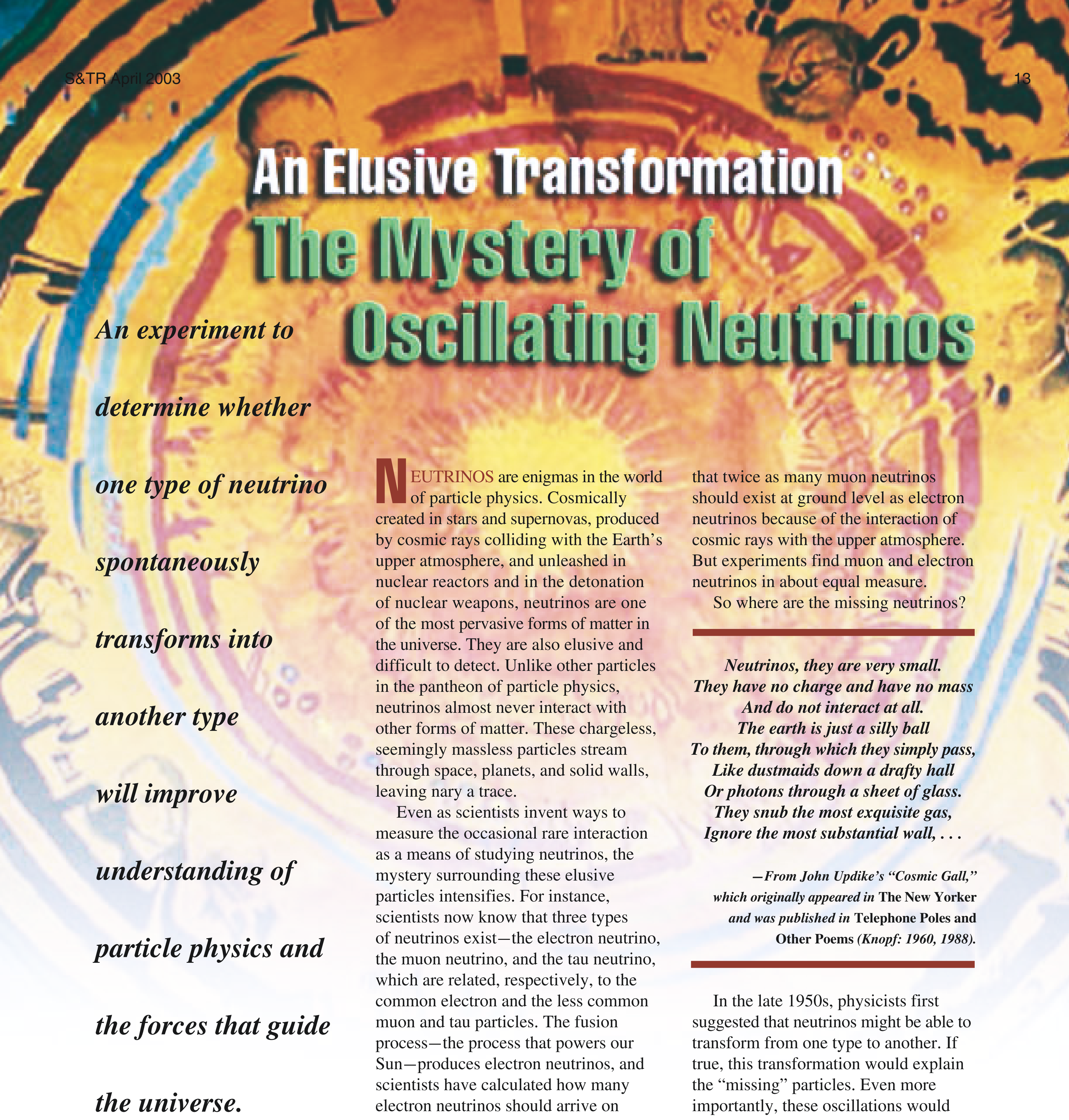


An Elusive Transformation

The Mystery of Oscillating Neutrinos

An experiment to determine whether one type of neutrino spontaneously transforms into another type will improve understanding of particle physics and the forces that guide the universe.

