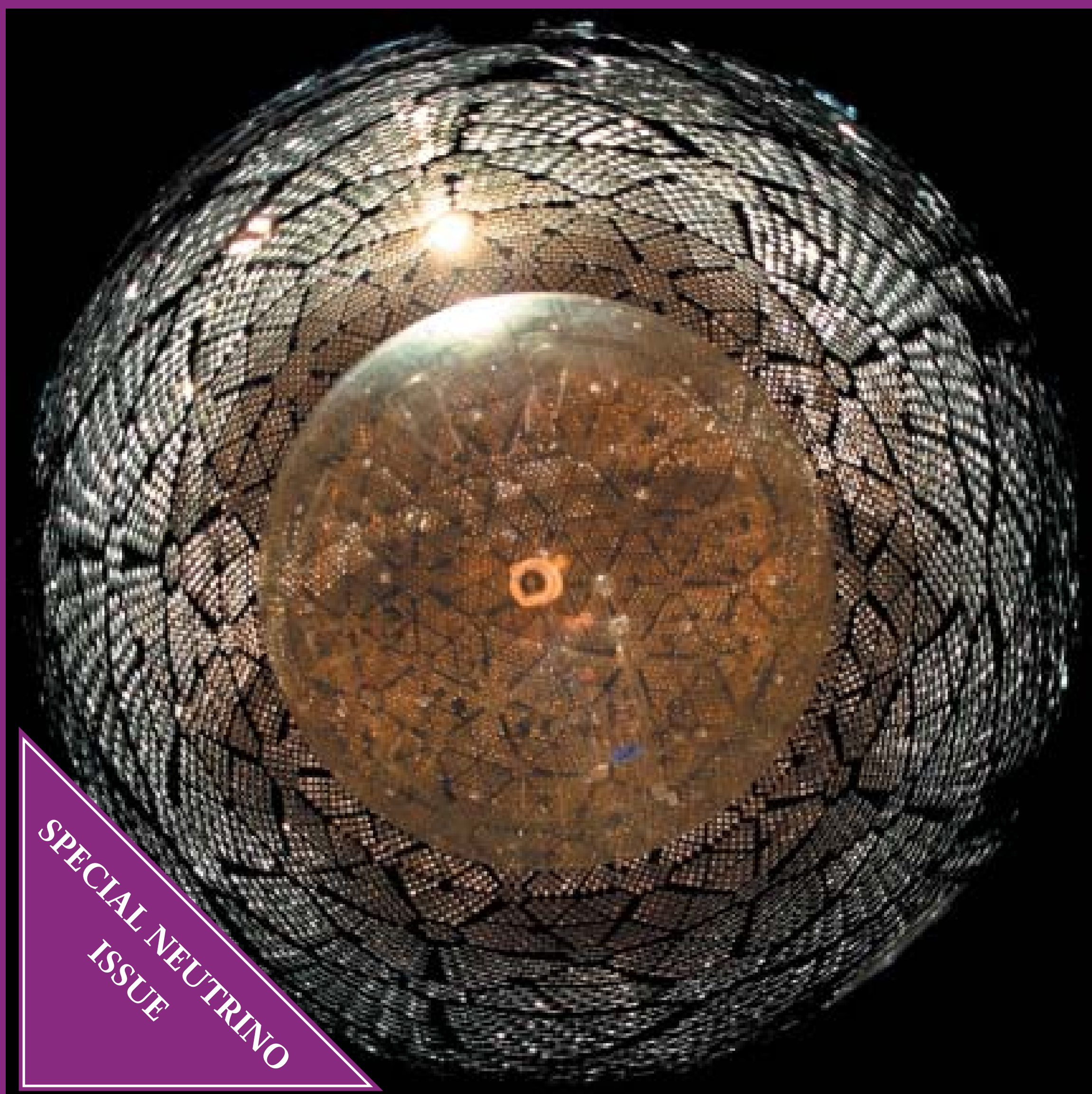
STANFORD LINEAR ACCELERATOR CENTER

Beam Line

Fall 2001, Vol. 31, No. 3



Beam Line

A PERIODICAL OF PARTICLE PHYSICS

FALL 2001 VOL. 31, NUMBER 3

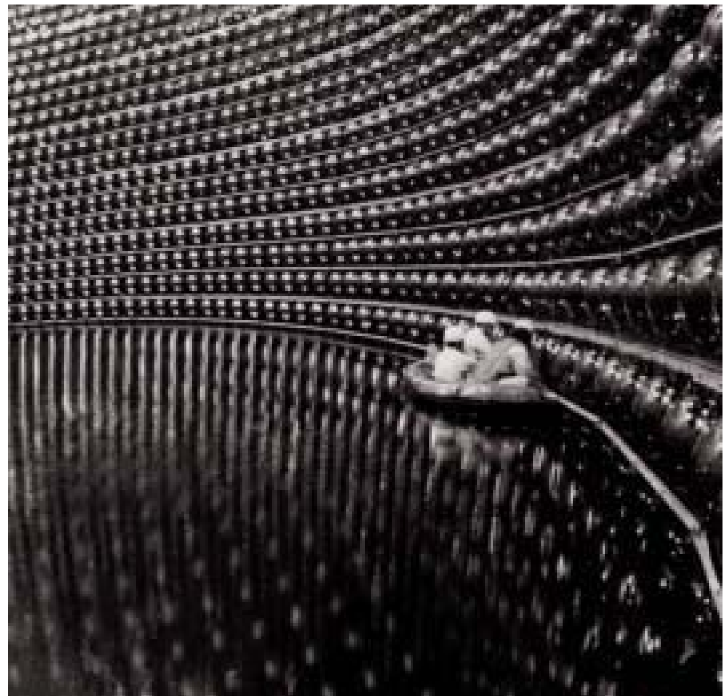
The *Beam Line* is published quarterly by the Stanford Linear Accelerator Center, Box 4349, Stanford, CA 94309. Telephone: (650) 926-2585. EMAIL: beamline@slac.stanford.edu FAX: (650) 926-4500

Issues of the *Beam Line* are accessible electronically on the World Wide Web at http://www.slac.stanford.edu/pubs/beamline. SLAC is operated by Stanford University under contract with the U.S. Department of Energy. The opinions of the authors do not necessarily reflect the policies of the Stanford Linear Accelerator Center.

Cover: The Sudbury Neutrino Observatory detects neutrinos from the sun. This interior view from beneath the detector shows the acrylic vessel containing 1000 tons of heavy water, surrounded by photomultiplier tubes. (Courtesy SNO Collaboration)

Printed on recycled paper

CONTENTS



FEATURES

Neutrino Experiments at

by PAUL NIENABER

Neutrino physics is thriving in the Nation's heartland.

PARTICLE PHYSICS EXPERIMENTS often get lumped under the general heading of "big science." Particle accelerators are gargantuan, detectors are huge and complex, and today's multi-institutional collaborations generate social dynamics whose unraveling would baffle the most sophisticated supercomputer. Neutrino experiments are no exception to this observation; the detectors come in three sizes: large, extra-large, and positively Bunyanesque. Yet, like the graceful hippopotami in Walt Disney's *Fantasia*, a "little" neutrino experiment can on occasion dance briskly in, do some beautiful tour-de-force physics, and take a bow—all for a relatively modest ticket price. Two premier danseurs of this sort on the Fermilab stage are the DONUT and BooNE experiments. DONUT (Direct Observation of the Nu-Tau) has completed its run and is now accepting bravos for being the first experiment to detect the tau neutrino. BooNE (Booster Neutrino Experiment) is waiting in the wings, warming up to delve more deeply into the peculiar pas de deux of neutrino oscillations.

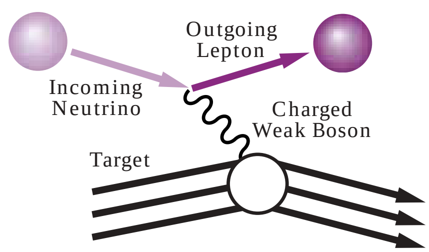
According to the Standard Model, our current best working theory of elementary particles and fundamental forces, a neutrino can interact and change into its electrically charged lepton partner by emitting or absorbing the charged carrier of the weak force, the *W* boson. This type of exchange is called a "charged-current" interaction (to distinguish it

Fermilab

from the exchange of a neutral Z boson). The weak force also obeys a twofold lepton-number conservation rule: both the number of leptons and their kind remains unchanged. Interacting electron neutrinos yield only electrons, muon neutrinos only muons, tau neutrinos only taus. Neutrinos and their charged partners can switch back and forth within a Standard Model generation, but they cannot jump between generations. This conservation rule makes the charged-current interaction a useful "generation tagger": if you see a muon zipping through your neutrino detector, and you can ascertain that it came directly from a neutrino interaction, you can be sure it was produced by a muon neutrino.

