Searching for Neutrino Oscillations

by MAURY GOODMAN

Experiments of the past forty years have revealed three families of the ghostly particles called neutrinos. Continuing studies hint that a neutrino of one family might sometimes change into a neutrino of a different family, by a mechanism known as neutrino oscillation. The author describes why understanding this phenomenon might be critical to the question of whether neutrinos have mass.

PHYSICISTS FROM AROUND the world are engaged in a wide variety of experiments to determine whether neutrinos have mass. This possibility has intrigued physicists and cosmologists for two decades, ever since neutrinos emerged as a leading candidate for the dark matter thought to inhabit the Universe. A comprehensive new experiment is being built in Illinois and Minnesota to study neutrinos from an intense new Fermilab beam impinging on a detector 500 miles away. It is one of the most ambitious of a new round of experiments being planned and proposed to search for neutrino oscillations, a process in which neutrinos can transform from one kind into another—if they have mass. A positive result could have implications for the density of the Universe, as well as for the generation of energy by the Sun.

Often, given a well-defined physics problem, one or two well-designed experiments can answer the question one way or the other. But this is not the case for neutrino mass, because there are three different kinds of neutrinos and a wide range of possible mass scales. This situation has led physicists to attempt a large number of experiments that are quite different from each other.

In this article, I relate why so many physicists are excited by neutrino-oscillation experiments. First, I describe the properties of neutrinos themselves. Then I cover some of the experimental hints supporting neutrino oscillations. Finally, I close with a description of the Fermilab-to-Soudan, Minnesota, long-baseline neutrino project, an ambitious program to search for changes in the properties of a neutrino beam as it speeds silently beneath the farms and prairies of the American Midwest.

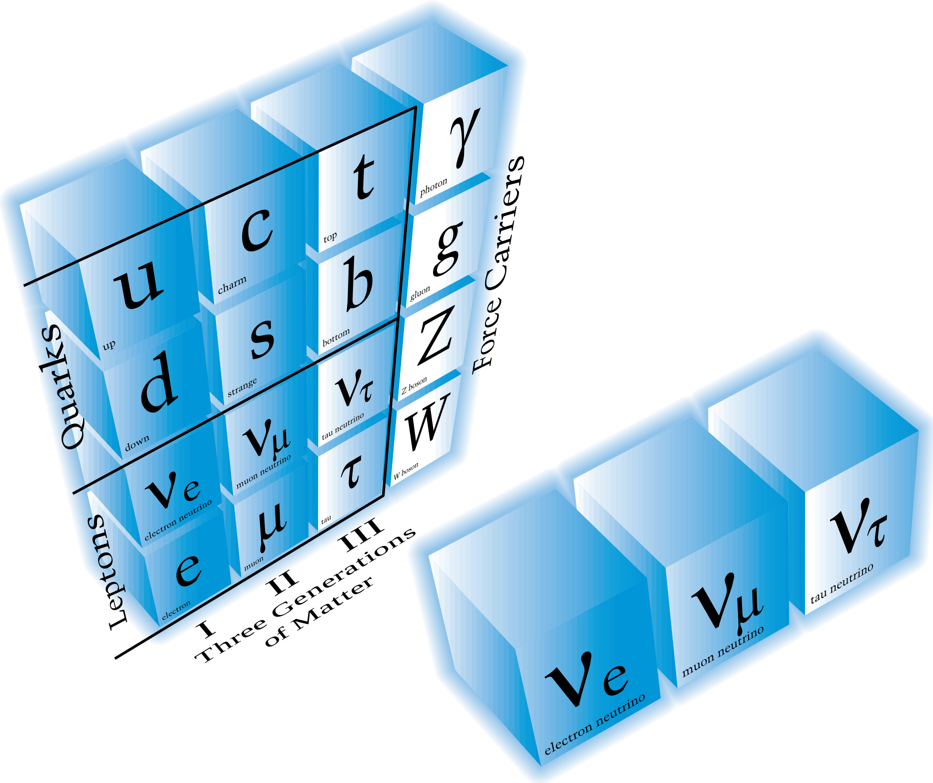
Melvin Schwartz in front of the Brookhaven detector that showed experimenters in 1962 that the muon had its own neutrino, different from the electron neutrino. Schwartz, Leon Lederman, and Jack Steinberger won the Nobel Prize in 1987 for this discovery. (Courtesy Brookhaven National Laboratory)