NEUTRINOS are enigmas in the world of particle physics. Cosmically created in stars and supernovas, produced by cosmic rays colliding with the Earth's upper atmosphere, and unleashed in nuclear reactors and in the detonation of nuclear weapons, neutrinos are one of the most pervasive forms of matter in the universe. They are also elusive and difficult to detect. Unlike other particles in the pantheon of particle physics, neutrinos almost never interact with other forms of matter. These chargeless, seemingly massless particles stream through space, planets, and solid walls, leaving nary a trace.

Even as scientists invent ways to measure the occasional rare interaction as a means of studying neutrinos, the mystery surrounding these elusive particles intensifies. For instance, scientists now know that three types of neutrinos exist—the electron neutrino, the muon neutrino, and the tau neutrino, which are related, respectively, to the common electron and the less common muon and tau particles. The fusion process—the process that powers our Sun—produces electron neutrinos, and scientists have calculated how many electron neutrinos should arrive on Earth. But more than two decades of experiments have found less than half the predicted number. The same conundrum appears with the neutrinos produced by cosmic rays. Theory says that twice as many muon neutrinos should exist at ground level as electron neutrinos because of the interaction of cosmic rays with the upper atmosphere. But experiments find muon and electron neutrinos in about equal measure.

So where are the missing neutrinos?

Neutrinos, they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall, . . .

—From John Updike's "Cosmic Gall," which originally appeared in* The New Yorker *and was published in* Telephone Poles and Other Poems *(Knopf: 1960, 1988).

In the late 1950s, physicists first suggested that neutrinos might be able to transform from one type to another. If true, this transformation would explain the "missing" particles. Even more importantly, these oscillations would prove that neutrinos are not massless—as originally theorized in the 1930s by physicist Wolfgang Pauli and declaimed in 1960 by writer John Updike—but "weigh" something after all, albeit very little. (See the box below.) If the electron neutrino has a mass, it would be less than one-hundred-thousandth that of the electron.

If these subatomic particles do indeed have mass—and more and more evidence seems to point in that direction—that fact will have vast implications for understanding cosmology and for the prevailing physics theory that describes the elementary particles and forces of the universe.

Since measuring neutrino mass directly is beyond present-day technology, scientists must use indirect methods, such as determining whether neutrino oscillations occur. A team from Lawrence Livermore—including physicists Peter Barnes, Douglas Wright, and Edward Hartouni—are part of an international collaboration of 200 scientists from 26 institutions taking part in an experiment centered at the Fermi National Accelerator Laboratory (Fermilab) to look for neutrino oscillations and begin to understand their particulars. Results from the Main Injector Neutrino Oscillation Search (MINOS) will help illumine the nature of neutrinos and, ultimately, the universe.

MINOS to Shed Light on Mystery

The job of detecting neutrino oscillations is a daunting one. The neutrinos must travel far enough (that is, travel a long enough time at nearly light speed) for a significant portion of them to change into a different neutrino type. The beam of neutrinos must also be intense enough to produce measurable interactions at the detector, because the neutrino beam, like a flashlight beam, will fan out over distance, going from about 30 centimeters wide about 1 kilometer from the source to nearly 1 kilometer wide at a detector over 700 kilometers away. Finally, out of 5 trillion neutrinos a year passing through the detector, only about 9,000 will interact and produce a measurable signal.

The MINOS experiment will use a beam of neutrinos generated at Fermilab,

Pursuing Neutrinos

Neutrinos—those mysterious bits with almost no mass at all—are central to the continuing quest to understand the fundamental structure of matter and the nature of the universe. Researchers have been pursuing and wooing them for over 60 years. In 1930, physicist Wolfgang Pauli postulated a new particle to explain the physics dilemma involving certain radioactive decays in which a neutron transforms into a proton and electron and some energy and angular momentum seem to vanish. Pauli proposed that a particle, later dubbed the neutrino, would carry the missing energy and momentum. To fit the bill, the neutrino had to be a neutral, uncharged particle, have practically no mass, and have almost no interactions with matter. In other words, it would be almost impossible to observe.

