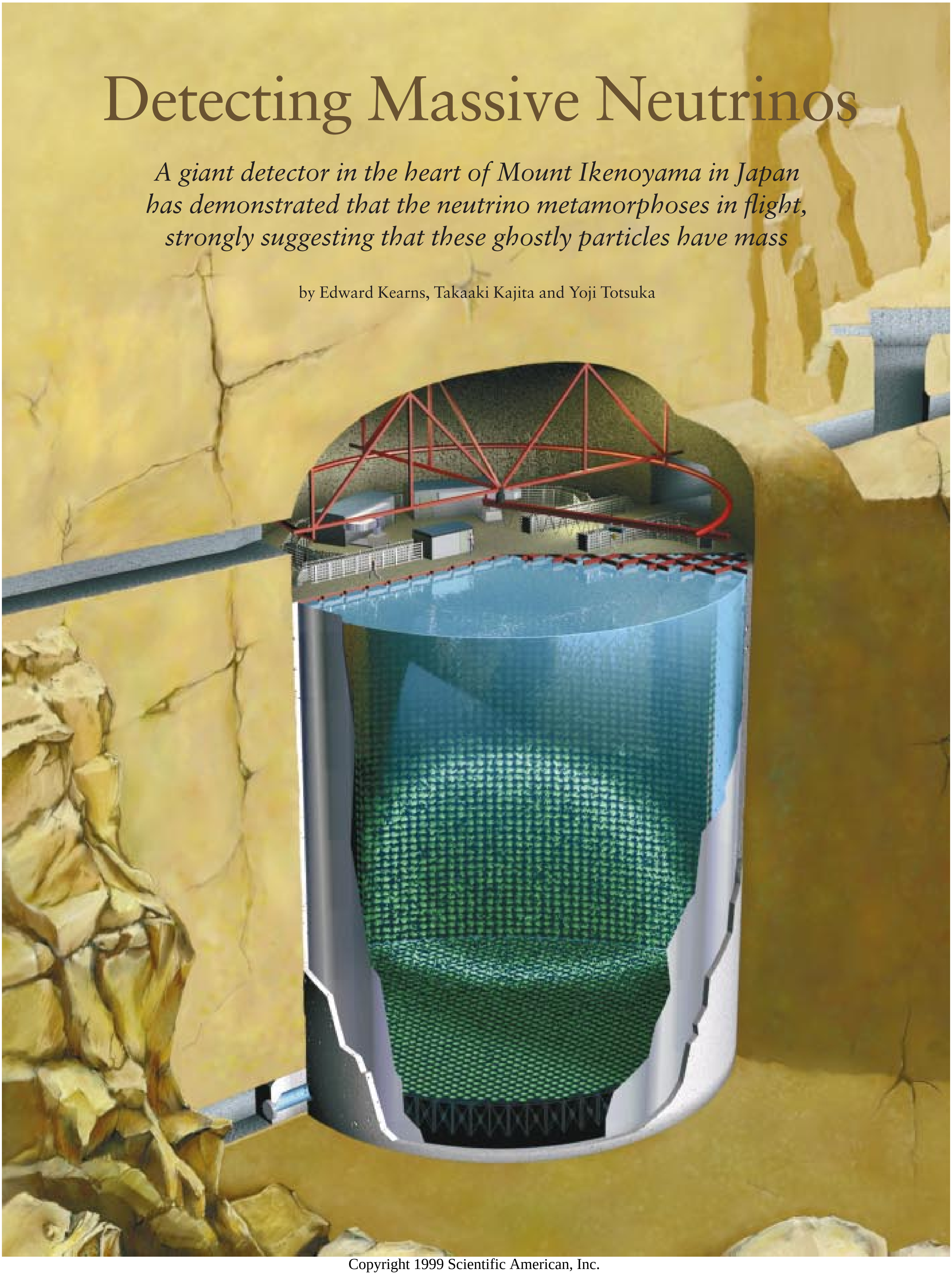
Detecting Massive Neutrinos

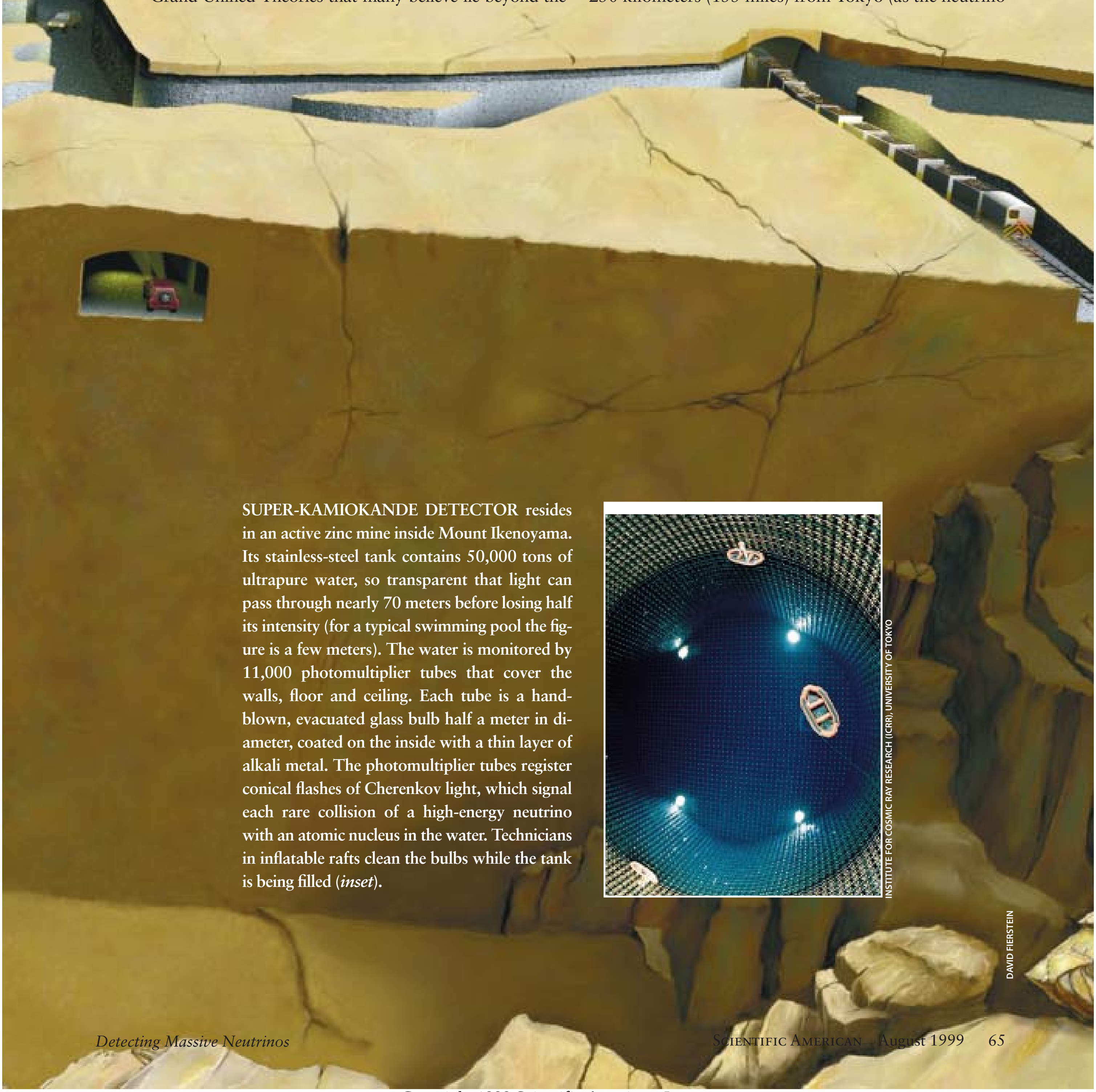
A giant detector in the heart of Mount Ikenoyama in Japan has demonstrated that the neutrino metamorphoses in flight, strongly suggesting that these ghostly particles have mass

by Edward Kearns, Takaaki Kajita and Yoji Totsuka



One man's trash is another man's treasure. For a physicist, the trash is "background"—some unwanted reaction, probably from a mundane and well-understood process. The treasure is "signal"—a reaction that we hope reveals new knowledge about the way the universe works. Case in point: over the past two decades, several groups have been hunting for the radioactive decay of the proton, an exceedingly rare signal (if it occurs at all) buried in a background of reactions caused by elusive particles called neutrinos. The proton, one of the main constituents of atoms, seems to be immortal. Its decay would be a strong indication of processes described by Grand Unified Theories that many believe lie beyond the extremely successful Standard Model of particle physics. Huge proton-decay detectors were placed deep underground, in mines or tunnels around the world, to escape the constant rain of particles called cosmic rays. But no matter how deep they went, these devices were still exposed to penetrating neutrinos produced by the cosmic rays.

The first generation of proton-decay detectors, operating from 1980 to 1995, saw no signal, no signs of proton decay—but along the way the researchers found that the supposedly mundane neutrino background was not so easy to understand. One such experiment, Kamiokande, was located in Kamioka, Japan, a mining town about 250 kilometers (155 miles) from Tokyo (as the neutrino



SUPER-KAMIOKANDE DETECTOR resides in an active zinc mine inside Mount Ikenoyama. Its stainless-steel tank contains 50,000 tons of ultrapure water, so transparent that light can pass through nearly 70 meters before losing half its intensity (for a typical swimming pool the figure is a few meters). The water is monitored by 11,000 photomultiplier tubes that cover the walls, floor and ceiling. Each tube is a handblown, evacuated glass bulb half a meter in diameter, coated on the inside with a thin layer of alkali metal. The photomultiplier tubes register conical flashes of Cherenkov light, which signal each rare collision of a high-energy neutrino with an atomic nucleus in the water. Technicians in inflatable rafts clean the bulbs while the tank is being filled (*inset*).