THERE ARE THREE "flavors" of neutrinos, the electron neutrino ν_e, the muon neutrino ν_μ, and the tau neutrino ν_τ. Each is closely related to the corresponding lepton: the electron, muon, and tau lepton. These six leptons together with six quarks constitute the fundamental "matter" particles of the Standard Model of high energy physics.

The three neutrinos interact very weakly with ordinary matter. Physicists originally thought that the great weakness of the interaction would make them impossible to detect, but neutrinos have been seen coming from accelerators, from nuclear reactors, from cosmic-ray interactions in the atmosphere, from the sun, and from Supernova 1987A. (Nuclear weapon explosions are also the source of copious neutrinos, but I am not aware of any experiment that has detected them.) Neutrinos are either massless or far lighter than the quarks and other leptons. This difference might be related to the fact that neutrinos have no electric charge, while the quarks and other leptons do have charge. The question of mass remains one of the big mysteries remaining in particle physics. There is no clear prediction relating the masses of the nine charged fermions, and none for whether the neutrino masses are zero or just very small.

However, most physicists expect that if neutrinos do have mass, even a tiny amount, the phenomenon of neutrino oscillations should exist (see the box on the opposite page). These transformations are closely related to the quantum-mechanical phenomenon of mixing. If neutrinos oscillate, they can be produced in one flavor, such as ν_μ, and be detected as another flavor, such as ν_τ, some distance away.

When Pauli predicted the existence of the neutrino in 1930, he did not suppose there would be more than one kind. He was only trying to explain the wide distribution of electron energies observed in nuclear beta decay. The idea that neutrinos come in different flavors became accepted in 1962, when an experiment at Brookhaven National Laboratory directed neutrinos from pion decay at a target and found that almost all of the events had a muon, and not an electron, emerging from the point of the neutrino interaction. This result led to the idea that each lepton flavor (e, μ, τ) has a conserved quantity—something that doesn't change in an



interaction—associated with it. When the pion decays, it almost always becomes a muon and a neutrino and hardly ever an electron and a neutrino. The Brookhaven National Laboratory result could be explained if the π^+ decays into a μ^+ and a ν_μ; when they interact with the target nuclei, the ν_μ's generate muons, not electrons.

When the third lepton, the tau, was discovered at the Stanford Linear Accelerator Center in 1975, it was natural to conjure up a third neutrino, the ν_τ, to account for missing energy in tau decays. In the 1980s physicists discovered and began producing copious numbers of Z bosons; this particle served as a neutrino counter because its decay rate is proportional to the number of fundamental particles with less than half its mass. Measurements of this rate at CERN and SLAC confirmed that there are only three neutrino-like particles in the elementary particle zoo—a result that had been predicted by cosmologists. So far, there has not been any convincing evidence that the ν_τ interacts with nuclei to make taus in a manner equivalent to the other two neutrinos. But a current Fermilab experiment is expected to find these ν_τ interactions.

The two factors affecting neutrino oscillations (see adjacent box) that are under the control of the experimenter are the neutrino energy E_ν and the distance L between their source and the detector. These appear in the ratio L/E_ν, so an experiment designer needs a large distance and low energies in order to measure small values of the mass difference between two neutrino types. This requirement must be balanced against the fact that large distance and low energy both make it more difficult to detect a large number of neutrino events.

