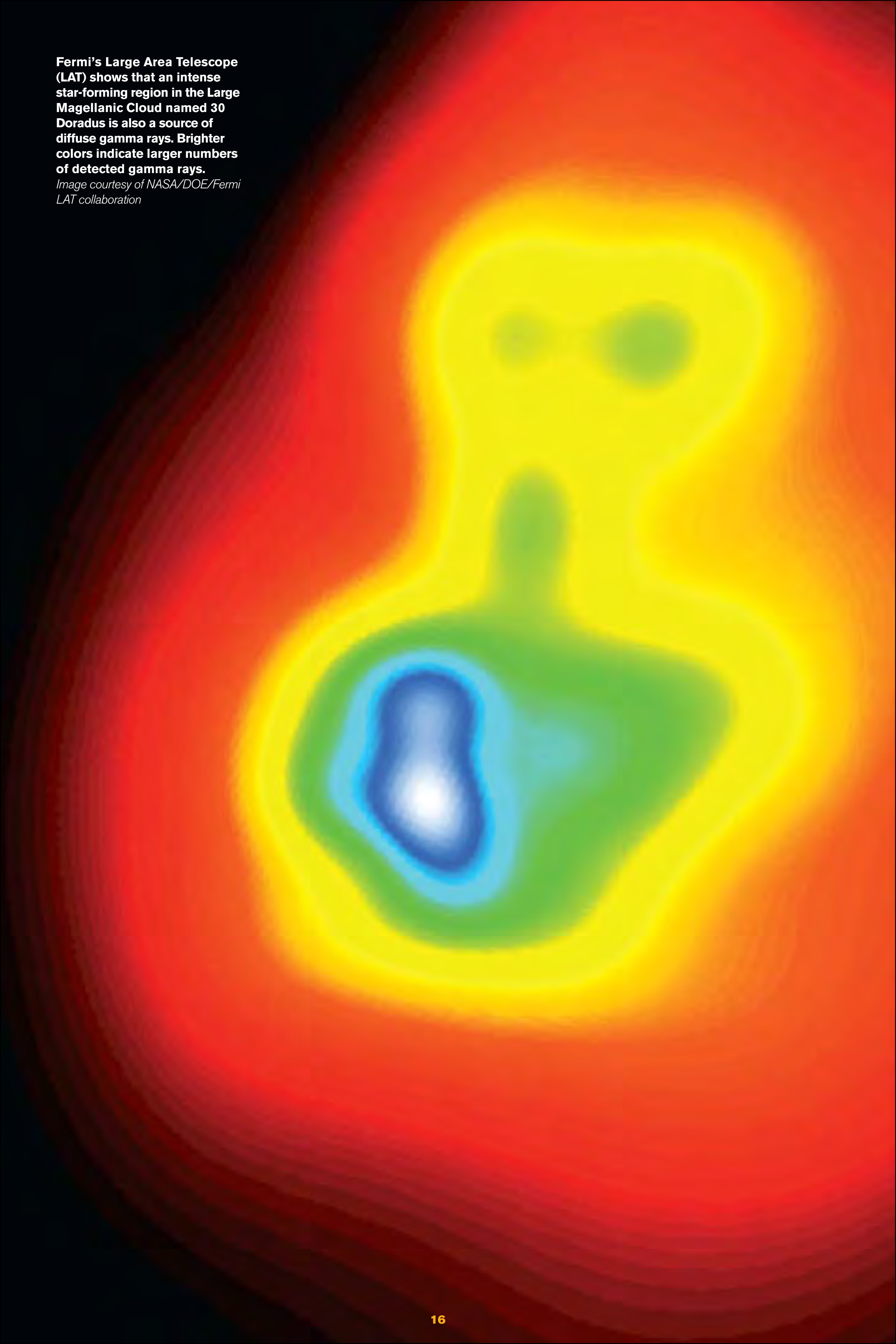
Similarly, EGRET reported finding an excess of gamma rays over most of the sky, including a bright halo surrounding the center of the Milky Way. Some researchers theorized that this excess was the byproduct of dark matter interactions; but the LAT has detected no such strong signal.

The hope of discovering dark matter is not lost, however. Over the coming years, Fermi researchers may be able to detect it in other ways.

One promising hunting ground is the core of the Milky Way, where theorists think the density of dark matter is greatest. If that is the case, Fermi should see an excess of gamma rays flowing from this direction. In fact, several groups of researchers outside the LAT collaboration, working with data that was publicly released after the instrument's first year of operation, have reported seeing such a signal.

However, Simona Murgia, an astrophysicist at the Kavli Institute who co-coordinates the LAT collaboration's dark matter and new physics group, says it's much too early to say if these reports are valid.

"This region of the sky is very complicated," she says. "It's a promising place to look for dark matter, but there's so much going on there that we really need to understand it better before we can make a solid dark-matter claim." The center of the galaxy is a boisterous place; unlike our own galactic neighborhood, where



Fermi's Large Area Telescope (LAT) shows that an intense star-forming region in the Large Magellanic Cloud named 30 Doradus is also a source of diffuse gamma rays. Brighter colors indicate larger numbers of detected gamma rays.
Image courtesy of NASA/DOE/Fermi LAT collaboration

each star is typically a few light years from its closest neighbor, there are two million stars within a single light year of the center. Add to that a black hole more than four million times the mass of the sun, a sprinkling of pulsars and jets, and a fog of gas and dust, and you have very complicated region. Murgia suggests the evidence for dark matter seen by other researchers could just as easily be attributed to one—or several—of these more conventional objects.

"We need to be cautious and rule out the other, simpler explanations before we make a dark matter claim," she says. "But I believe that if there is something out there to find, we have a good chance of seeing it."

Fermi researchers are also combing the extragalactic gamma-ray background—a diffuse and relatively uniform blanket of gamma rays emanating from all directions—for signs of dark matter. If dark matter annihilations contribute to this gamma-ray fog, researchers expect to see a specific signature.

So far, the collaboration has seen no conclusive evidence of dark matter. But this in itself is useful, because it rules out models of dark matter that predict a very strong gamma-ray signal.

"Our studies of dark matter are only just beginning," says SLAC Professor Elliott Bloom. "This is not the low-hanging fruit on this mission, and we'll need years of data before we can set the most constraining dark matter limits."

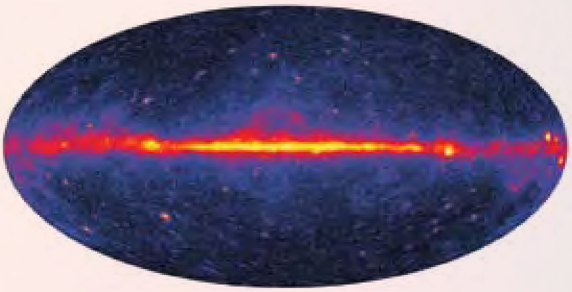
The road ahead

The collaboration is making advances in other areas as well. Fermi researchers are investigating "starburst" galaxies that serve as stellar nurseries; the extended emissions left by supernovae; pairs of stars, pulsars, and other cosmic objects that orbit each other; a soft gamma-ray glow from an abundance of sources in our galaxy and others; and even gamma rays from the sun and the moon. Wherever they look, the sky is ablaze.

As researchers move past the "low-hanging fruit" and push on to more complicated and advanced analyses of these objects, the LAT and GBM will continue to take data 24 hours a day, seven days a week for at least another four years.

"Fermi has no real consumables, so it could last quite a while longer. The Fermi team hopes to operate for 10 years," says Blandford. "The science will continue for all those years, and longer. There's 10 years worth of good observing there, that's for sure."

The avalanche of results has begun.