More than 20 years later, physicists Frederick Reines and Clyde Cowan used the nuclear reactor at the Department of Energy's Savannah River Plant in South Carolina to find the first direct evidence of Pauli's elusive neutrino. Then in 1957, physicist Bruno Pontecorvo theorized that if different species of neutrinos existed, they might be able to "oscillate," or transform, into each other. In 1962, Brookhaven National Laboratory and Columbia University conducted the first accelerator neutrino experiment, demonstrating the existence of two species: the electron neutrino and the muon neutrino. Just as this mystery was laid to rest, another arose: Electron neutrinos were detected from the Sun for the first time—but in far fewer numbers than predicted by solar models. Other experiments found a deficit of muon neutrinos from the interactions of cosmic rays with atoms in the upper atmosphere. The question became: Where are the missing neutrinos?

If neutrinos have mass, then according to physics theory, they could oscillate, which could explain a great deal—including the missing neutrinos. It could also account for some fraction of dark matter, the 90 percent of the mass of the universe that cannot be seen.

Meanwhile, in 1975, an experiment at the Stanford Linear Accelerator Center provided strong evidence of a third species—the tau neutrino. In 1995, Los Alamos scientists reported results that hinted at the existence of neutrino oscillations, in which muon neutrinos seemed to be oscillating into electron neutrinos. In 1998, physicists from the Super-Kamiokande experiment in Japan presented new data on the deficit in muon neutrinos that should be produced in Earth's atmosphere by cosmic rays. Japanese scientists also found a difference in the type of neutrinos that arrived at their detector from directly overhead compared with those that had passed through an extra 13,000 kilometers of Earth's subsurface to enter the detector underneath. These differences suggested that the distance traveled was a factor in the makeup of neutrinos—an indication that neutrinos oscillate and, therefore, have mass.

In April 2002, the Sudbury Neutrino Observatory in Canada announced results conclusively showing that solar neutrinos (electron neutrinos) oscillate before reaching Earth, thus solving the problem of missing solar neutrinos raised nearly 25 years ago.

In December 2002, KamLAND, an underground neutrino detector in central Japan, produced results indicating that antineutrinos emanating from nearby nuclear reactors were "disappearing." Because antineutrinos are the antimatter counterpart to neutrinos, these results confirm earlier studies suggesting that neutrinos oscillate and have mass.

With MINOS, the Main Injector Neutrino Oscillation Search, the story continues to unfold.

40 miles west of Chicago, one of the few facilities able to generate a beam intense enough for the experiment. Fermilab is constructing a new particle beamline to direct a nearly pure beam of muon neutrinos at a detector deep in a former iron mine in Soudan, Minnesota, 735 kilometers away. “Fermilab will tune the beam to an energy spectrum of 0.5 to 8 gigaelectronvolts,” says Barnes, “which, according to calculations, is the energy range that allows the most neutrino oscillations for the distance the beam needs to travel to the ‘far’ detector.”

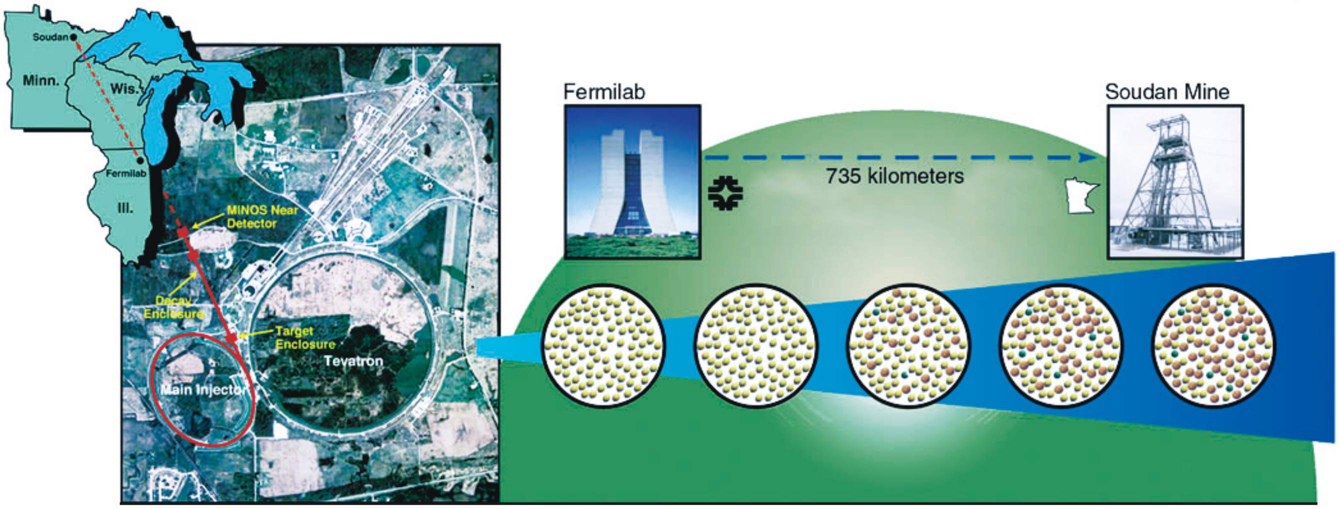
Before reaching Soudan, though, the neutrino beam will zoom through a smaller “near” detector a mere 1 kilometer from the beam source. This detector will measure how many muon neutrinos are at each energy. During the next 2 milliseconds, the beam will flash beneath northern Illinois and Wisconsin—2 milliseconds during which some of the muon neutrinos are expected to oscillate into tau neutrinos. The beam will then encounter the far detector, 800 meters deep in the Soudan mine. Some of the remaining muon neutrinos—about one in a million—will interact with the detector. “We won’t be able to identify the tau neutrinos,” explains Barnes, “but we will see a decrease in the number of muon neutrinos, and we’ll be able to measure how many remain at each energy. The decrease will tell us that some of the muon neutrinos in the beam have changed into another type. The oscillations will help confirm that neutrinos have mass.”

