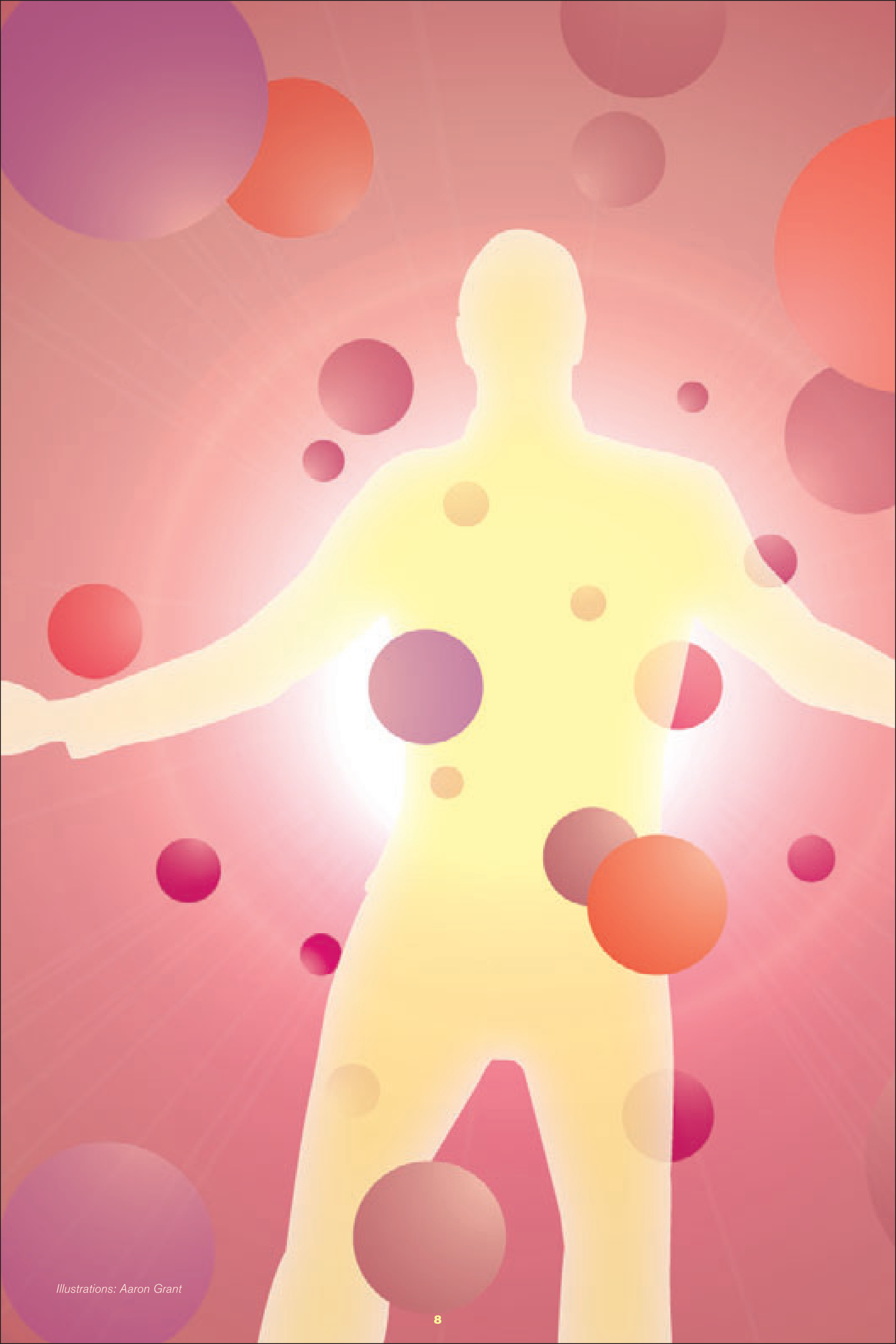


Illustrations: Aaron Grant

The Elusive Neutrino

by Kurt Riesselmann

Not only are neutrinos hard to catch, but they also change form as they travel through space. New experiments hope to understand their chameleonic nature.

Life on Earth depends on light and heat provided by the sun. But the next time you are sitting outside, catching some rays, take a moment to think of some of the invisible particles emitted by the sun: neutrinos. As you read this sentence, hundred trillions of neutrinos pass through your body, doing no harm and leaving no trace.