Let's go back to the Brookhaven experiment that discovered the muon neutrino. If the mixing strength and mass difference had both been large enough, that experiment would not have been able to discover the ν_μ. It would have seen both electrons and muons coming from the point of the neutrino interactions! We can use the success of that experiment to place limits on the combination of the two parameters. We usually do this by making a graph in the parameter space called the "$\Delta m^2 - \sin^2(2\theta)$ plane," these being two parameters that specify the mixing strength and mass difference (see the box on the next page). An

Probability of Neutrino Oscillations

IN ORDER TO MEASURE neutrino oscillations, the experimenter wants the probability that one neutrino transforms into another to be as large as possible. This probability is given by

$$P_{\nu_1\to\nu_2} = \sin^2(2\theta_{12})\sin^2(1.27\Delta m^2_{12}L/E_\nu),$$

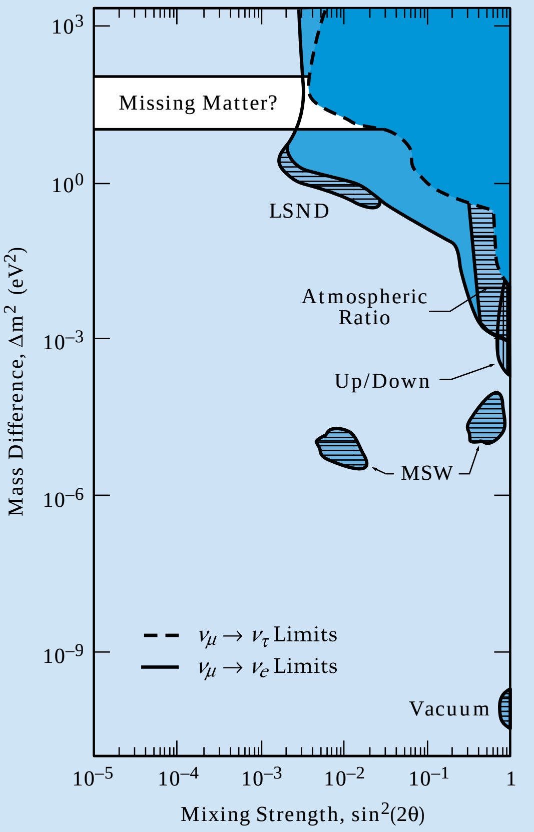
where $\sin^2(2\theta_{12})$ is the mixing angle, $\Delta m^2_{12} = m^2_1 - m^2_2$ is the difference in mass squares of the two neutrinos, L is the distance (in km) from the neutrino production point to the experiment, and E_ν is the neutrino energy in GeV. If either $\sin^2(2\theta) = 0$ or $\Delta m^2 = 0$, the phenomenon of neutrino oscillations does not exist. If all three neutrinos are massless, $\Delta m^2 = 0$.

As a result of the above equation, the neutrino "oscillates" with a strength $\sin^2(2\theta)$ and an "oscillation length"

$$L_{\text{osc}} = \frac{\pi E_\nu}{1.27\Delta m^2}$$

The oscillation probability varies as $\sin^2(\pi L/L_{\text{osc}})$. It is the sinusoidal nature which gives the name to "neutrino oscillations."

Relevant Neutrino Parameter Space



This graph shows the regions of neutrino mass (Δm^2) and mixing strength [$\sin^2(2\theta)$] which are suggested and ruled out by present data. The shaded regions are ruled out above and to the right of the curves labeled $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$. The hatched areas are suggested regions of parameter space from the LSND, atmospheric, and solar neutrino experiments. The band labeled "Missing Matter" is where one might expect to find neutrino oscillations if neutrinos contribute significantly to the Dark Matter problem. New long-baseline experiments will explore the region of parameter space suggested by the atmospheric ratio and up/down results.

experiment that is consistent with small or no neutrino oscillations corresponds to a curve in that plane that excludes the values of mixing strength and mass difference above and to the right of the curve.