Physicists hope to uncover other details about the nature of neutrino oscillations as well. For instance, they hope to discover the oscillation probability of the beam—that is, the fraction of a beam that can change from one type to another at a given energy—by measuring the fraction of oscillations at each energy. In addition, they hope to determine the oscillation length, which is the distance a beam of neutrinos of a particular energy must travel to transform from one neutrino type to another and back again.

Down in the Mine

The experiment itself is impressive enough—but putting it all together presents another set of challenges no less daunting. A key issue is how to design the steel planes of the detectors. Each plane is 8 meters in diameter and weighs 10,000 kilograms, and 450 of them must be transported 800 meters underground. Plus the only access and egress underground is a mine shaft 2 meters across.

Several designs were put forth by different collaborators, including making the plate in one long, coiled strip—like an old-fashioned watch spring—that could be uncoiled and snaked downhole. Because much of the Laboratory’s research has coupled physics and engineering, Livermore’s Douglas Wright, a physicist with engineering training and experience, was selected to lead the steel design work for the MINOS collaboration. By 1995, Livermore engineers Marcus Libkind and Johanna Swan came up with the selected solution: make the planes from plates of steel—2 meters across, 8 meters long and 1.25 centimeters thick—that could be lowered down the mine shaft and assembled underground. This concept was fully developed at Livermore by engineer Tony Ladran (now with Lawrence Berkeley National Laboratory). The crucial feature of the design is that each plane is composed of



A beam of muon neutrinos will travel 735 kilometers in 2 milliseconds, from a linear accelerator in Chicago, Illinois, to a detector in Soudan, Minnesota. In that brief interim, some of the muon neutrinos will oscillate, or change, into tau neutrinos. This oscillating will be further proof that neutrinos have mass.

two layers of steel formed by strips laid at right angles. The two layers are joined by welds through precut holes in the steel. The technique results in a monolithic plane that is exceedingly flat and magnetically similar to a solid plane.

Even this solution presented challenges. The long, wide, thin plates were the steel equivalent of strips of paper. Unfortunately, unlike paper, which can bend but keep its structural integrity, steel doesn’t have as much yield strength, and excessive bending causes it to tear. Also, once assembled, the steel planes could not be simply mounted on the floor with all the weight on the bottom edge. In addition, the edges all around the detectors had to be kept free for optical and electrical cables to snake in and out.

But how can 450 such planes be supported so they don’t buckle under their own weight? The answer lies in a filing cabinet, says Barnes. “We decided to suspend them like hanging file folders, using two metal ears on each plane that rest on metal rails.” For each plane, 9,000 kilograms of steel plate and 900 kilograms of plastic scintillator strips are supported on two 5- by 10-centimeter areas, one under each ear, resting on 10-centimeter-wide rails.

By July 2003, the entire detector system will be assembled in the mine. Fermilab is using the same design on a smaller scale for the near detector, and the MINOS experiment is expected to be up and running in early 2005.