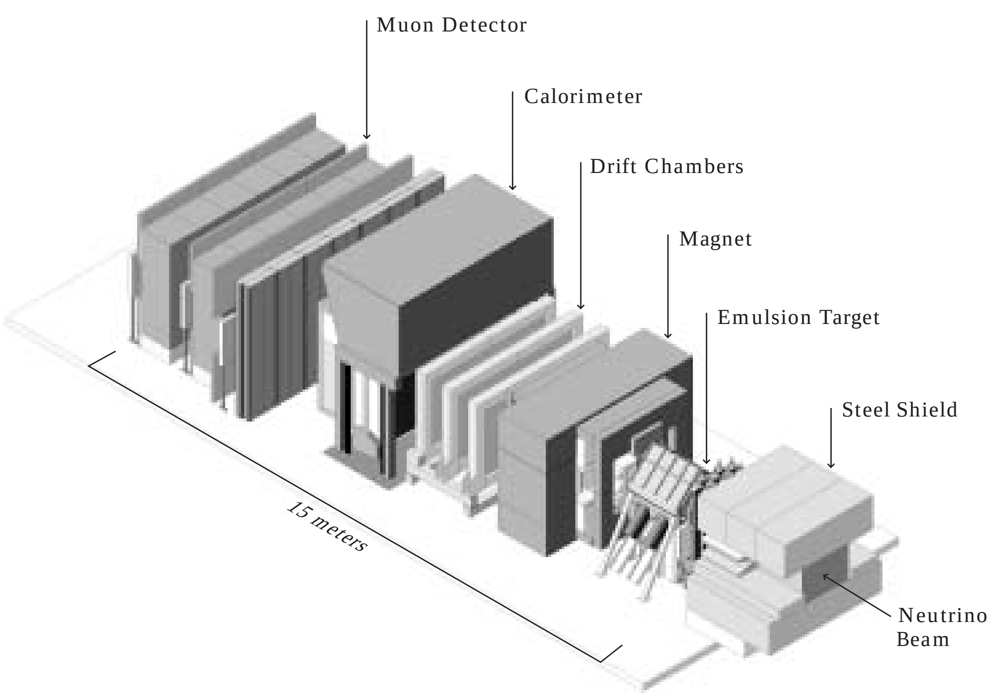
Because neutrinos are immune to the strong and electromagnetic interactions, they provide a unique "weak force scalpel" for investigating the properties of particles. Electron neutrinos are difficult to concentrate into a beam whose direction and energy can be varied, so muon neutrinos have become the scalpel of choice. The recipe is fairly straightforward: take a proton beam, smack it into a block of material, magnetically focus and direct the charged pions and kaons spewing forth from the collision, allow them to decay into muons and muon neutrinos, filter out the charged decay products and any other unwanted debris, and voila! You have a beam of muon neutrinos.

But because neutrinos interact so weakly, the chances of any single one interacting in a detector are minuscule. The probability of witnessing an interaction depends on the number of neutrinos, their energy, and the number of other particles available for them to hit. Getting a reasonable number of events therefore requires lots of neutrinos, lots of energy, and lots and lots of detector material—hence the Brobdingnagian scale of neutrino experiments.



A neutrino charged-current interaction.

DONUT detector for direct observation of tau neutrinos.



WITH THE DISCOVERY of the top quark at Fermilab in 1995, the set of six fundamental constituents of the strongly interacting particles in the Standard Model was complete. The lepton six-pack, however, still had one gaping hole—the tau neutrino remained the most elusive of its standoffish cousins. Experiments at SLAC and CERN had determined that there were at most three conventional, lightweight neutrinos, and there was indirect evidence from the missing momentum observed in decays of the tau lepton, but no definitive sightings (see "Pauli's Ghost," by Michael Riordan, this issue).

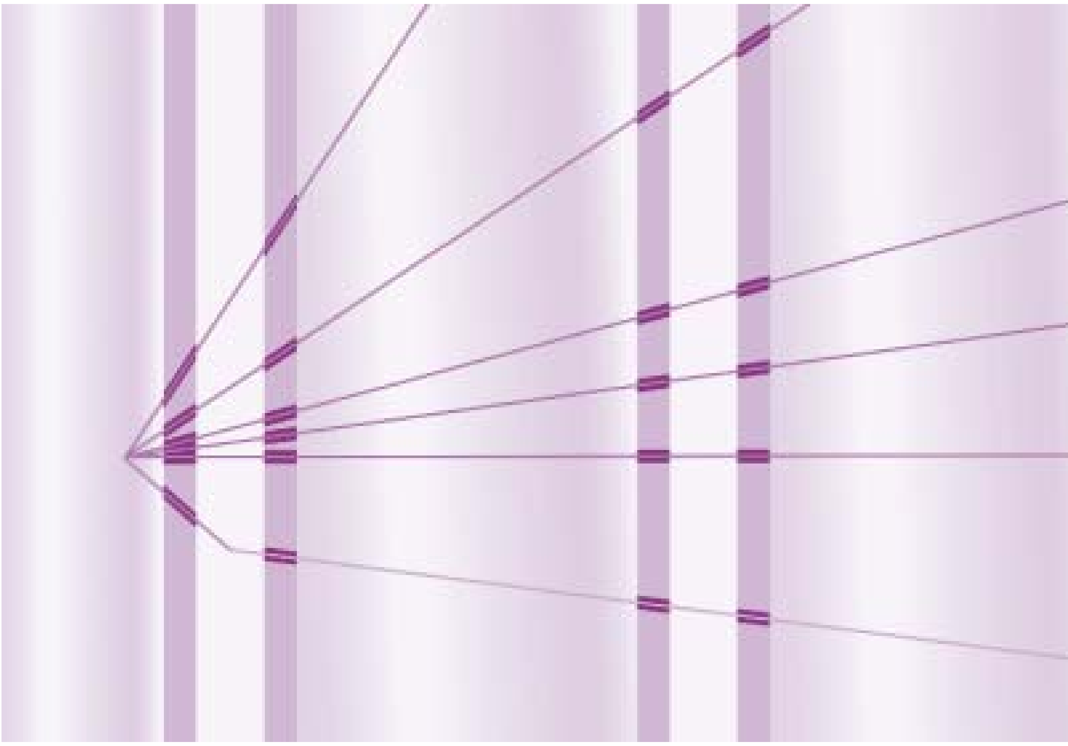
Understanding why the tau neutrino is so camera shy takes us back to the charged-current interaction. Electron neutrinos make electrons, which interact almost immediately in detector material and produce a distinctive shower of particles. Muon neutrinos engender muons, which travel relatively undisturbed through matter before decaying and thus leave long tracks in detectors. Tau neutrinos make taus—and there's the rub. The tau lifetime is less than one third of a trillionth of a second; multiply this brief instant by the speed of light and you get a decay length literally the size of a gnat's whisker, about 90 microns. If a tau is extremely relativistic, it may travel a few millimeters before decaying, but tracing these microscopic paths to discover any kinks in them demands extremely high-precision tracking. This requirement, coupled with the small likelihood of tau neutrinos ever interacting, makes detecting them an extraordinary challenge. To rise to that challenge came the DONUT experiment, which ran at the Fermilab Tevatron in 1997.