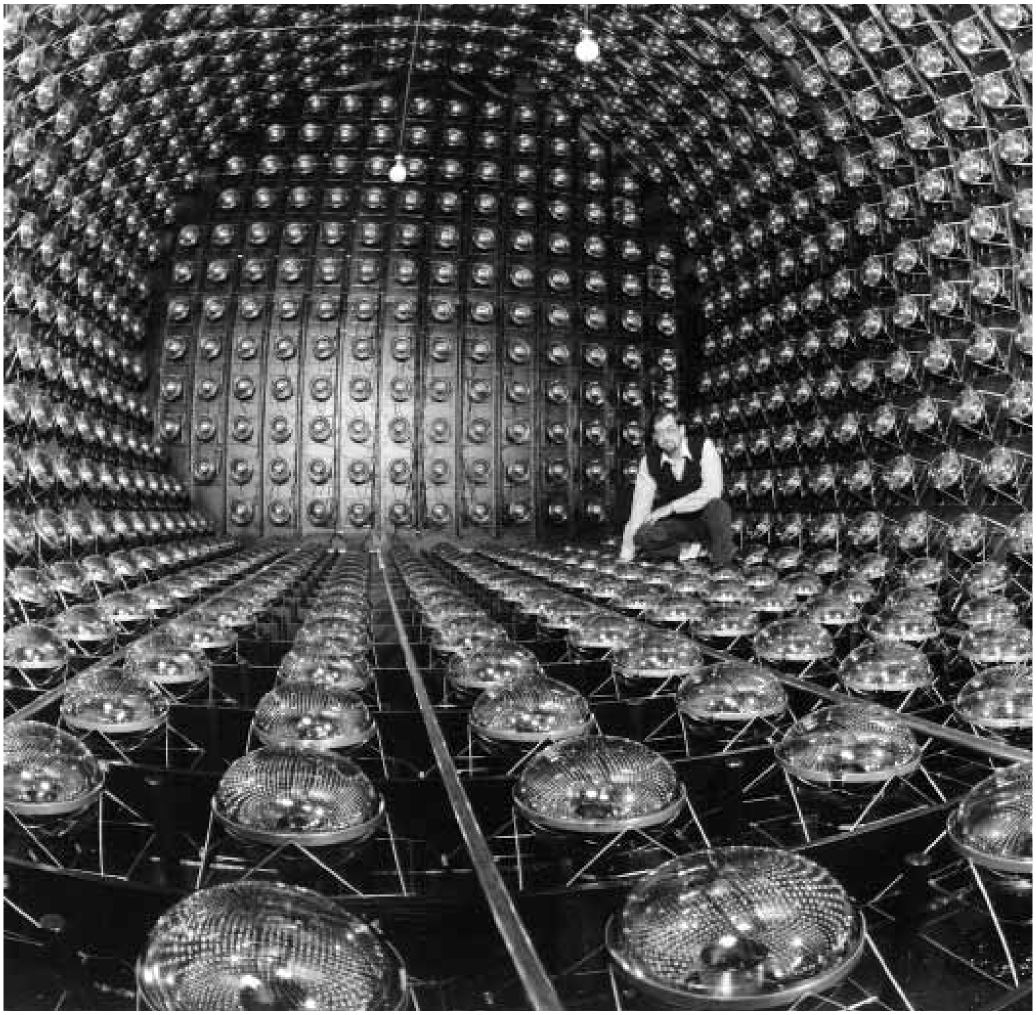
Since the early 1960s, neutrino experiments at Brookhaven, Fermilab, CERN, and the Institute for High Energy Physics at Serpukhov, Russia, have grown from tens to thousands to millions of neutrino events. None of these experiments has witnessed evidence for $\nu_\mu \rightarrow \nu_e$ or $\nu_\mu \rightarrow \nu_\tau$ oscillations. And at the same time, experiments at nuclear reactors have found no evidence for ν_e oscillations in detectors situated up to a kilometer from the reactor. The published limits have steadily crept to lower values of the neutrino mixing strength and mass difference.