Neutrinos are capable of traversing the entire Earth in the blink of an eye. At close to the speed of light, these particles travel straight through rock and space, and nothing stops them. Well, almost nothing. Once in a blue moon, a neutrino will come across a nucleus and they will interact.

"Neutrinos are always referred to as ghostly particles, as if they are of little interest and have to be apologized for. Nothing could be further from the truth," says Michael Turner, the National Science Foundation's Assistant Director for Mathematical and Physical Sciences. "Neutrinos account for as much of the mass of the universe as do stars, and they may well explain the origin of the neutrons, protons and electrons that are the building blocks of all the atoms in the universe."

In 1930, theorist Wolfgang Pauli introduced the neutrino as a theoretical "remedy" to account for an energy imbalance in nuclear reactions. He worried that scientists might never be able to detect this seemingly invisible particle. But a quarter century later, a Nobel Prize-winning experiment observed the first signs of neutrinos, recording their occasional collisions with matter. Later experiments revealed that nature provides for at least three different types of neutrinos.

Scientists think that the abundance of neutrinos—they outnumber all other known matter particles by far—may have played a key role in the shaping of the early universe. For decades, most physicists assumed the particles to be massless as experimenters found no hint for neutrino mass. In the 1990s, new and improved measurements provided the first evidence for neutrinos to have mass, putting a huge crack into the theorists' Standard Model of particles and interactions.

Neutrino scientists must be patient. Observing neutrino interactions requires large detectors weighing thousands of tons, preferably built deep underground to shield them from other cosmic particles bombarding the Earth. Building these detectors takes years and they can cost one hundred million dollars each. When operational, the experiments need to run for a long time: a lot of neutrinos must cross a particle detector to produce a single "neutrino event," either its deflection off a nucleus or its destructive collision. The latter produces a detectable tell-tale signal in form of an electron or one of its heavier relatives, the muon and the tau.

Nobel Prize winner Ray Davis and his team needed 30 years to "catch" 2000 solar electron neutrinos in a mine in South Dakota. His count was much lower than predicted by theoretical calculations. While some scientists began to question the validity of the Standard Solar Model, other scientists began to wonder whether electron neutrinos could "disappear" by transforming into other particles, avoiding their detection in Davis' experiment. The disappearance of neutrinos seems to be tied to a rather mind-boggling behavior of these elusive particles: neutrino oscillations. As neutrinos travel through matter and space, they transform from one type into another, either appearing as electron neutrinos, muon neutrinos, or tau neutrinos.

When a car becomes a van

Completely unknown in the macroscopic world, neutrino oscillations are a quantum effect. They are equivalent to a sports car changing into a minivan or a bus, and then, many miles farther down the road, reappearing as a sports car. If initially there were only sports cars on a highway, the road would soon be populated with a mixture of all three types of vehicles.

Only neutrinos with non-zero mass can perform this trick, and measuring the details of the oscillation process allows scientists to determine the mass difference among the three neutrino species. (Measuring the absolute mass requires different, more challenging experiments.) Over the last ten years, a number of experiments have looked for neutrino oscillations studying either neutrinos created in the sun, the Earth's atmosphere, nuclear reactors, and—more recently—particle accelerators. In each case, scientists know the particular types of neutrinos that the source (sun, atmosphere, reactor, or accelerator) produces, and they examine the types of neutrinos they find away from the source.

The probability with which neutrinos transform into each other depends on the energy of the initial particles ("horsepower of the sports cars"), the differences in mass among the three neutrino types ("weight of the vehicles"), the mixing angles that are characteristic for transitions between two neutrino types ("a number assigned to each pair of vehicle types"), and the distance the initial neutrinos have traveled from their point of creation ("miles driven on the highway").