This view of the gamma-ray sky constructed from one year of Fermi LAT observations is the best view of the extreme universe to date. The map shows the rate at which the LAT detects gamma rays with energies above 300 million electron volts–about 120 million times the energy of visible light–from different sky directions. Brighter colors equal higher rates.
Image courtesy of NASA/DOE/Fermi LAT Collaboration

PRESERVING THE DATA HARVEST

Canning, pickling, drying, freezing–physicists wish there were an easy way to preserve their hard-won data so future generations of scientists, armed with more powerful tools, can take advantage of it. They've launched an international search for solutions.

By Nicholas Bock

Photos: Reidar Hahn, Fermilab

When the BaBar experiment at SLAC National Accelerator Laboratory shut down in April 2008, it brought an end to almost nine years of taking data on the decays of subatomic particles called *B* mesons. But that was hardly the end of the story for the 500 scientists working on the experiment. In November they celebrated the publication of their 400th paper, and they expect the next few years will yield at least 100 more.

These BaBar results and discoveries stem from more than two million megabytes of data. As impressive as this number is, it's only a fraction of the data that will come out of the next generation of high-energy physics experiments. For instance, the ATLAS detector at CERN's Large Hadron Collider will produce a whopping 320 megabytes of data every second, surpassing BaBar's total output within three months.

BaBar's treasure trove of data, which may contain answers to questions we don't even know how to ask yet, raises an increasingly important question in high-energy physics: When the party's over, what do you do with the data?

In the past, this was not so much of a concern. New experiments came along in a regular drumbeat, regularly superseding one another in terms of what could be done with the data they produced. Today, as experiments get bigger, more complex, and much more expensive, the drumbeat has slowed considerably, and physicists are starting to realize the value of wringing as much insight out of every experiment as they possibly can.

But without a conscious effort to preserve them, data slowly become the hieroglyphs of the future. Data preservation takes a lot of work, and with that, a lot of resources. Researchers have to think not only about where to store the data, but also how to preserve it in a way that it can still be used as technology and software change and experts familiar with the data move on or retire.

"Preserving the bits for all time is probably not difficult, but the data themselves become very, very rapidly an arcane, dead language," says Richard Mount, SLAC's head of scientific computing. "Preserving the ability to fully understand the nuances of a dead language is not without its cost."

It's an investment, though, that a growing number of physicists and collaborations are seriously considering. A study group known as DPHEP, for Data Preservation and Long Term Analysis in High Energy Physics, has been holding workshops to look at the issue. The BaBar collaboration has also emerged as an important force in the effort to solve the puzzle, with members striving to provide a working model of how data preservation can be done.

DIGGING FOR TREASURE

The value of old data was recently demonstrated by Siegfried Bethke of the Max Planck Institute for Physics in Munich. His group resurrected 25-year-old data from the JADE experiment at DESY, the Deutsches Elektronen-Synchrotron laboratory in Hamburg, Germany, and combined it with more recent data taken by the OPAL experiment at CERN. They wanted to study the strong coupling constant—a value that reflects the strength of the strong nuclear force that binds quarks and gluons together into protons and neutrons. Equipped with improved analysis tools and refined theory, Bethke and his colleagues were able to get a better feel for how the strong coupling constant changes at different energy levels.

Old data have also proven to be an invaluable teaching tool. Physics professors can use simplified sets of real experimental data to guide students through the basic steps of conducting an analysis. BaBar physicist Matt Bellis has taken this idea one step further, working with colleagues to develop outreach programs for high school and college students that use old data to introduce high-energy physics.

But some physicists report that older data sets have been getting harder and harder to access. Files have become damaged or lost, old software is incompatible with newer operating systems, and the knowledge needed to put everything together for analysis has dissipated. As time goes on, trying to do an analysis with the data becomes more of an archaeological dig than a physics experiment. In Bethke's case, the analysis required the help of experts who had originally worked on the JADE experiment. It also required a lot of hard work and luck. Whole chunks of the data thought to have been lost were recovered in the form of computer printouts. While this was a great find, members of Bethke's team had to go through the printouts page by page and re-enter the data by hand. It was worth the effort, though, since the JADE data had been taken at an energy level where no other data existed.

In an October 2008 survey of more than 1000 physicists, an overwhelming majority indicated that data preservation is important. More than 43 percent reported that access to old data sets could have improved their more recent results, and more than 46 percent expressed concern that important data had been lost in the past.

The survey was conducted by a group of CERN scientists involved in PARSE.Insight, a project funded by the European Commission to provide insight into data preservation across fields of science. CERN physicist Salvatore Mele, who runs the CERN group and is also a member of the DPHEP study group, offers a blunt analysis of the issue, describing high-energy physics as a worst-case scenario in terms of data access and preservation.

"We have funding streams to build accelerators, we have funding streams to build experiments, we have funding streams to operate experiments, we have funding streams to write software, we have funding streams to analyze data," he says, "but we don't have funding streams to preserve data."

HOLDING DATA CLOSE

For particle physicists, it's a surprising place to be; the field has been at the forefront of information technology and open access for decades. Since the 1960s, particle physicists eager to share results with colleagues have distributed preprint manuscripts of their results, initially on paper and then electronically on the arXiv repository, which has accrued more than half a million documents on its servers. In the late 1980s, CERN software consultant Tim Berners-Lee invented the World Wide Web to facilitate communication within the high-energy physics community. And in 1991, the particle-physics article database SPIRES became the first Web site outside Europe, helping set into motion events that have revolutionized information technology.

Other fields have run with this model, using online databases to share not only results and publications, but also raw data. Bioinformatics is buoyed by the efforts of thousands of researchers who make genetic sequence data publicly available, and data from NASA experiments goes public within a year after it's taken. But this exuberance for open-source data seems to have passed over high-energy physics, with collaborations tightly guarding the data from their experiments.

"Typically, in high-energy physics, if you have any interest in somebody's data, you have no access to it unless you know somebody on the team and they're willing to work with you," SLAC astrophysicist Richard Dubois says.

A MATTER OF CULTURE

Dubois found a much different attitude toward data-sharing and preservation when he left particle-physics experiments at SLAC in 1999 to work on the Fermi Gamma-ray Space Telescope, a joint mission of the Department of Energy and NASA (see "Fermi's excellent adventure" in this issue). The space telescope's detectors are similar to those used throughout high-energy physics to record the trajectories of subatomic particles. But in return for NASA's collaboration, Fermi scientists had to make some concessions. They agreed to organize their data in a format called FITS, which is used by all NASA science missions. And they pledged to make all their data public one year into the mission, along with any tools needed to analyze it.

NASA "basically says, 'If you want to build this thing, these are the conditions under which we'll let you do it,'" Dubois says. "Their goal is that anybody can make scientific discoveries with this public data."

For astrophysicists, the model has its pros and cons. The simplicity of the FITS format can limit the breadth of analyses collaborations are able to undertake. But at the same time, because all NASA experiments use FITS, it becomes easy for researchers to use data across different collaborations. NASA also promises to store and maintain FITS data indefinitely.

There is no analogous organization for high-energy physics. The Department of Energy underwrites many high-energy physics experiments conducted in the United States, but does little in the way of mandating what is to be done with the data produced. The responsibility of preserving data often falls on the collaborations themselves and, as a result, can become something of a bugbear, channeling money away from research projects and offering little in the way of immediate returns.

"You don't get tenure because you invested six years of your life preserving data," Mele says. "You get tenure because you do physics."

WHAT YOU SEEK IS WHAT YOU GET

In high-energy physics, data collection starts with a detector—an oftentimes enormous piece of scientific equipment that measures the outcomes of collisions between subatomic particles.

To get an idea of what a collision looked like, researchers reconstruct it from tracks the debris left in the detectors. Then they compare the actual data with the results of simulations based on what they had expected to find. Only then can they draw conclusions about what it all means. Further complicating things, their reconstructions depend on the kind of event they're looking for; using the same data set, a researcher studying tau physics might come up with a completely different reconstruction than a researcher studying beta decay.