Bring on the Beam

Livermore is also a key participant in another MINOS-related effort to look at exactly what happens in creating the neutrino beam—or indeed, any beam of particles. The answers will have important ramifications for Livermore’s basic science and stockpile stewardship missions.

To produce neutrinos for MINOS, a 120-gigaelectronvolt proton beam will slam into a graphite target, producing pions and other particles as well. Because

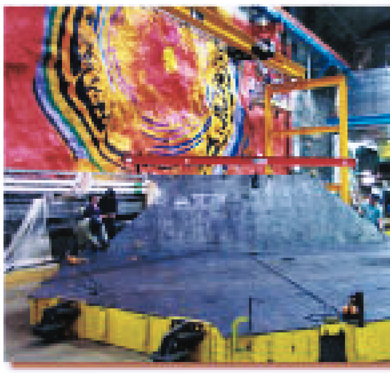
Head frame of the Soudan Mine shaft.

Steel plates 2 by 8 meters are lowered down the mine shaft.

Livermore engineers and physicists worked together to come up with a design that would allow sections of the 450 detector planes to be lowered into the mine and assembled underground. All equipment must be broken down to fit into the 2 meter by 2 meter shaft and then reassembled underground.

Scintillator modules are welded to the steel planes.

A dozen steel plates ready for assembly.



Two layers of steel plates (four plates per layer) are welded together on a detector frame.

pions—precursors to muon neutrinos—are charged particles, they can be focused with magnetic fields and directed into a vacuum pipe of sufficient length to give them time to decay into neutrinos. (See the box at the right.)

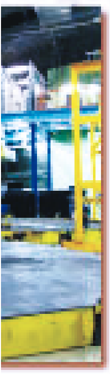
"The focusing properties of pions are well understood," says Barnes. "Propagation in the decay pipe is also well understood. What isn't well characterized is the nature of the stuff produced at the target by the proton beam. How many of what particles? And at what angles do they leave the target and at what energies? We need to characterize these details better. In addition, we know that the muon neutrino

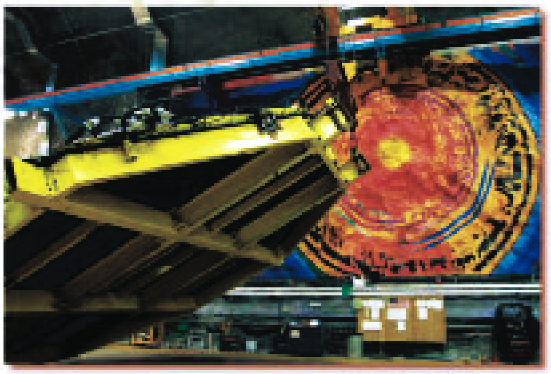
Recipe for a Neutrino Beam

1. Take a beam of 120-gigaelectronvolt protons.
2. Aim the beam on a graphite target, where the protons can interact with the carbon atoms.
3. Take the beam produced from this interaction (which will contain mostly pions and kaons), and use magnets to focus the positively charged particles.
4. Direct these positively charged particles down a decay pipe. The pions will decay into muons and muon neutrinos. The kaons will also decay into muons and muon neutrinos and sometimes into electrons and electron neutrinos as well.
5. Send the subsequent beam through 229 meters of rock and steel to remove unwanted particles and muons.

Result: A beam of muon neutrinos, with a few scattered electron neutrinos.

A CAUTION TO THE COOK: Neutrinos, being neutral, cannot be steered, so be sure your focusing system and decay pipe are pointing in the direction of the desired beam. For the Main Injector Neutrino Oscillation Search (MINOS) experiment, point the pipe 3 degrees down and north-northwest toward Minnesota.





Each assembled 8-meter-diameter detector plane is raised into place to join the array of 450 planes that comprise the MINOS detector.

The MINOS detector with 348 of its 450 detector planes in place.

beam produced in the decay pipe is not pure—it contains some electron neutrinos. We need to know more about these particles as well.”

Because the beam will be only 30 centimeters in diameter at the MINOS near detector, the entire beam will pass through it. But only a small fraction of the beam ends up aimed at the far detector, explains Barnes. “Since the beam spreads out to a diameter of 1 kilometer at the far detector, we won’t be measuring the whole beam. We need to know the angular distribution of the particles produced at the target and their energy spectrum. This information will help us understand the differences between the whole beam seen by the near detector and the subset seen by the far detector.”