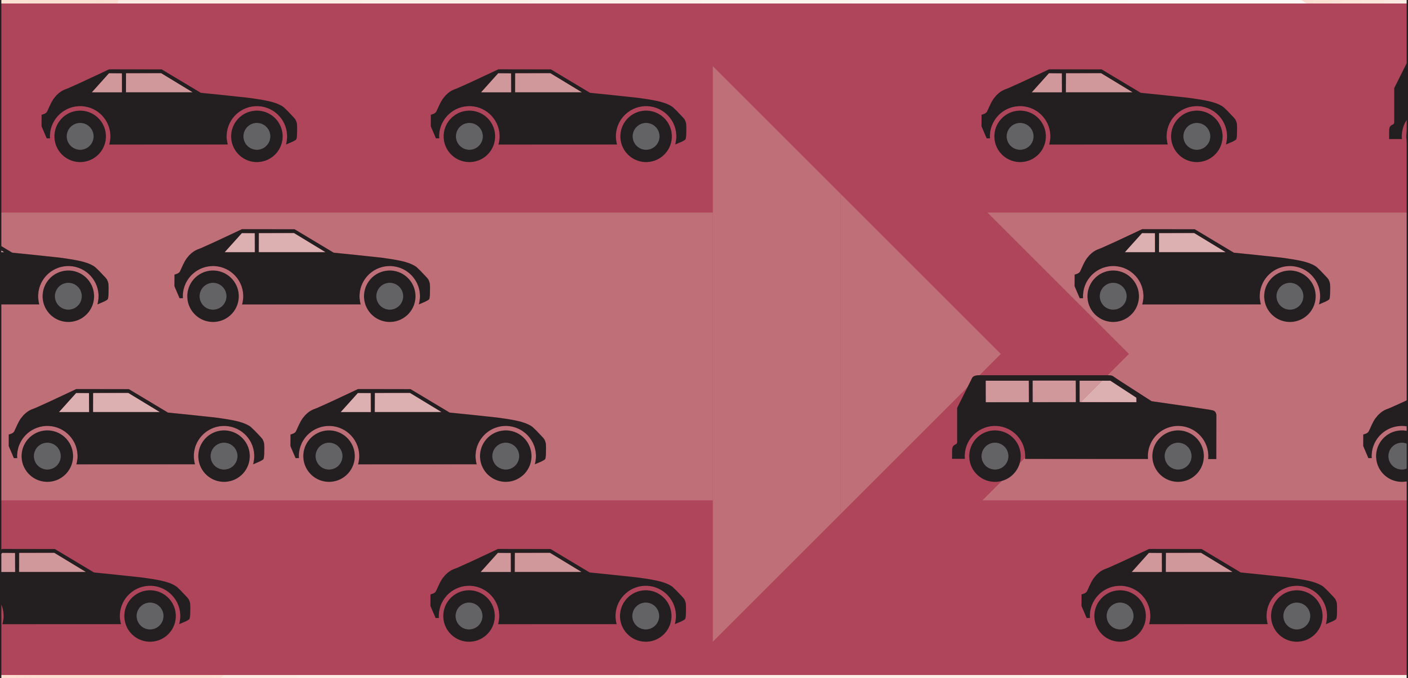
Ups and downs

The idea of neutrino transformation gained significant support in 1998, when the Super-Kamiokande collaboration improved on earlier experiments and announced that some muon neutrinos produced in the Earth's atmosphere also "disappeared" before traversing the Super-Kamiokande detector, 2000 feet underground in an old zinc mine in Japan. In particular, a deficit was observed for atmospheric neutrinos originating on the opposite side of the Earth, traveling the largest distance.

Today, scientists agree that a neutrino can indeed transform into a different one, and faith in the Standard Solar Model has been restored. But do neutrinos really oscillate? Or is the transformation a one-way street? The ultimate answer requires the reconstruction of the full oscillation curve—including the reappearance part—not just the observation of neutrino disappearance.

In the last four years, the Sudbury Neutrino Observatory (Canada), the KamLAND experiment (Japan), and the CHOOZ experiment (France) have yielded good information on the transformation of electron neutrinos. The experimental data fit the oscillation predictions, but Fermilab theorist Boris Kayser notes that the final clincher is still missing.

"We haven't seen a lot of wiggling yet," says Kayser, referring to the ups and downs of



a typical oscillation curve. "Ideally, you want the experimental observations to determine the shape of each curve. That is not yet the case. There is a pretty strong suggestion of a wiggle in KamLAND's observation of electron neutrinos from reactors, but it's not definitive yet. Super-Kamiokande measures atmospheric [muon] neutrinos, and it sees only a hint of an oscillatory dip."