"There's no way to analyze a high-energy physics data set and get all the information out of it. That doesn't happen," Mount says. "If you make completely different guesses about what you might be looking for, you might get different things."

Reconstructing the data and running the simulations require a thorough familiarity with how the detector works—something that's developed over years of working within a collaboration. Because tools tend to be so unique, it is difficult for physicists from different collaborations to work with each other's data.

A COMPUTING CHALLENGE

When it comes to figuring out how to make this kind of exchange work, though, the data itself plays a relatively small role. The real challenge comes from preserving the software used to access and analyze the data, the software needed to run simulations, the operating system needed to run the software, and, perhaps most importantly, the knowledge of how to use the software with the data to produce results.

It's something that BaBar Computing Coordinator Homer Neal spends a lot of time thinking about. Neal oversees all of BaBar's computing tasks, from how the collaboration goes about doing computer-intensive analysis jobs to which operating systems it uses. He is also heavily involved with the data preservation effort, participating in DPHEP workshops and helping draft a report on the group's findings.

The challenges involved in data preservation are very real for Neal, who last summer helped oversee the ultimate reprocessing of BaBar's data. This reprocessed data and the corresponding raw data are being transferred to newer, high-density tapes, a process that will take about a year. By about 2012, he says, BaBar's archival system will store several copies of the data on disk and/or solid-state drives.

"This is our legacy data, because it is very unlikely that we will ever have the resources again to reprocess all the data," Neal says. The archival system will ensure that it remains in a form that can be analyzed.

Dealing with the operating system could prove to be a lot trickier. Once a software distributor stops providing security upgrades for an operating system, running equipment on it quickly becomes a liability. To keep servers safe, the operating system has to be upgraded regularly. But all the analysis and simulation software must be upgraded with it, lest researchers be overwhelmed with a deluge of error messages when they try to access the data.

EXPLORING SOLUTIONS

During the past year, members of DPHEP have been meeting to try to hash out some solutions. The group's first workshop was held in January 2009 at DESY. The group met at SLAC in May, and is scheduled to meet again this month at CERN. In August 2009 its efforts were endorsed by the International Committee for Future Accelerators, which provides a forum for discussions of particle physics worldwide.

One topic at these workshops has been virtualization, a technique that takes advantage of multi-core processors to run likenesses of old machines on new operating systems. The main computer would run on the latest operating system available, while the old, or virtual, machines securely run old software without having to worry about the periodic cycle of updates.

Neal and other BaBar researchers hope that data storage and virtualization methods will soon progress to the point where all the experiment's data and software can be housed in a self-contained archival system. According to Neal, new members of the collaboration could be working exclusively from the system as early as 2013. Another model, proposed by BaBar members at the University of Victoria, operates on the same idea, but with data and software housed at computer centers around the globe rather than at a central location. The team recently got $577,000 from Canada's Advanced Innovation and Research Network to design a prototype of the system.

BaBar researchers are also working to find easier ways to share data. While the complexity of most data sets eliminates any hope of creating a universal data format like FITS, researchers have been trying to develop data formats that at least let similar experiments exchange data. This can decrease statistical uncertainty in analyses and provide a good way to double-check results. Researchers at DESY have already started combining data sets from that lab's H1 and Zeus experiments, and recently submitted publications signed by both collaborations.

Physicists at BaBar are trying to build on that model. They are exploring ways their data can be combined with data from the Belle experiment at Japan's KEK lab, which also investigates decays of *B* mesons.

Amidst all the uncertainties of the data preservation debate, two things seem clear: the amount of data produced by high-energy physics experiments will continue to increase. And finding ways to preserve that data and make it reusable will be a challenge.

"There are voices saying that this will never be possible for high-energy physics," says H1 Spokesperson and DPHEP Chair Cristinel Diaconu. "It is very complicated, but it is not impossible. We have to just aim toward some form of open access and see how far we can get."


H1
DESY
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Chugging along in the background, old physics machines are the workhorses behind many cutting-edge projects, from the world's most powerful X-ray laser to the Large Hadron Collider and a lab that tests microchips bound for Mars.

By Rachel Carr

Recycle, Reuse, Re-accelerate

The two-mile-long linear accelerator at SLAC National Accelerator Laboratory is the second-longest building in the world. After 42 years of contributing to particle physics experiments, its particle beams are being redirected to two new projects: the world's most powerful X-ray laser and a test bed for advanced accelerator technology.
Photo: Peter Ginter

Berkeley Lab is home to more than one old accelerator that's evolved to keep up with the times. The 184-inch cyclotron, for instance, has given way to the Advanced Light Source. Founding lab director E.O. Lawrence (top left) sits overlooking the construction of the cyclotron's domed building, which began in the 1940s. The building and magnets being assembled (above).

It's always the new stuff that makes the news. Consider the Large Hadron Collider, the enormous ring beneath the Swiss-French border that has swamped magazine covers, newspaper stands, and even movie screens in the lead-up to its first particle collision. Amidst all the buzz about innovation, you might think scientists can't discover new physics without a brand-new machine.

But a corps of durable, versatile, and carefully maintained accelerators from the 1970s, 60s, 50s, and even 40s proves that time-tested accelerators can still spawn cutting-edge science.

Upgraded, adapted, and sent off on new missions, these veteran accelerators represent recycling and reuse on a grand scale, saving hundreds of millions of dollars while freeing money for projects at the forefront of experimental physics. In fact, in some cases they've been absorbed into those new projects. Old-school machines feed into Fermilab's Tevatron collider; the world's most powerful X-ray laser, at SLAC National Accelerator Laboratory; and even the LHC, which surpassed the Tevatron as the world's most powerful particle accelerator just 10 days after its successful restart in November.

Built to last

The first cyclotron, at what is now Lawrence Berkeley National Laboratory, was small enough to hold in your hand (see "The particle physics life list" in our Aug 07 issue). That diminutive accelerator evolved into Berkeley's 88-inch-wide cyclotron, which accelerated its first particles around the time the Beatles performed their first songs.

"This was just post-Sputnik," says Claude Lyneis, a physicist who has helped oversee Berkeley Lab's accelerators for 30 years. Legend has it that Glenn Seaborg, the discoverer of plutonium, had gone to Washington, DC, to secure funds for the University of California's physics program. Asked what was needed to keep American science competitive, Seaborg replied, "We need a new cyclotron."

By 1961, the new cyclotron was churning out rare isotopes, variations on the standard chemical elements that have slightly different atomic masses. This helped physicists work out the structure of the atomic nucleus. While the 1970s saw the breakup of the Fab Four, the 88-inch kept right on going. Today, perched on a hill overlooking San Francisco Bay, it still performs superbly.

What's allowed this legacy of the Atomic Age to keep up in the fast-paced world of experimental physics? A combination of factors, Lyneis says.

For one, there's a lucky difference between studying elementary particles, like quarks or the Higgs boson, and studying atomic nuclei. When the

(above) Gov. Mike Rounds of South Dakota toured the Advanced Light Source in June with Berkeley Lab's Zahid Hussain, left, and Kevin Lesko. In the far left of this photo you can see all that's left of the original cyclotron–a giant magnet yoke, in gray, and the red crane on top of it. Both are still in use. (top right) The historic dome today, with its view of San Francisco Bay.

Photos courtesy of Berkeley Lab

objective is fundamental physics, scientists often seek the highest-energy accelerator they can find, with the aim of packing the most energy, typically measured in electronvolts, into every particle collision.

"That's not so true in nuclear physics," Lyneis says. "It turns out that between eight million and 30 million electronvolts, the nuclear physics is not very interesting. Most nuclear structure research is done in the four-to-seven-million electronvolt range."