There are two hurdles to overcome if you want to bag a tau neutrino: first you gotta make 'em, and then you gotta take 'em. To make tau neutrinos, you employ a variation on the muon-neutrino recipe, but instead of using pions and kaons as the parents, you must employ much heavier mesons. The lepton-number conservation rule says you can only make a tau or its neutrino in tandem with an antilepton of the third generation. To get tau neutrinos, therefore, you have to produce a parent particle that includes a tau (whose mass is a whopping 1777 MeV, almost twice the mass of a proton) in its decay chain. DONUT's tau neutrinos come from the decay of D_S mesons, produced by slamming the Tevatron's

800 GeV protons into a tungsten target. These mesons are also heavy (1970 MeV) and short-lived, so no attempt to focus them is made.

The aim of the experiment is to look for charged-current scattering of the resulting tau neutrinos. This process will make final-state taus, but how does one corral these evanescent heavyweights? The key to this experiment, the factor that makes it both beautiful and rather difficult, is the use of a large target composed of photographic emulsion plates. These plates are just standard black-and-white film medium, silver bromide, suspended in a gel. Instead of a thin layer of this substance coating a 35 mm piece of plastic film, however, DONUT's plates contain the bulk emulsion deposited on square sheets about the size of a large pizza box (50 cm square). Charged particles traversing the emulsion leave tracks of exposed grains, and finding a vertex (where the tau neutrino interacted) that spawns a kinked track (where the resulting tau lepton subsequently decayed) provides the "smoking gun," evidence for a tau neutrino.

Isolating such a vertex with a track that kinks a scant few millimeters downstream of it is no easy feat. The emulsion stack is only 36 meters downstream of the tungsten target, which means that extensive shielding must be used to keep the emulsion from being swamped by superfluous tracks. The usual passive shielding (which filters out unwanted particles by letting them interact in material) is not enough; DONUT's emulsion stack needed active elements (magnetic fields to divert charged detritus) as well.



One of the four tau neutrino events recorded by the DONUT detector. The track with a kink is a tau lepton decaying into an invisible tau neutrino and another particle.

DONUT was also in the unusual position of having to deal with neutrino backgrounds, since the proton interactions in the tungsten produce plenty of electron and muon neutrinos, too. These extra neutrinos can interact in the emulsion as well and render the stack awash in tracks.

To help pick out a few specific bent needles from this huge haystack of tracks, the experimenters positioned a series of scintillating-fiber tracking detectors among the emulsion plates. These trackers, together with other detectors downstream of the emulsion array, helped identify the particles and trace out their paths. The vertex and track reconstruction enabled a tiny, precisely selected region of the emulsion to be pinpointed for closer scanning and measurement. The actual digitization and scanning of the emulsion, section by tiny section, was done at a unique facility in Nagoya, Japan, one of the few of its kind in the world. In July 2000, after data reduction and a careful analysis to screen out backgrounds, the DONUT team showed the world four events with a distinctive kink in one track, indicating a tau lepton decay. The first direct sightings of the tau neutrino, these events confirmed at last that it indeed exists.