A new type of experiment

Scientists have now set out to conduct a new generation of neutrino experiments, studying the elusive particle under laboratory-controlled conditions. The new experiments probe high-intensity neutrino beams produced by particle accelerators with a finely tuned energy range. The beams travel hundreds of miles through the Earth—no tunnels needed—to large underground detectors that measure changes in the composition of the neutrino beam. These long-baseline experiments will either reveal the missing pieces of the sought-after oscillation curves, or they will provide evidence for the true mechanism responsible for the neutrinos' Jekyll and Hyde syndrome.

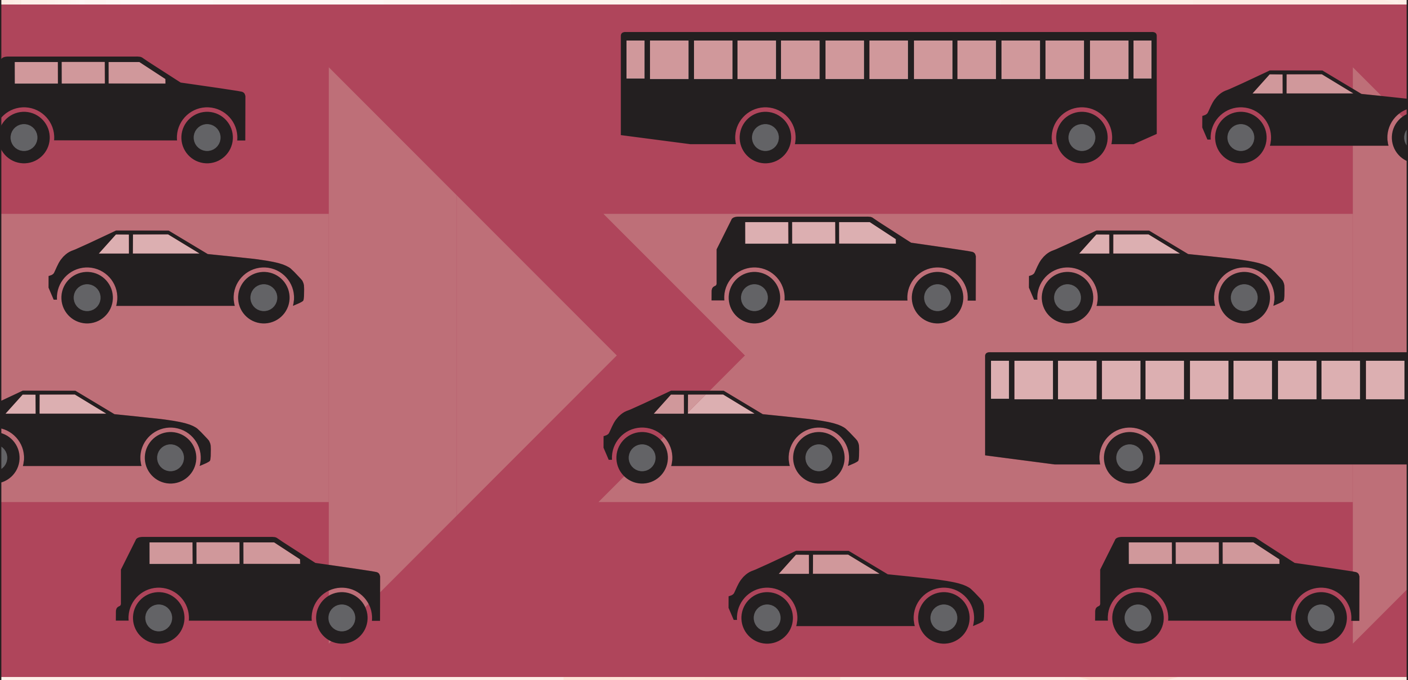
In November 2004, the 130 scientists of the K2K collaboration, including members from seven US institutions, finished the first long-baseline experiment with a muon neutrino beam. The project began in the mid-1990s when researchers adapted an accelerator already operating at the Japanese laboratory KEK to send a neutrino beam 156 miles through rock to the existing Super-Kamiokande neutrino detector. In four and a half years, the K2K experiment recorded 107 neutrino events, 44 fewer than expected in the absence of neutrino transformation. The experiment confirmed the neutrino deficit observed for atmospheric neutrinos. But the initial hopes of measuring the oscillation curve were dashed.