That's a range the 88-inch could reach even in its earliest years. So rather than increase the machine's energy, scientists decided in the mid-1980s to give it a wider variety of ions to accelerate. Ions are atoms stripped of their outermost electrons; the lightest one is the proton, a hydrogen atom with its single electron taken away. The ions were injected into the cyclotron with a newly invented system called an electron cyclotron resonance ion source, or ECR.

"The ECR saved not just us but many cyclotron facilities," Lyneis recalls. "It allowed us to expand into heavy ion work. Before the ECR, we could only accelerate ions up to argon. With the installation of our first ECR, we could accelerate ions as heavy as xenon. After we installed a second ECR in the mid-1990s, we were able to run essentially any element for days at a time."

Those upgrades opened the door to new research possibilities—figuring out how heavy elements form in exploding stars, for instance, or what keeps the biggest nuclei from breaking apart as theoretical models predict they should. The development of new detectors brought even more opportunities for studying isotopes spawned by the cyclotron. Today, a still-more-advanced detector is under construction.

"It's like a better microscope, so it will give us a higher-resolution picture of the nuclei we study," Lyneis says. And that old reliable, the 88-inch cyclotron, will keep doing its part.

"I can't predict where we will be 10 years from now, but I know we are blessed at LBL to have had very high-quality engineering behind us," he says. "The strength of that engineering is one reason I believe the cyclotron has worked so well."

Learning new tricks

Solid construction goes a long way, but adaptability may be the key to accelerator longevity. That's the case at Brookhaven National Laboratory on New York's Long Island, where two Van de Graaff accelerators are still humming nearly four decades after they began operation.

"Our ability to evolve as a facility has been very useful," says Peter Thieberger, a physicist who works closely with the accelerators.

If you've ever put your palm on the bulb of a basic Van de Graaff generator, you know they're powerful machines. Even a small one can channel enough charge to make your hair stand on end. Robert Van de Graaff built the first in 1929, using a tiny motor and a dime-store silk ribbon, and by the 1970s, much bigger versions became workhorses of nuclear physics. Brookhaven has two, each of which is called a Tandem Van de Graaff because it accelerates its allotment of ions twice. They were manufactured in the late 1960s and first operated as a pair in 1971.

"At the beginning, ours was the highest-energy tandem facility in the world," Thieberger says. In those early days, the focus was basic research into the structure and interactions of nuclei, and the territory was wide open. But soon, other laboratories caught up.

At that point "there was talk of shutting down Brookhaven's Tandem Van de Graaff facility," Thieberger says. "But fortunately we had developed a method for running at a high intensity" by upgrading the accelerators so they would propel more particles per pulse. That allowed the Van de Graaffs to take up a new job: injecting heavy ions into a larger Brookhaven accelerator called the Alternating Gradient Synchrotron, and from there into RHIC, the Relativistic Heavy Ion Collider, which turned on in 2000.

All along, flexibility has been the machines' supreme virtue.

The Tandem Van de Graaffs "have the capability to produce very weak or very intense beams. They can also operate at a wide range of energies," Thieberger says. "With a cyclotron, for instance, it's usually time-consuming

(top left) The installation of the Tandem Van de Graaff accelerators at Brookhaven in 1967; (above) The Relativistic Heavy Ion Collider (RHIC) accelerates gold and other heavy ions produced at the Tandem Van de Graaff.

Photos courtesy of Brookhaven National Laboratory

(top) In 1970, Brookhaven employees celebrated when both accelerators started running at design energy. (bottom) The Tandem Van de Graaff today.

to make large changes in the beam energy or change the ion species, but with a tandem, you can do it much faster. You can also accelerate a large range of ions. You could change from hydrogen to gold in 15 or 20 minutes."

Brookhaven is building a new accelerator to take over heavy-ion injection, but the ever-versatile Van de Graaffs will move on to a new job: testing components for space missions.

"With these machines, you can generate a very stable voltage, so you can create beams with very stable and uniform intensity and energy," Thieberger says. "That uniformity is important for testing microchips, and the range in intensity is good for simulating space conditions."

In recent years, the test facility has attracted more than 100 companies from the United States, Europe, and Japan that use it to test microchips and other electronics bound for space. Materials tested there have found their way into communication satellites, weather trackers, and NASA's Pathfinder lander, which explored the surface of Mars in 1997.

New applications crop up every month. The facility recently began collaborating with a company that produces extremely fine filters for biological procedures. And after the new RHIC injector comes on line, Thieberger says, the Tandem group hopes to sign on even more facility users.

Good as new, if not better

The most valuable product of older accelerators may be a new generation of scientists. Several American universities, including UC-Davis, Indiana University, and Michigan State University, host cyclotrons with deep-rooted histories. Those machines play a hands-on role in the training of graduate students, who may never have a chance to work directly on a big machine such as the Tevatron or LHC.

Particularly when university budgets are tight, holding onto older equipment can have tremendous payoffs. That's a lesson Texas A&M University's Cyclotron Institute was pleased to learn not long ago.

For two decades, an 88-inch cyclotron that had helped jumpstart the university's nuclear science program and that fueled research until 1986 had been gathering dust in a storage building on campus.

"We basically mothballed the 88-inch. We sort of bolted it up and left it," says Robert Tribble, director of the Cyclotron Institute. "We would have given it away if someone had wanted it. But we're very fortunate that we didn't."

Now, the institute's scientists are pulling the machine out of storage, giving it a significant revamping, and sending it back to work. The iron and coils of the original magnet will remain, but new power supplies, vacuum pumps, and other components will allow the machine to generate radioactive ion beams for acceleration in an existing superconducting cyclotron.

"There's a bit of déjà vu," Tribble says, "but the program won't look the same this time around. It's a whole different field of research today. When the cyclotron was built, no one was really thinking about the possibility of creating radioactive ion beams and accelerating them. That didn't catch people's imagination until a decade or two ago."

Perhaps the most impressive aspect of the upgrade is the savings it means for the institute. Building a new 88-inch cyclotron would take something like $10 million, says Tribble. Refurbishing the veteran machine will cost about one-fifth as much.

While the upgrade will not be complete until 2011, the new facility's potential has already started to lure scientists.

"We have groups from around the world coming to use the radioactive beams we can already produce, anticipating the higher-quality beams we will be able to produce after this upgrade," Tribble says.

Tribble hopes the freshly energized facility will also draw new students to the institute, which has a strong history of educating scientists, engineers, and policymakers. Hundreds of Texas A&M undergraduates and graduate students have used the cyclotrons in their studies, Tribble says. University alumni now work in a variety of universities, national labs, private companies, and government agencies.

(above) Technicians Ray Hren and Jim Wendt helped build Fermilab's Cockroft-Walton, and they serve as the main brains behind the machine's maintenance today. Hren (top photo, right) and Wendt were in their early 20s when they joined the laboratory in 1968. They were among the first technicians to be hired. (left) An open door reveals the inside of the equipment dome of the Cockroft-Walton at Fermilab.

Still kicking particles

Perhaps it's not a complete surprise to find working cyclotrons and Van de Graaff accelerators with 40- or 50-year vintages. But you might not expect old-school machines to play a part in the most advanced, ultra-energetic accelerators in the world.

In fact, the protons that zip through the Tevatron get their first kick from an accelerator built around 1970 and based on a design from the 1930s. The look of the Cockroft-Walton generator hasn't changed much since its inception, and the apparatus' strange, shiny contours continue to fascinate visitors on tours.

"It's really a showpiece," says Ray Hren, who remembers assembling the Cockroft-Walton in a half-built building while wearing his winter coat. "It's fun to see visitors get a look at it now. They don't know that it's old technology. It's just neat-looking. To them it looks state-of-the-art."