AT ABOUT THE TIME that the DONUT collaboration was looking for telltale kinks, evidence was accumulating from other quarters that the Standard Model might not be quite right. Several experiments had seen hints that two fundamental features thought to hold for neutrinos—the expectation that they are massless and that they cannot change from one kind to another—were in fact incorrect. Rather loose upper bounds had been set on the neutrino masses by carefully adding up all the visible energy in certain particle decays that produce neutrinos. And the prohibition on leptons jumping from one generation to another had been probed by searches for exotic processes such as $\mu \rightarrow e\gamma$.

One way to establish more stringent limits is to examine the curious possibility of neutrino oscillations (see box at left). Understanding how such oscillations might occur requires us to step into the sometimes-counterintuitive world of quantum mechanics. According to the Standard Model, neutrinos are massless and conserve lepton number. But if this is not in fact the case, then neutrinos can have different masses, and a neutrino created as one kind (say an electron neutrino, produced in the nuclear reactions occurring in the Sun's core) could evolve, or oscillate, into another kind as it zooms along through space.

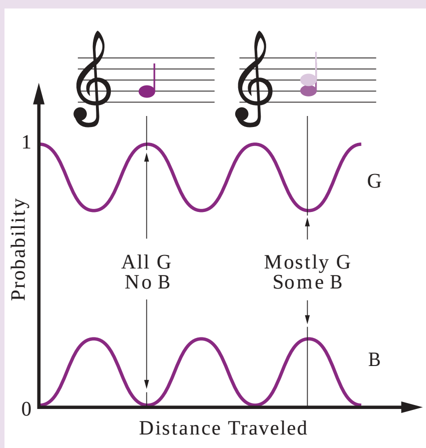
Quantum mechanics tells us that the characteristics of any neutrino oscillation—its amplitude and repeat

Neutrino Oscillations

HERE'S A GOOD WAY to think about neutrino oscillations. Suppose you could only hear a single pitch (or frequency) of sound at a time: That is, your "sound detector" could only tell that a note was a G, or a B, or a D; it could not detect a mixture of these notes. If a note (you hear) starts out as a G (or a B or D for that matter), it would stay that way forever. This is the way that charged leptons behave.

Neutrinos play by different rules, however, and admit the possibility that a note originating as a G (an electron neutrino, say) can "detune" as it travels, developing B or D components (a muon or tau neutrino). This kind of behavior is analogous to that of the strings in a guitar, which—once plucked—can excite lesser vibrations on the other strings.

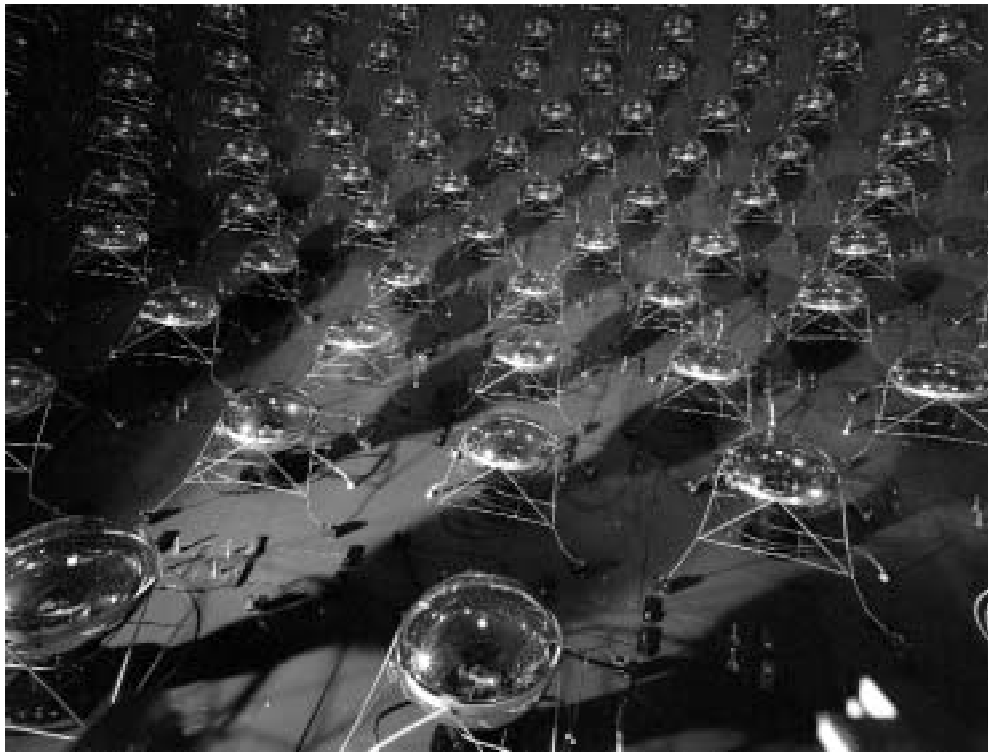
Does this mean that one would hear chords in neutrino beams? No—remember, you can detect only one "pitch" at a time. What it does mean, however, is that if you create a pure beam of 1000 Gs, say, and set up a listening post some distance away, you might get 990 Gs and 10 Bs. What fluctuates in neutrino oscillations is the probability that a neutrino created as one specific kind will be detected as that same kind (or another kind) of neutrino.