"Super-Kamiokande's atmospheric neutrino result in 1998 had a big impact on the K2K goal," says KEK scientist Kenzo Nakamura, a member of the K2K Executive Committee. "When we designed the K2K experiment and started construction of the neutrino beamline and near detector, we knew the old Kamiokande's atmospheric neutrino result. If this [had remained unchanged], K2K could have confirmed muon neutrino oscillation with more than five sigma significance," a statistically compelling level of certainty.

Instead, the 1998 results shifted one of the crucial parameters in the muon neutrino oscillation function, the neutrino mass difference, and the K2K experiment lost most of its sensitivity to oscillations. "Unfortunately, with a given proton accelerator and a given far neutrino detector, we had no means to recover the sensitivity," says Nakamura.

The most powerful beam

In early 2005, Fermilab celebrated the start-up of its long-baseline experiment (see page 13). The Main Injector Neutrino Oscillation Search (MINOS) uses a high-intensity muon neutrino beam traveling 450 miles through the Earth to a detector in an old iron mine in Soudan, Minnesota. Every two seconds, Fermilab's Main Injector accelerator slams a pulse of high-energy protons into a graphite target, producing the world's most intense neutrino beam. About two thousandths of a second later, the neutrinos cross the 6000 tons of steel and scintillating



plastic of the MINOS detector, half a mile underground. Every day, the steel stops on average three neutrinos, each one creating a muon easily recorded by the detector.

Like the K2K experiment, MINOS will observe the disappearance of muon neutrinos. But the longer distance and the higher neutrino beam energy should allow MINOS scientists to map a significant stretch of the oscillation curve, too. The neutrinos crossing the MINOS detector have an energy spread from less than 1 GeV to about 30 GeV (gigaelectronvolts). Mapping the entire range should reveal the dip in the curve as theoretical predictions indicate the disappearance to be greatest at 2 GeV.

"For the first time, physicists will explore a wide band of neutrino energies," says MINOS co-spokesperson Stan Wojcicki of Stanford University. "We will trace out the oscillation curve."

Where do they go?

But some scientists believe the MINOS experiment will not provide all the answers. Yves Desclais is the spokesperson of the OPERA experiment (Oscillation Project with Emulsion-tRacking Apparatus), currently under construction at the Gran Sasso underground laboratory in Italy. For him, the measurement of muon neutrino disappearance and reappearance is only half the equation. He and his 150 colleagues of the OPERA collaboration would like to observe the particle that the muon neutrinos presumably oscillate into: the tau neutrino.

The OPERA experiment will utilize a high-intensity neutrino beam traveling 450 miles straight through the Earth from the European particle accelerator laboratory CERN, in Switzerland, to the Gran Sasso cavern. The energy of the neutrinos leaving CERN will be higher than the neutrinos leaving Fermilab, reflecting two different experimental strategies.

"To observe tau neutrino appearance, you need to run at higher energy, above the tau production threshold," explains Desclais. "But then you are not in a good position to do a disappearance experiment. The two types of experiments cannot be done at the same beam."

OPERA scientists expect to install half the detector by June 2006, coinciding with the launch of the first high-intensity neutrino pulses from CERN to Gran Sasso. The second half of the detector will be finished by the end of 2006. Capturing a few tau neutrinos per year—a challenging task—will be enough to settle an important question.

"We want to check that the [anticipated] MINOS results are not related to neutrino decay to sterile neutrinos," says Desclais.

According to the Standard Model, there are three types of neutrinos with very similar properties. The French CHOOZ experiment has ruled out any significant transformation of muon neutrinos into electron neutrinos. Hence muon neutrinos can only morph into tau neutrinos—if the Standard Model is correct.

But history has taught physicists that the obvious answer is not always the correct one. In the case of neutrinos, there is even corroborating evidence. In the 1990s, the LSND experiment at the Los Alamos National Laboratory made observations that—in connection with results from other experiments—indirectly suggest the existence of a fourth type of neutrino, dubbed the sterile neutrino because it must be even less reactive then the three "ordinary" neutrinos. Results from the ongoing MiniBooNE neutrino experiment at Fermilab may confirm or refute the LSND results before the end of the year.