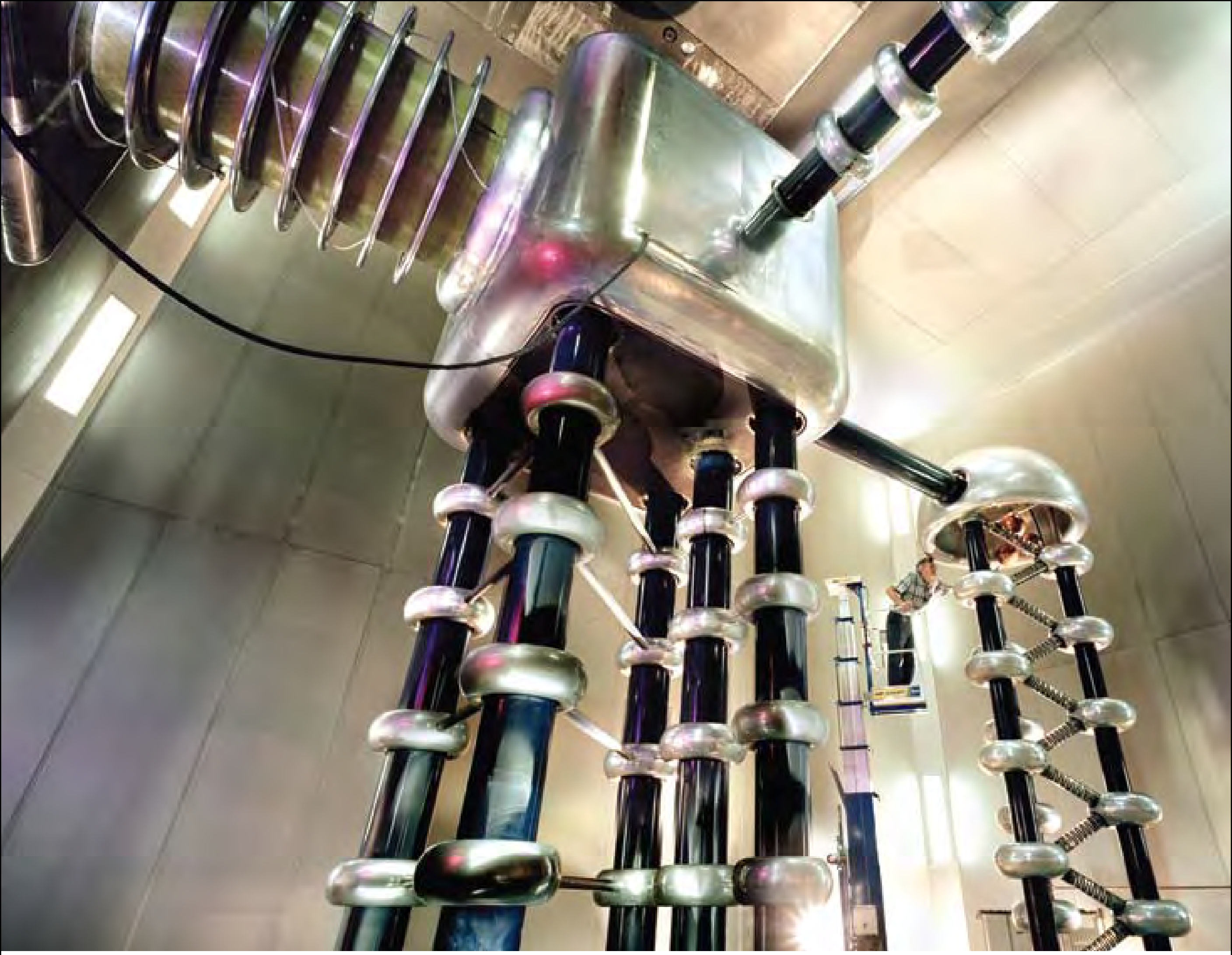
In his 40 years at Fermilab, Hren has seen plenty of changes. The laboratory's original fixed-target experiments gave way to the Tevatron collider, which smashes particles together at nearly the speed of light. Rather than ferrying computer tapes from place to place by station wagon, researchers now send data to colleagues over the Internet. But aside from some incremental updates, the Cockroft-Walton has remained a solid force at the start of the beamline.

"It's a very reliable machine, and it's a fairly cheap system to operate," Hren says. There have been proposals to replace it with a newer system, he says, but ultimately, the answer has always been the same: "We have a good, working system. Why change it?"

In California, SLAC's two-mile-long linear accelerator—the second-longest building in the world—was at the forefront of particle physics research for 42 years, contributing to discoveries that earned three Nobel prizes. When its last particle physics experiment shut down in spring 2008, the old linac wasn't put out to pasture; instead it's been incorporated into two projects that are considered key to the laboratory's future.

In 1969, Fermilab technicians set up a Cockroft-Walton borrowed from Argonne National Laboratory to test Fermilab's pre-accelerating column and the first tank of the linear accelerator.

Photos courtesy of Fermilab



Today, one-third of the linac accelerates electrons for the Linac Coherent Light Source, the world's most powerful X-ray laser and an all-purpose tool for exploring matter at the atomic and molecular levels. John Galayda, head of the LCLS accelerator systems division, estimates that this saved the lab well over $400 million. The other two-thirds of the linac will feed into FACET, a test bed for a technology known as plasma wakefield acceleration that could lead to much smaller, cheaper accelerators for science, medicine, and industry (see "Crashing the size barrier" in the Oct 09 *symmetry*).

Across the Atlantic, the same combination of practicality and thrift has kept CERN's Proton Synchrotron running for half a century. Incredibly, this old workhorse, the first ring-shaped accelerator at the European laboratory, is an early stop for protons on their way to the Large Hadron Collider.

In the late 1960s, when the plan for CERN's Super Proton Synchrotron was conceived, scientists considered shutting down the original PS. Quickly, however, they realized they could incorporate the PS into the new scheme as an injector, which brings protons up to a moderate speed before unloading them into a chain of more advanced accelerators.

"From the time when the SPS came on line," says CERN physicist Simon Baird, "it was obvious that the PS was an asset that CERN had and could put to good use."

Over the decades, as the PS moved on to work in a slew of other experimental complexes and now at the LHC, most parts have been replaced. Several new components were installed specifically to meet the needs of the Large Hadron Collider.

"There is only a bit of hardware left from the original construction—the steel of the magnets," Baird says. "But the principle is still the same. The design was well thought out. We still use the same designs today when magnet coils need to be replaced. The coils themselves get worn out, but there is no question about changing the design. They got it right."

What opera and physics may have in common, more than anything else, is their tendency to make most people cringe or fall asleep. Can an avant-garde opera that compares self-exploration to the physics of multiple dimensions invigorate audiences? The creators of *Hypermusic Prologue, A Projective Opera in Seven Planes* seem to think so.

Baritone James Bobby and soprano Charlotte Ellett explore their relationship in extra dimensions.

Hector Parra learned about physics from his father and studied it until he was 18, when, as he says, “The piano took all of my energy.” Now a composer, Parra has an unmistakable passion for opera’s grand expression of human emotion. Yet he also rebels against traditional styles of composition. His latest work, called *Hypermusic Prologue, A Projective Opera in Seven Planes*, is so different from classical opera in subject matter and musical style that Parra says, “I don’t know if it’s an opera. It’s an experience.”

Hypermusic Prologue is about the physics of extra dimensions. It was inspired by the book *Warped Passages* by Lisa Randall, a professor of theoretical physics at Harvard University. Parra was so moved by the book that he asked Randall to write the libretto—something she had never done before. But she hopped on board and wrote a love story sprinkled with ideas from her physics research. Based on that story, Parra composed music that expresses frustration, desire, passion, and the experience of traveling into the fifth dimension.

The two characters, a soprano and a baritone, live on the same stage and interact day to day. But the soprano is searching for change and depth, and longs to explore higher dimensions. The baritone is satisfied with a static world, where he remains while his companion finally breaks through. To save the relationship, he must also make the leap and follow her.