The lack of information about the particle production of the proton beam is the largest systematic uncertainty in the MINOS system. Details of particle production also turn out to be important for other efforts where particle beams interact with targets, such as future accelerator concepts like muon colliders and Livermore’s stockpile stewardship work with proton radiography. (See the box below.)

To better understand the details of particle production, Livermore is leading the Main Injector Particle Production (MIPP) experiment in collaboration with Fermilab and a group of 10 universities, colleges, and institutes of technology. In preparing for MINOS, MIPP will examine what happens when 120-gigaelectronvolt protons hit graphite targets. Beams of protons, kaons, and pions at energies from 5 to 100 gigaelectronvolts will also be generated to examine particle production on target materials as diverse as hydrogen and lead. The experiment, which takes place at Fermilab, is just getting under way. MIPP begins this summer and will continue until MINOS comes on line.

Bringing in the Next Generation

In addition to providing results of interest to basic science and stockpile stewardship efforts, the MIPP and MINOS experiments are introducing postdoctoral fellows and others just entering the field of high-energy nuclear and particle physics to some of the work being done at Livermore. Barnes explains, “Most of the particle and high-energy nuclear physics experiments take a long time to plan and execute. One set of postdoctoral fellows works on the early part of the experiments—setting up the systems, doing early calculations, and so on—and then, years down the road when they’ve moved on, another set comes in

Proton Radiography

In addition to supplying information critical to the Main Injector Neutrino Oscillation Search (MINOS) experiment and other basic physics experiments, results from the Main Injector Particle Production (MIPP) experiment will contribute to Livermore’s stockpile stewardship efforts. For seven years, Livermore has been exploring whether beams of high-energy protons could be used to create three-dimensional images or movies, much the way that x rays are used to create medical computed tomography scans. (See *S&TR*, November 2000, pp. 12–18.)

Such proton radiographic systems could be used in stockpile stewardship to image deep inside dynamic systems and obtain information about materials too dense for x rays to penetrate. One of the roadblocks to using proton beams is the tendency for protons to scatter at small angles off other particles, leading to blurry images. In 1995, researchers at Los Alamos National Laboratory came up with the idea of using a magnetic lens to refocus the charged protons, much as an optical lens refocuses a blurry image.

Such focusing techniques can be effective but present another problem. Just as MINOS physicists need to understand the scattering processes in detail, so physicists need to understand the scattering processes of proton radiography in detail. The beam that reaches the film also contains other particles produced as the beam passes through the target material. “We need to better understand these other particles,” says physicist Peter Barnes. “Some of them reach the radiographic film and add their own signal. Not only do they blur the image, but their added signal also lightens the image, making the imaged materials appear to be less dense than they really are.”

Because sharpness and density of image are critical to interpreting what is happening inside these complex systems, stockpile stewards need to know what the secondary particles are and how they affect the final image. MIPP will provide a more complete picture of the particles produced, including their energy spectrum and angular distribution.

and gathers and interprets the data. But for MIPP, we started work a year ago and now we're almost ready to take data. It's a three-year project, from building the system, to taking data, to producing a paper. It has a much shorter cycle than most experiments, allowing someone in a postdoctoral position to be involved in the project from start to finish." Through MIPP, a new generation of researchers is introduced to the Laboratory.

"The work on neutrino oscillations and proton radiography is a good example of how the Laboratory integrates basic science research with its missions," says Barnes. "Ultimately, the answers gained about neutrino oscillations through MINOS will connect to the early history of the universe. With MIPP, we're supporting that search for answers as well as supporting the Laboratory's stockpile stewardship work. It's a perfect example of what high-energy physics at the Laboratory can achieve."

—Ann Parker

Livermore's Main Injector Particle Production team in its laboratory with the test stand and computers. Team members are (from left) David Lange, Peter Barnes, Ron Soltz, Ed Hartouni, Doug Wright, Michael Heffner, Steve Johnson, and David Asner.

Key Words: Fermi National Accelerator Laboratory (Fermilab), high-energy physics, Main Injector Neutrino Oscillation Search (MINOS), Main Injector Particle Production (MIPP), neutrino oscillation, particle physics, proton radiography.

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For more information on the MINOS experiment, see:

www-numi.fnal.gov/index.html