The quest continues

Questions about neutrino oscillations and a fourth neutrino are only some of many neutrino puzzles yet to be solved. Exactly how heavy is a single neutrino? What do neutrinos tell us about the origin of mass? Are neutrinos connected to extra dimensions? Do neutrinos violate the matter-antimatter symmetry or other fundamental symmetries of the universe? Are neutrinos their own antiparticles, unlike any other matter particle?

With its new muon neutrino beam line, Fermilab is in an excellent position to confront these questions. Japan has begun the construction of a new 184-mile high-intensity neutrino beam line, which will be operational in 2009, and US laboratories are contemplating a similar project. Ultimately, physicists hope to build a neutrino factory based on muons circling in a ring-shaped accelerator. Turning this dream project into reality will require years of research and development to overcome the technological challenges—nothing new for neutrino physicists, who have seen the need for patience when unraveling the mysteries of the universe is their goal.

"Ideas like transformations from one neutrino kind to another, proposed some 50 years ago, seemed then a far-out and unlikely concept to most physicists. But today this phenomenon appears to be a reality," says Wojcicki. "There are a number of other far-out ideas being proposed today about neutrinos. Will any of them turn out to be reality?"

Official Startup of **MINOS**

Tapping a key on a laptop, House Speaker Dennis Hastert (left) unveils the beam signal, with Fermilab Director Michael Witherell, Rep. James Oberstar, and DOE Office of Science Director Raymond Orbach looking on.
Photo: Reidar Hahn, Fermilab

At a dedication ceremony on March 4, 2005, Speaker of the US House of Representatives Dennis Hastert officially started the MINOS neutrino experiment at Fermilab. Tapping on a computer keyboard, he launched the graphic displaying the live signal of Fermilab's new neutrino beam line on a large screen.

"Now we have a date with the future and destiny," said Hastert shortly before launching the experiment. "This bold, innovative project will keep Fermilab on the cutting edge of physics research for years to come. It highlights the importance of the work done day in and day out at national laboratories such as Fermilab. These projects keep our nation at the forefront of scientific discovery."

Every two seconds, Fermilab now sends a pulse of neutrinos from Batavia, Illinois, to the MINOS detector in Soudan, Minnesota, 450 miles straight through rock. Located half a mile deep in the Soudan Underground Laboratory, the detector will record a sample of the beam, unveiling changes in its composition.

"In time, the MINOS project will be viewed as a landmark event in the history of physics. This world-class research is a bold, visionary initiative, which will have profound implications for our understanding of the structure and evolution of the universe," said Congressman James Oberstar, Minnesota. "The billion-year-old rock formations in the Soudan Underground mine have provided some of the world's richest iron ore. Now the mine may help unlock mysteries about the origins of the universe."

The MINOS collaboration includes over 200 scientists from six countries: Brazil, France, Greece, Russia, the United Kingdom and the United States. The US Department of Energy provides the major share of the $180 million funding of the NuMI/MINOS project, with additional funding from the US National Science Foundation, the UK's Particle Physics and Astronomy Research Council, the State of Minnesota, and the University of Minnesota.

"I would like to offer congratulations on the successful start for this new experiment and the beginning of an exciting new age of physics discoveries for Fermilab," said Raymond Orbach, director of the DOE Office of Science, at the dedication ceremony. "Neutrinos are fascinating particles. What Fermilab is doing today is the first step in long-baseline studies that will open up untold excitement as we learn more about the properties of these mysterious particles. This lab and those of you who work here have a very bright future."

MINOS co-spokesperson Doug Michael, Caltech, added a unique and emotional perspective to the ceremony. His schedule of chemotherapy treatment for recently-diagnosed multiple non-Hodgkin's lymphoma required him to stay in California, hence MINOS colleague Stan Wojcicki, Stanford University, read some remarks on his behalf.

In his letter, Michael thanked the American people for funding basic research, pointing out that "basic scientific research proves to be a wise investment for the future through creation and development of new technologies to which it invariably leads…In my recent diagnosis and treatment, I have frequently found myself marveling at the technology that is available for 21st-century medical care. It is very gratifying to me to know that many of the basic ideas and techniques for modern imaging equipment were either first developed in our own field of high-energy physics or by people trained in our field. I have gotten a first-hand view of the remarkable achievements in the engineering, technology, chemistry, and medicine which enable us to effectively treat diseases like the one that I have."