At times, Parra’s score is a collection of disjointed noises. It is rarely melodic, and segments often stop before any kind of recognizable song structure develops. The percussionist uses odd instruments such as broken glass in a crystal container, wood scratching on a chalkboard, and a makeshift instrument that sounds like a furiously scribbling pen. Yet this style works well to illustrate the characters’ inner turmoil and rocky relationship.

The baritone’s half of the stage, a static world of concrete objects and pale colors, is ruled by classical physics. On the other half, the soprano journeys through vibrant colors, warping shapes, and twisting scenery. Both sometimes express themselves in physics terms:

Text by Calla Cofield
Photography by Aymeric Warmé-Janville

Soprano: *The forces change*
[She moves across the stage. Different colors converge.]

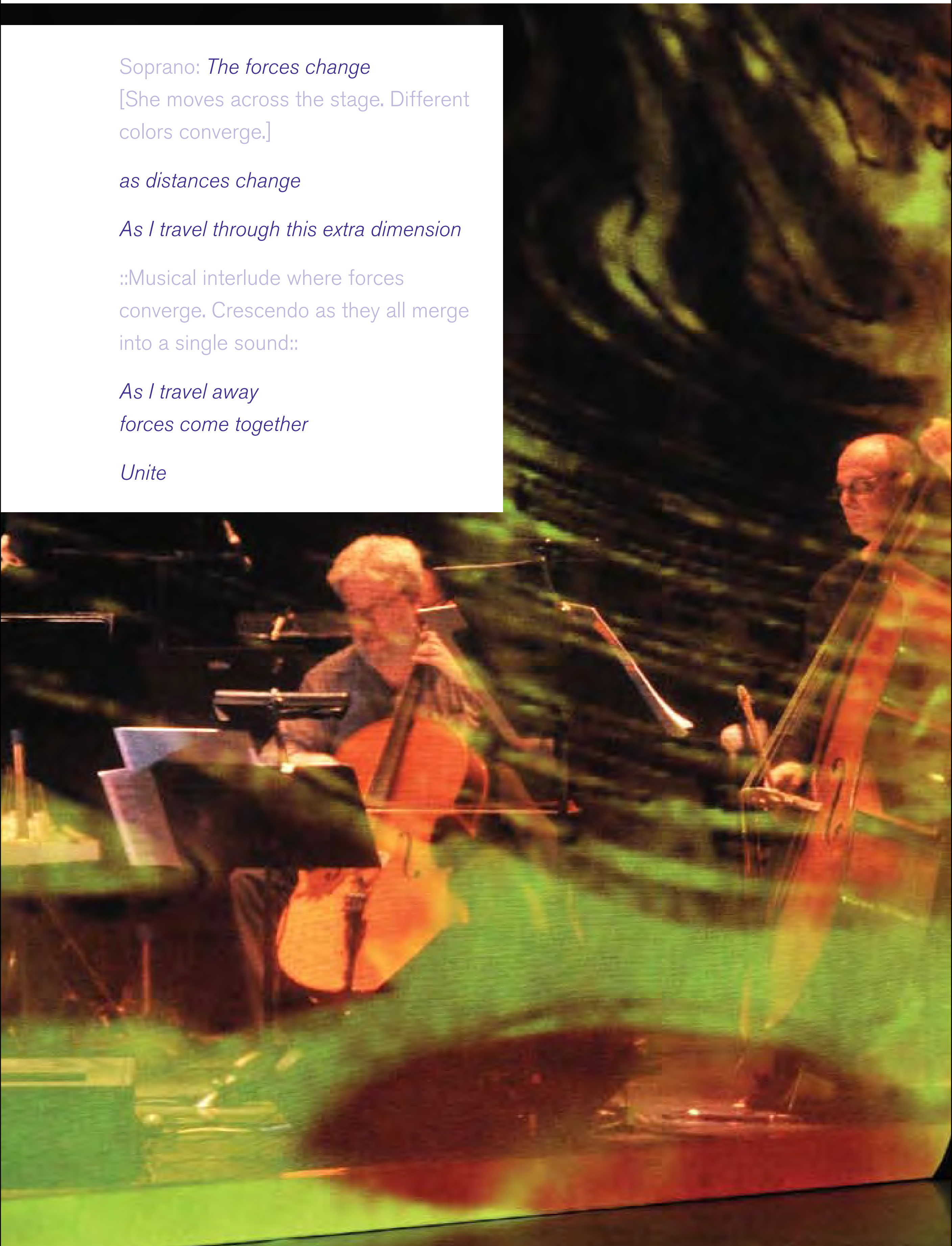
as distances change

As I travel through this extra dimension

::Musical interlude where forces converge. Crescendo as they all merge into a single sound::

As I travel away
forces come together

Unite



Rather than concealing the orchestra in a pit, set designer Matthew Ritchie put it on stage behind a screen that becomes translucent when the lighting is right.

Each of the two singers occupies half of the stage. The baritone lives in the static, concrete world of classical physics. The soprano's colorful, vibrant world reflects her longing for change and depth.

The set was designed by artist Matthew Ritchie, who is based in New York City and knew Randall from previous ventures into artistic representation of science. While the set incorporates physics ideas—distortion of the fabric of space-time, for instance, is reflected in spiraling images and tie-dye swirls of color—he says the visuals were not meant to be direct translations of those ideas. "I want to tread carefully because it's not science," Ritchie says. "It's a kind of emblem."

To create the illusion of traveling through a different dimension, Ritchie projected video onto a gray stage. This allowed rapid background changes and intricate, morphing color schemes. While the orchestras for most opera performances are concealed in a pit in front of the stage, the musicians in *Hypermusic* sit onstage behind a screen that becomes translucent when the lighting is right, so they appear in the same space as the singers.

With three creative minds completing most of the work for the opera from different locations—Parra in France, Randall in Massachusetts, and Ritchie in New York—*Hypermusic Prologue* could have been a train wreck of ideas; instead it manages to be harmonious, engaging, and adventurous.

The production debuted in Europe in the summer of 2009 and continues to tour. Excerpts from the opera are scheduled for performance January 11th and 12th at the Guggenheim Museum's Spiral Hall in New York City. Parra says he hopes to bring the full production to the United States in 2011.

Rapbassador for science

By Tona Kunz

If there's one form of music instantly recognized around the globe, it's rap. The American genre informs, entertains, and has a low barrier to participation. You don't need a large vocal range or a backup band. You just need a message, delivered rapid-fire with style and bravado.

For a growing number of so-called Nerdcore rappers, the message is that people need to support basic research and math and science education if they want to hand future generations a nation worth bragging about. Rather than rapping about drugs, guns, and thug life, they take rap back to its roots as a tool for enlightenment and political discourse, with science and technology as common themes. The most famous example in the particle-physics world is "The Large Hadron Rap," which has racked up more than five million hits on YouTube; but there are plenty of others celebrating astrobiology, orbiting planets, computer codes, even $E=mc^2$.

Steve Rush, aka funky49, a science enthusiast from Florida and *Wired* magazine Nerdcore Hip Hop All-Star, gained notoriety in 2009 when he was commissioned by the Tampa Museum of Science and Industry to make the album *Rapbassador*. He came to Fermilab in August to premier a song, "Particle Business," about experimenters racing to discover the Higgs boson at the lab's Tevatron Collider. Dan Lamoureux, producer of the documentary *Nerdcore For Life*, filmed funky49 rapping in front of Wilson Hall, in the CDF experimental hall and the Tevatron main control room, and next to the Cockcroft-Walton particle accelerator.

When he's not rapping, funky49 works for a medical imaging company that uses MRI, a technology based on powerful magnets made of superconducting wire and cable that were developed in the 1970s to meet the needs of the Tevatron. "I have a job because of magnetic fields," he says. "I have a job because of science."

Here are funky49's lyrics, with commentary.