BUT THE STORY by no means ends there. While experiments at reactors and high energy accelerators have found no evidence for them, four hints have emerged suggesting the real possibility of neutrino oscillations and hence mass. These are the solar neutrino deficit, the atmospheric neutrino deficit, the Liquid Scintillator Neutrino Detector (LSND) experiment at Los Alamos National Laboratory, and the missing matter problem. These hints suggest the existence of neutrino oscillations in regions of the parameter space that have not been completely ruled out by accelerator experiments.

The solar-neutrino deficit has been around for thirty years. (See "What Have We Learned About Solar Neutrinos" by John Bahcall in the Fall 1994 issue of the *Beam Line*.) Simply put, five solar-neutrino experiments have measured a significantly smaller number of neutrino interactions than expected, based on the measured heat output of the Sun and nuclear physics models of both the Sun and the detectors. Each experiment observed fewer neutrinos than expected, but the actual deficit each measures depends on the detecting medium and energy threshold. While it is not possible to explain the data with alternate models of the Sun, one can account for all the data within the framework of neutrino oscillations.

As discussed in the box on page 11, the length scale of an experiment provides a possible oscillation length. There are two possible scales for solar neutrinos: the distance from the Sun to the Earth and the radius of the Sun. Each length scale leads to a separate neutrino-oscillation solution for the solar neutrino deficit. One (labeled "vacuum" in the illustration on the left) arises from a straightforward solution of the relationship between neutrino mass and oscillations (see the box on the left). The other solutions (labeled "MSW" after Stanislav Mikheyev, Alexei Smirnov, and Lincoln Wolfenstein, who formulated the relevant theory) obey more complicated equations that take into account the huge density and density gradients of matter in the Sun, and how they can affect neutrinos emerging from its core. Both of these solutions involve oscillations of electron neutrinos into other kinds.

The atmospheric neutrino deficit takes us underground to experiments that were originally built for another purpose—to search for proton decay.



The LSND detector is designed to search for the presence of electron anti-neutrinos with great sensitivity. Over 1200 photomultiplier tubes line the inner surface of the oil tank, shown above with LSND physicist Richard Bolton of Los Alamos. (Courtesy Los Alamos National Laboratory)

These massive detectors, which weigh from one to fifty thousand tons, haven't discovered proton decay, but they do observe about a hundred interactions of atmospheric neutrinos per year for every thousand tons of detector mass. These neutrinos are created near the top of the atmosphere when cosmic-ray protons initiate a particle cascade, making one or more charged pions, each of which decays into a muon and a ν_μ. The muon subsequently decays into an electron, a ν_μ, and a ν_e. Thus, the ratio of ν_μ flux to the ν_e flux observed in an underground detector should be about two. This is quite a strong prediction, regardless of cosmic-ray rates and the subtleties of calculating the number of particles produced in the cosmic-ray cascades. Underground detectors seem to be measuring the expected number of electron neutrinos, but only sixty percent of the expected muon neutrinos. This ν_μ deficit could be explained by $\nu_\mu \to \nu_\tau$ oscillations, with the ν_τ too low in energy to produce a tau lepton by interacting with a nucleus. This deficit seems to indicate a value of Δm^2 betyween 10^{-3} and 1 eV^2 (see region labeled "Atmospheric Ratio" in the illustration on page 12).

The distance that atmospheric neutrinos travel before hitting a detector varies from 25 kilometers for those coming from overhead to 12,000 kilometers for those coming from the other side of the Earth. This provides an opportunity to determine whether there is any difference in the signal between the up-going and the down-going neutrinos. If so, the oscillation length for typical atmospheric neutrino energies (500 MeV) would be between 25 km and 12,000 km. There is strong evidence from the SuperKamiokande experiment this is the case. This "up/down asymmetry" observed seems to favor a value of Δm^2 between 10^{-4} and 10^{-2} eV^2 (region labeled "Up/Down" in the illustration).