Oscillation probability: even though the neutrino beam starts out as 100 percent G's, as it moves through space, the beam can gain (and lose, and then regain) some B's. What oscillates is the probability.

length—are governed by four factors. Two of them are experiment-specific: the neutrino energy E and the source-to-detector distance L. The other two are intrinsic properties of how the neutrinos fluctuate back and forth from one kind to another: the oscillation strength itself (the amplitude of the wave) and the absolute difference between the squares of their two masses $\Delta m^2 = |m_1^2 - m_2^2|$. One of the current problems in neutrino-oscillation physics has to do with this last parameter, Δm^2. Since there are three known kinds of neutrino, there can only be two independent differences between their mass states. The three classes of experiments currently yielding positive indications of neutrino oscillations—those studying neutrinos from the Sun, those observing neutrinos from muons produced in Earth's atmosphere, and two accelerator-based experiments—do not yield a coherent set of Δm^2 values (see article by Boris Kayser, this issue). This discrepancy could point to a new, fourth kind of neutrino (called a "sterile" neutrino because it cannot interact with ordinary matter). Or it could imply that one (or more) of these experiments is not really seeing oscillations but another effect.

The one accelerator-based experiment that reported a neutrino-oscillation signal is the Liquid Scintillator Neutrino Detector (LSND), which detected neutrinos from pions produced by a medium-energy proton beam at the Los Alamos National Laboratory. The collaboration observed an excess of events above background that can be explained by the oscillation of muon neutrinos into electron neutrinos, with a Δm^2 of about 1–2 eV^2. A result of no small importance, it cries out for independent confirmation. Enter the second of Fermilab's lissome leviathans, the Booster Neutrino Experiment.

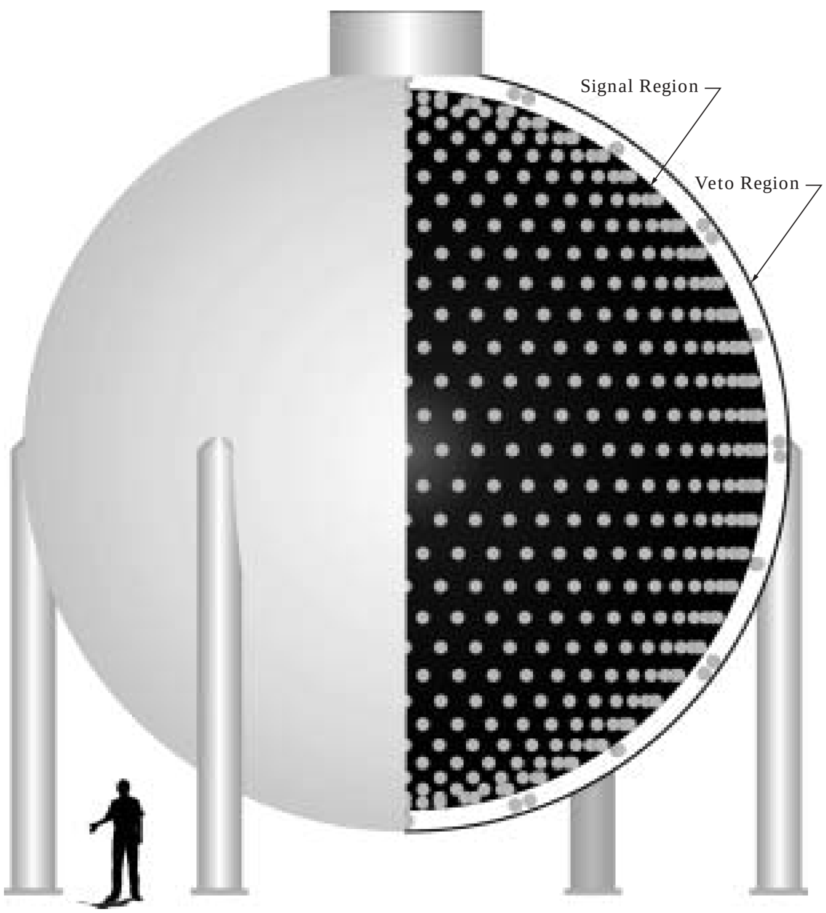


Some of the 1200 photomultiplier tubes on the inside of the BooNE detector.

BooNE's main raison d'etre is to test the LSND result. It will either provide confirming evidence (and get enough events to establish the ν_μ to ν_e transformation once and for all) or prove LSND wrong—and set more stringent limits on this particular type of oscillation. There are some surface similarities between LSND and BooNE: both use large tanks filled with mineral oil and lined with photomultiplier tubes. But the detector geometries are different (LSND is cylindrical, while BooNE is spherical), the source-to-detector distance L and beam energy E are different (although the ratio L/E for the two experiments is the same), and the backgrounds for BooNE will be different from those of LSND.