Photo courtesy of funky49

Physicists from the Collider Detector at Fermilab, or CDF, experiment have a 20-year tradition of playing in a rock band called Drug Sniffing Dogs, which was featured in the 2008 documentary *The Atom Smashers*. (See "Physicists Rock!" Jan/Feb 08.)

A common rap term, OG is short for original gangster but has also come to mean authentic or the first incarnation of something.

Particle physics researchers compete to get results first, but also use each other's results to cross-check discoveries, work with collaborators from all over the world, and tap the knowledge and infrastructure of past competitors to build the next generation of experiments.

$E=mc^2$ Albert Einstein's formula relates the mass of an object to its energy content.

Fermilab's first director, Robert Wilson, established a herd of bison at the laboratory in 1969 as part of his plan to blend science, art, and the environment and make the 6800-acre site a welcoming place. The bison also represent the site's frontier history.

Fermilab's two collider experiments, CDF and DZero, compete to make discoveries first.

Matter consists of two fundamental types of particles: the force-carrying bosons and the quarks and leptons, which are collectively called fermions.

To front is to put up a facade or make appearances.

Science classrooms use triple-beam scales to weigh chemicals; in rap, the term describes measurements of cocaine.

Brain drain: the migration of scientists to other countries in search of better research opportunities. For instance, many American particle physicists have been moving to Europe to work on the next big machine in the field, the Large Hadron Collider.

Through popular science books and a TV series, Carl Sagan educated people about astronomy, astrophysics, and other natural sciences. The Greek composer Vangelis created the music for Sagan's TV series.

Funky49: http://funky49.com and http://rapbassador.com
Videos by Dan Lamoureux: http://www.crapbotproductions.com

Particle Business

by funky49 (a.k.a. Steve Rush)

Rock stars of physics, particle business
smash matter, anti-matter and witness
quarks, bottom to top
they don't stop
"Where the Higgs at?"
Yo that's their mark!
Go! Go! Go!

Tevatron, OG atom smasher
Say Hello to CERN's party crasher
The new 'Lord of the Rings' LHC hear me
This be competitive collaboration baby
Strippin' electrons, makin ions
Of hydrogen, now pull that proton
Give it that speed we need to make
Real Science get achieved, I believe
Shock protons, Greatly accelerated
Two tera electron volts they rated
Fated to smash and get mated
Creatin' smaller bits, energy still equated
We love collisions, Take snap shots
Till we set the right shot, learn a lot
Yo, a mad grip of events do occur
Blast fast, Data stream is a blur
Normal events–They get ignored
Higgs events–They get adored!

High over frontier. Wilson Hall tall
With aesthetics, it's a science cathedral
For the people that see with math
Collider detector and massive graphs

DZero or CDF, who's the best?
If pressed I guess who's closest
To quench the measurement thirst
And who got their results in first

Collision detectors, Fermion collectors
This ain't the GO's with pocket protectors
These peeps cool like super-conducted
Magnets, you know four nine ain't frontin'

To me, triple beams don't mean
Pushin' mad coke, Its scientists in lab coats
So you ready for insight twilight or limelight?
Research in basic science, I'll fight

Whose side you with? R&D dollars?
Or pork spending for anyone who hollas?
Brain drain. No technology policy
Ballot box for better decisions in D.C.

Rap Carl Sagan over new Vangelis Keys
Science cutter clowns get smacked down please
I'm trippin' at students slippin' in
Test scores, Against the world they're dippin'

Let's be liftin', Positive like positrons
Before we ask where we gone wrong
Down with MTV, forget what you heard
Get lost in Cosmos and Mister Wizard

Quarks exist in six types: top, bottom, up, down, strange, and charm.

A reference to the J.R.R. Tolkien book series and how the Tevatron, now the world's highest-energy accelerator ring, will cede its title to the much bigger and more powerful Large Hadron Collider at CERN.

The combined energy of the Tevatron's proton-antiproton particle beam collisions is about 2 TeV, or two tera-electronvolts. "Tera" means "trillion." (See "Explain it in 60 seconds: terascale," Dec 07.)

Of the 10 million proton-antiproton collisions that take place in the Tevatron every second, physicists select fewer than 100 for further study. They program computers to make this selection automatically, based on which collisions produce the most interesting sprays of particles.

The design of Fermilab's 16-story Wilson Hall was inspired by a Gothic cathedral in Beauvais, France.

In a quench, super-cold superconducting magnets warm up and no longer conduct electricity without resistance. These events can damage the accelerator if not controlled. (See "Explain it in 60 seconds: magnet quench," Nov 08.)

The antisocial, nerdy scientist is a stereotype. Physicists, like anyone else, have a wide range of interests and social connections.

Basic research, the foundation for new technologies and industries, competes for federal money against legislators' pet projects—known as pork-barrel projects—for a limited pool of taxpayer money.

Taxpayers can use their votes to influence spending choices through the officials they elect.

On high-school proficiency tests, American science and math scores lag behind those of most other developed nations. Elementary and middle-school scores have been rising in math but have stagnated in science since the mid-1990s, according to *The Condition of Education 2009*, a report from the National Center for Education Statistics.

Positrons are the antimatter equivalents of electrons, with positive rather than negative charge.

Who needs coasters when you have electron beams?

Particle accelerators provide clues as to how the universe began, but they also prevent coffee rings.

For about 25 years, companies around the world have been using beams of electrons from particle accelerators to make scratch- and stain-resistant furniture. The surfaces of these treated desks, shelves and tables may resemble wood. But if it's nearly impossible to scuff, the furniture is likely covered in a coated, treated paper with a wood-grain design.

"It's rice-paper thin, but it's tougher than nails," says Ed Maguire, general manager at Energy Sciences Inc. The Massachusetts-based company is one of several that sell electron accelerators used to manufacture these durable coverings for furniture and flooring, among other things.

Before this technique was available, some companies coated furniture in plastic. "It was tough and stain-resistant," Maguire says. But it was difficult to work with, expensive, and tough to print with that wood-grain pattern.

Others coat decorative paper with a polymer dissolved in water or a solvent that evaporates, leaving a solid, protective surface. However, as it dries, harmful chemicals evaporate into the atmosphere.

"Most sizeable coating operations will use a thermal oxidizer, a big oven that burns off the solvent and lessens the environmental impact," says Josh Epstein, a representative from Advanced Electron Beams. "But it uses a lot of energy and doesn't eliminate the harm to the environment."

In contrast, coatings made with electron beams don't contain water or solvents, and involve a negligible amount of evaporation. Instead, the electron beam promotes polymerization, the linking up of small molecules to form long, sturdy chains. This takes a small fraction of the energy used to dry conventional coatings and leaves a durable solid, which resists scratching and blocks other molecules from seeping into the fibers of the printed paper beneath.

"Today with taxation against pollutants, it can actually be cheaper to use technology that's better for the environment," Maguire says.