The LSND experiment at Los Alamos, unlike the solar and atmospheric neutrino experiments, was explicitly built to look for neutrino oscillations. Operating near the target of the LAMPF accelerator, it uses a very intense π^+ beam. The pions stop in the target, decay into a μ^+ and a ν_μ, and the μ^+ decays into an e^+, a ν_μ, and a ν_e. Except for a small and calculable background from negative pion decays, there are no $\bar{\nu}_e$'s in the beam. So if excess numbers of these particles are detected, they probably arose from $\bar{\nu}_\mu \to \bar{\nu}_e$'s oscillations. The experiment has a 170 ton tank of mineral oil that can detect the reaction $\bar{\nu}_e p \to n e^+$ by measuring a 15–30 MeV positron in coincidence with a signal from neutron capture, which yields a 2.2 MeV gamma ray. The experiment has reported a signal that could be explained by neutrino oscillations with a strength $P_{(\nu_\mu \rightarrow \nu_e)} = 0.003$.

Unlike the atmospheric and solar neutrino deficits, the LSND signal has been observed in only one experiment. In fact, other experiments that are sensitive to these oscillations over similar regions of parameter space have obtained negative results. The region favored by LSND but not ruled out by other experiments (labeled "LSND" in the figure on page 12) suggests a value of Δm^2 around 1 eV^2.

The final hint, the missing matter problem, is really suggestive of neutrino mass rather than oscillations. There is a critical density of matter in the Universe (see article by Alan Guth in the Fall 1997 issue of the *Beam Line*, Vol. 27, No. 3), about one hydrogen atom per cubic meter, above which the Universe is closed and will someday collapse back into a single point. If the density is at or below this critical density, the Universe is open and will expand forever. There are strong theoretical arguments that the density should just equal the critical value, though there are recent observational data which suggest only twenty percent of that value. Ordinary baryons, the stuff that makes up stars and stuffed pizza, is only about five percent of the critical value, based on both observational data and the rates of light element production during the Big Bang. Some of this missing matter may well be neutrinos; there are hundreds of them in every cubic centimeter of the Universe. If they had a mass of just 5 eV, neutrinos would outweigh all the stars and pizza in the Universe.

Select Present/Future Neutrino Experiments[a]

Experiments	Neutrino Energy	Location	Status
Solar			
SuperKamiokande	7 MeV	Kamioka, Japan	Current
Sudbury (SNO)	4 MeV	Ontario, Canada	Beginning
Atmospheric			
Soudan 2	600 MeV	Minnesota	Current
MACRO	5 GeV	Gran Sasso, Italy	Current
Reactor			
Chooz	5 MeV	France	Current
Palo Verde	5 MeV	Arizona	Future
Short-baseline			
NOMAD	50 GeV	Geneva, Switzerland	Current
LSND	40 MeV	Los Alamos	Current
Long-baseline			
MINOS	20 GeV	Fermilab to Minnesota	Future
ICARUS	30 GeV	Switzerland to Italy	Future
K2K	1 GeV	Tsukuba to Kamioka, Japan	Future

[a] A more complete list of neutrino experiments can be found at http://www.hep.anl.gov/ndk/hypertext/nu_industry.html

Experimenters want to confront these hints of neutrino oscillations with more definitive measurements. New solar neutrino experiments are determining the size, time dependence, and energy dependence of the solar neutrino deficit. New short-baseline oscillation experiments are studying mass differences in the region of the missing matter problem. The reported LSND effect will be sought by another collaboration at the Rutherford Laboratory in Britain, and there is a proposal for a future follow-up detector at Fermilab (see table on the left for a small selection of these experiments).

WHILE UNDERGROUND experiments will continue to study the atmospheric neutrino deficit, there is another plan to study possible neutrino oscillations in the same region of parameter space. These are the long-baseline experiments. While short-baseline experiments are typically one kilometer from the point where the neutrinos are produced, long-baseline experiments in the United States and Europe will be located 730 km away from the source. And another experiment in Japan will have 250 km between neutrino production and detector. All three of these choices are matters of convenience—the distances between existing accelerators and existing underground facilities. As luck would have it, however, all three projects will substantively address the possibility that the atmospheric neutrino deficit is due to neutrino oscillations.