The BooNE experiment will follow the standard recipe for making a muon neutrino beam, starting with 8 GeV protons from the Fermilab Booster, a low-energy synchrotron in the Tevatron acceleration chain used to boost protons from 400 MeV to 8 GeV before passing them on to the Main Injector. Protons extracted from the Booster will strike a beryllium target; pions generated by these collisions will be focused by a magnetic horn, and their decay will produce the muon neutrinos speeding off toward the detector.

Artist's conception of the BooNE detector, showing some of the photomultiplier tubes lining its 250,000-gallon tank.



The BooNE detector is a 12 m diameter steel sphere filled with 770 tons (about 250,000 gallons) of mineral oil (see illustration on this page). A second light-tight inner wall divides the tank into an active central sphere and an outer "veto" shell used to flag exiting or extraneous incoming particles. Charged particles produced by neutrino interactions in the oil are detected by means of the blue Cerenkov light they generate, which will be detected by 1280 photomultiplier tubes lining the inner surface of the central sphere or the 330 tubes in the veto shell. Again, the charged-current interaction will allow physicists to identify the kind of neutrino involved; a long muon track (from the interaction of a ν_μ in the mineral oil) will generate a pattern of Cerenkov light distinct from that produced by an electron shower (from a ν_e interaction).

As this article goes to press, construction of the BooNE detector is nearing completion, and the proton-extraction beam line and target-horn systems are well underway. Data taking is expected to commence in early 2002, after which the experiment should run for one to two years. If a signal is observed, a second detector can be built downstream of the first—to make further detailed measurements of the parameters for $\nu_\mu \rightarrow \nu_e$ oscillations. Such a result would add to the growing body of evidence that neutrinos do indeed have mass, and point to the exciting possibility of new physics beyond the Standard Model.

NEUTRINO PHYSICS has long been a featured performer in Fermilab's multifaceted particle physics program. DONUT has made a major contribution, and the upcoming BooNE experiment bids fair to continue that history. Future neutrino-beam opportunities might include upgrading the Booster to allow it to provide even greater fluxes of neutrinos. There are also the exciting prospects of "long-baseline" neutrino experiments where the distance between the source and detector is hundreds of kilometers rather than hundreds of meters.

One such Bunyanesque experiment stretches all the way from Fermilab to the Soudan mine in northern Minnesota, where the detector for the MINOS (Main Injector Neutrino Oscillation Search) experiment will be located. The MINOS beam starts with 120 GeV protons from the Main Injector, which feeds the Fermilab Tevatron. The neutrino beam produced by these protons hitting a target will be directed north and slightly downward, to intercept a six-kiloton steel-and-scintillator detector in an iron mine some 750 km away—making MINOS one of the largest neutrino experiments on the planet. When this football field-length detector is complete, it will capture neutrinos beamed from Fermilab and further probe the mysteries of neutrino oscillations. The combination of neutrino energies and the long baseline between source and detector make MINOS sensitive to values of Δm^2 a hundred times smaller than BooNE. This is the same range of values that has been observed for oscillations of neutrinos in the upper atmosphere (see article by John Learned in the Winter 1999 *Beam Line*, Vol. 29, No. 3).

Peering still further into the future, one can glimpse the intriguing possibility of a "neutrino factory"—a storage ring for muons whose decay would provide a copious source of muon and electron neutrinos. Such a high-energy source of electron neutrinos would open whole new vistas for further exploration of the weak interaction. But whatever scenarios the future contains, neutrinos will surely play leading roles in them.