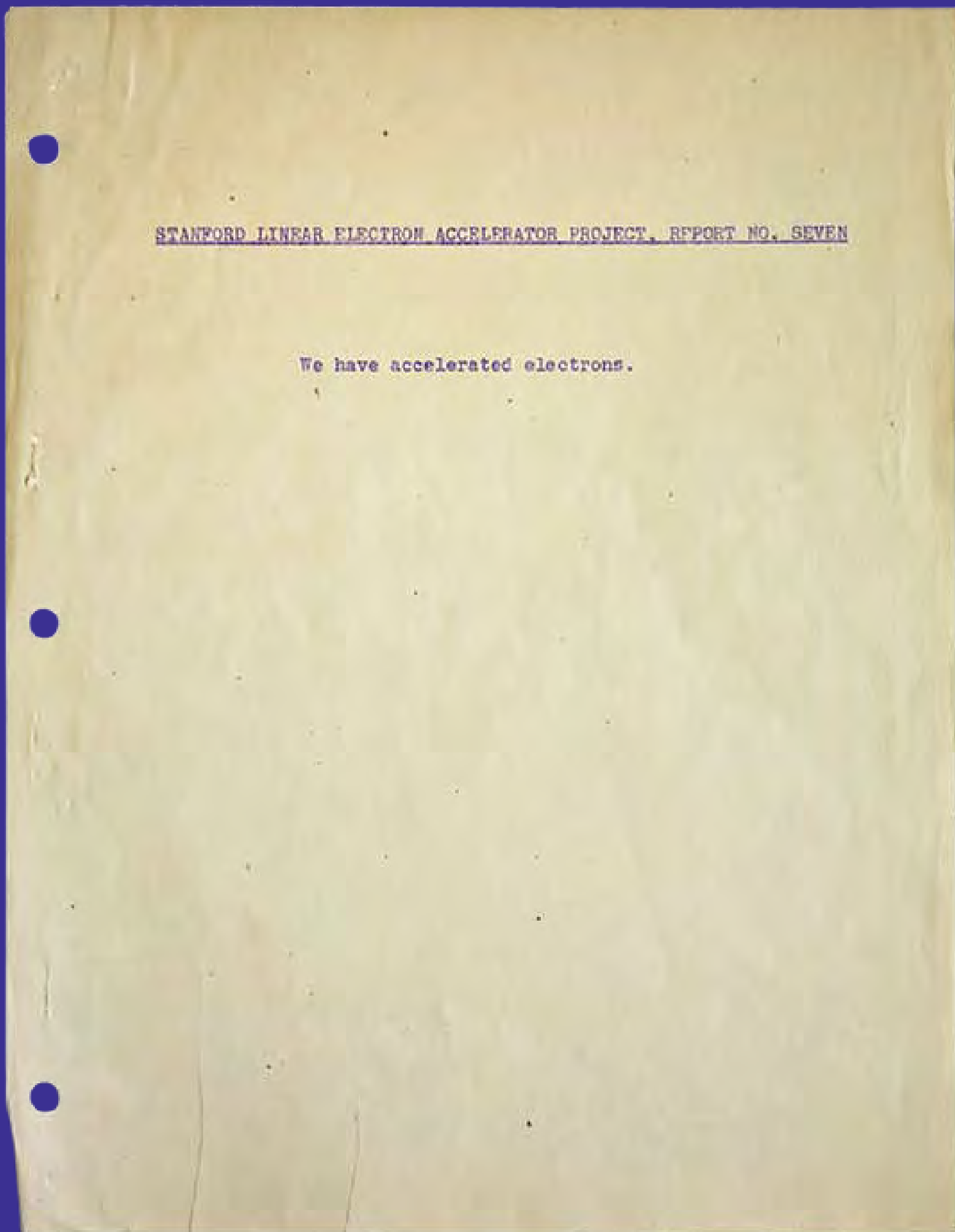
To test the effectiveness of the coating, companies try to stain the paper with all sorts of glop, such as coffee, wine, lipstick, nail polish remover, and mustard. "Mustard's pretty nasty stuff," Maguire says.

But if particle accelerators can take on the search for the origins of the universe, surely they are up the challenge of a little spill.

Kathryn Grim

Photo: Reidar Hahn, Fermilab

logbook: the shortest report


STANFORD LINEAR ELECTRON ACCELERATOR PROJECT, REPORT NO. SEVEN

We have accelerated electrons.

Document courtesy of William Webster Hansen Papers, SC 126, Stanford University

On April 28, 1947, Stanford Linear Electron Accelerator Project Report No. 7 announced the realization of a dream 15 years in the making: the linear acceleration of electrons.

William W. Hansen first imagined accelerating electrons using microwave power while teaching at Stanford University in the mid-1930s. In 1937, he played a key role in inventing the klystron tube, which generates microwave power for accelerating particles in a linear series of metal cavities.

Hansen and his team dedicated seven years of research during World War II to the Allied war effort, propelling the advancement of Doppler radar. Finally, just 18 months after Hansen returned to lead a new microwave lab at Stanford, zoom! Electrons streamed through his foot-long linear accelerator, reaching energies of six million electronvolts. Four words proclaimed this achievement to the project sponsors at the Office of Naval Research. Although a British team beat Hansen's group by a few months, the Stanford design was the one that stuck, eventually becoming the model for the two-mile-long linac at what is now SLAC National Accelerator Laboratory.

Lauren Knoche

symmetry
A joint Fermilab/SLAC publication
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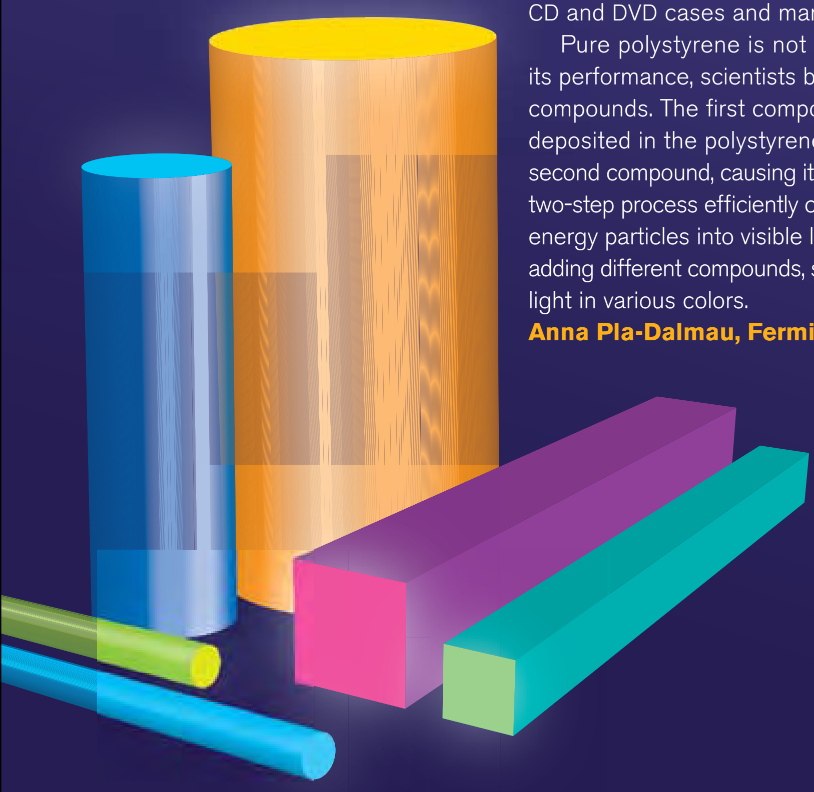
symmetry

U.S. DEPARTMENT OF ENERGY

explain it in 60



Scintillators are transparent materials that allow scientists to detect particles and other forms of radiation. When radiation hits a scintillator, the material absorbs some of its energy and makes it visible by emitting a flash of light. Even the tiniest amount of scintillation can trigger a signal in one of the state-of-the-art photodetectors that are attached to the edges of the scintillator.

Scintillation detectors have a wide array of applications, such as medical imaging, baggage scanning, oil exploration, monitoring of nuclear power stations, and—of course—particle physics.

Many types of transparent materials serve as scintillators, including plastics, liquids, crystals, and gases. One common, inexpensive material used in plastic scintillators is polystyrene, the plastic used in CD and DVD cases and many other consumer products.

Pure polystyrene is not an efficient scintillator. To improve its performance, scientists blend polystyrene with two fluorescent compounds. The first compound absorbs the radiation energy deposited in the polystyrene. It passes that energy along to the second compound, causing it to emit visible flashes of light. The two-step process efficiently converts radiation from X-rays and high-energy particles into visible light that can be easily detected. By adding different compounds, scientists can make the scintillators emit light in various colors.

Anna Pla-Dalmau, Fermilab