As an example of one of the most ambitious new neutrino oscillation projects, I will now focus on the Fermilab-to-Soudan long-baseline project (see map on the right). There are three elements to the project: the neutrino beam, a near detector at Fermilab, and a far detector at the Soudan underground physics laboratory in northern Minnesota.

A high-intensity neutrino beam from Fermilab will be made possible by a new high-intensity 120 GeV proton source called the Main Injector. Scheduled for completion in 1999, this facility is being built to replace the present Main Ring as one stage of acceleration. The Main Injector will also allow a very high-intensity neutrino program, known as NuMI for "Neutrinos at the Main Injector," to be run simultaneously with other experiments . The intense proton beam makes a neutrino beam by hitting a target to make the maximum number of pions and kaons, which are focused forward to give a beam with as little divergence as possible. Then they travel through a one kilometer pipe where many of them decay into neutrinos, which continue moving forward. The kinematics of the pion decay results in an average angle between a neutrino and the original beam of about 1/20th of a degree.

One obvious concern in aiming a beam at a target so far away is the precision required to hit it, but this turns out to be only a minor problem. Hitting the target is a similar to aiming a flashlight at the moon. Most people could hold the flashlight and point accurately enough. The problem comes in seeing the flashlight while standing on the moon. This could only be accomplished with a powerful enough light. The long-baseline neutrino problem is similar. The neutrino beam spreads out as it recedes from Fermilab, losing its intensity. And, neutrinos are very weakly interacting, so one needs a very massive target in order to detect just a few of them. In order to study such long oscillation lengths, the detectors must be far away from the source and can only intercept a small fraction of the beam. Thus it is necessary to make the beam very intense at its origin.

The far detector will be located in an old iron mine beneath the Soudan State Park in Minnesota. A half mile beneath the surface—at the deepest level of a historic iron mine—is the existing Soudan 2 fine-grained detector. The mine, which operated for almost one hundred years, is currently being maintained for tourists by the State of Minnesota Department of Natural Resources. Scientists plan to bring ten thousand tons of iron to build the MINOS detector, which will join the one thousand tons already in Soudan 2, to study neutrinos from Fermilab. It's a bit like taking coal to Newcastle.

Map showing long-baseline neutrino experiment planned from Fermilab in Illinois to Soudan in Minnesota.

The home of the MINOS detector—a cavern in Soudan, Minnesota—being installed in the 1980s. (Courtesy Fermilab)

The headframe atop a former iron mine at Soudan in northern Minnesota. (Courtesy Fermilab)

The new MINOS (for "Main Injector Neutrino Oscillation Search") detector will measure about twelve thousand neutrino interactions per year out of the five trillion that pass through. It will consist of six hundred layers each of scintillation counters and magnetized iron. If the atmospheric neutrino deficit is due to $\nu_\mu \rightarrow \nu_\tau$ oscillations, MINOS will observe different rates of events, different fractions of events with muons, and different energy distributions from those seen in the near detector.

A small version of the MINOS detector at Fermilab is a necessary part of the experiment. This detector will be used to understand the beam and calibrate its intensity, by measuring the interactions of neutrinos before they have had any chance to oscillate into other species.

Physicists hope to begin taking data with the existing Soudan detector and the first sections of the new MINOS detector in 2002. Given all the other neutrino experiments around the world, I can promise that there will be substantial progress in understanding neutrinos and the possibility of neutrino oscillations during the next decade. But I suspect that progress will come slowly and gradually. The large and growing effort being devoted to neutrino experiments is indicative not only of the interest in these ghostly particles but also the difficulty of doing precision work in this field. Even if we definitively show that neutrino oscillations exist, there will be a large set of neutrino mass and mixing parameters to determine. And if neutrino oscillations do not turn up, we will need alternative explanations for the present observational hints. In one form or another, the experimental study of neutrino oscillations will probably continue for the next twenty years!