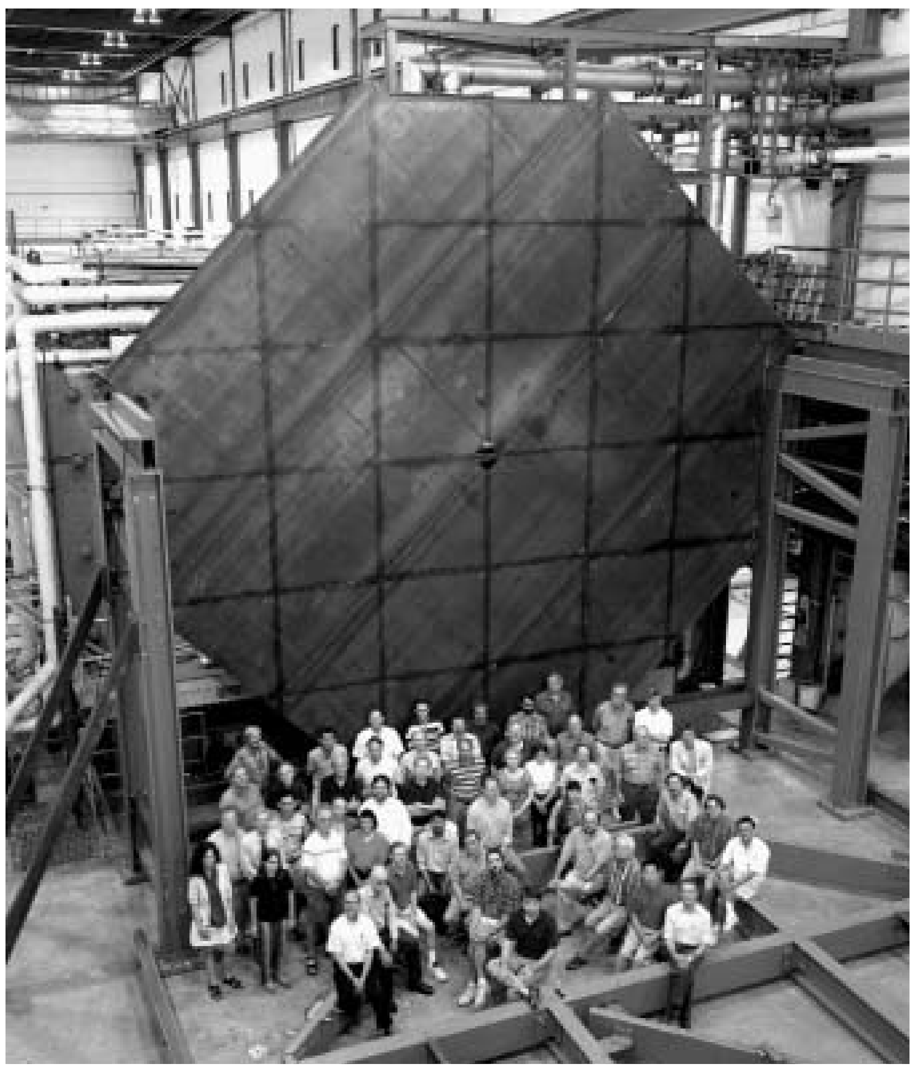
For Further Information

DONUT home page:
http://www-donut.fnal.gov

BooNE home page:
http://www-boone.fnal.gov/

Juha Peltoniemi's "ultimate neutrino" page:
http://cupp.oulu.fi/neutrino/

Members of the MINOS collaboration before one of its enormous steel plates.

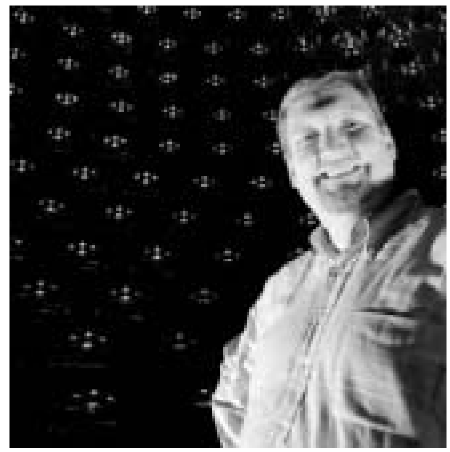


CONTRIBUTORS

MICHAEL RIORDAN is Assistant to the Director at the Stanford Linear Accelerator Center, Lecturer in the History and Philosophy of Science Program at Stanford, and Adjunct Professor of Physics at the University of California, Santa Cruz. A Contributing Editor of the *Beam Line*, he is author of *The Hunting of the Quark*, and coauthor of *The Shadows of Creation: Dark Matter and the Structure of the Universe* and *Crystal Fire: The Birth of the Information Age*. He leads a group of historians and physicists researching and writing the history of the Superconducting Super Collider. In 1999 he received a Guggenheim Fellowship to pursue research on this subject at the Smithsonian Institution in Washington, DC. While there, he also got married again.

JOSHUA KLEIN received his Ph.D. from Princeton University in 1994. He then moved to the University of Pennsylvania where he has worked on building and making measurements with the Sudbury Neutrino Observatory. He is currently Research Assistant Professor of Physics at Pennsylvania.

SNO is in many ways the quintessential particle astrophysics experiment featuring the Sun as a neutrino laboratory and neutrinos as solar probes. Klein's interest in SNO encompasses both of these features, including an interest in neutrinos themselves as the Standard Model's most enigmatic particle.



PAUL NIENABER has the great good fortune to be part of two extraordinary neutrino groups at Fermilab. He joined the NuTeV collaboration in 1992 and is now working on data analysis from that experiment; in addition, he became a member of the BooNE collaboration in 2000 and is participating in construction and testing of its detector.

The photograph above shows Paul inside the BooNE tank, surrounded by the photomultiplier tubes he helped install. He is a Jesuit priest, a Guest Scientist at Fermilab, and a member of the physics faculty at the College of the Holy Cross in Worcester, Massachusetts, where he thoroughly enjoys infecting college students' minds with the manifold pleasures of doing physics. This is his first article for the *Beam Line*.