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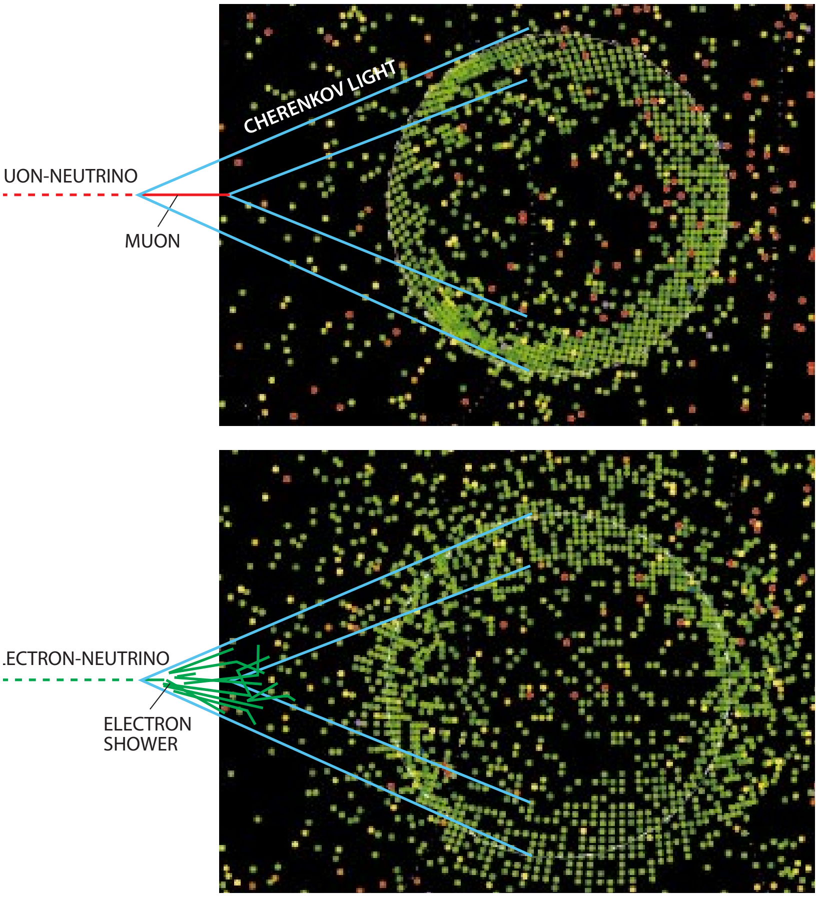

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CONES OF CHERENKOV LIGHT are emitted when high-energy neutrinos hit a nucleus and produce a charged particle. A muon-neutrino (*top*) creates a muon, which travels perhaps one meter and projects a sharp ring of light onto the detectors. An electron, produced by an electron-neutrino (*bottom*), generates a small shower of electrons and positrons, each with its own Cherenkov cone, resulting in a fuzzy ring of light. Green dots indicate light detected in the same narrow time interval.

flies). The name stood for "Kamioka Nucleon Decay Experiment." Scientists there and at the IMB experiment, located in a salt mine near Cleveland, Ohio, used sensitive detectors to peer into ultrapure water, waiting for the telltale flash of a proton decaying.

Such an event would have been hidden, like a needle in a small haystack, among about 1,000 similar flashes caused by neutrinos interacting with the water's atomic nuclei. Although no proton decay was seen, the analysis of those 1,000 reactions uncovered a real treasure—tantalizing evidence that the neutrinos were unexpectedly fickle, changing from one species to another in midflight. If true, that phenomenon was just as exciting and theory-bending as proton decay.

Neutrinos are amazing, ghostly particles. Every second, 60 billion of them, mostly from the sun, pass through each square centimeter of your body (and of everything else). But because they seldom interact with other particles, generally all 60 billion go through you without so much as nudging a single atom. In fact, you could send a beam of such neutrinos through a light-year of lead, and most of them would emerge totally unscathed at the far end. A detector as large as Kamiokande catches only a tiny fraction of the neutrinos that pass through it every year.

Neutrinos come in three flavors, corresponding to their three charged partners in the Standard Model: the electron and its heavier relatives, the muon and the tau particle. An electron-neutrino interacting with an atomic nucleus can produce an electron; a muon-neutrino makes a muon; a tau-neutrino, a tau. For most of the seven decades since neutrinos were first posited, physicists have assumed that they are massless. But if they can change from one flavor to another, quantum theory indicates that they most likely have mass. And in that case, these ethereal particles could collectively outweigh all the stars in the universe.

Building a Bigger Neutrino Trap

As is so often the case in particle physics, the way to make progress is to build a bigger machine. Super-Kamiokande, or Super-K for short, took the basic design of Kamiokande and scaled it up by about a factor of 10 [*see illustration on page 64*]. An array of light-sensitive detectors looks in toward the center of 50,000 tons of water whose protons may decay or get struck by a neutrino. In either case, the reaction creates particles that are spotted by means of a flash of blue light known as Cherenkov light, an optical analogue of a sonic boom, discovered by Pavel A. Cherenkov in 1934. Much as an aircraft flying faster than the speed of sound produces a shock wave of sound, an electrically charged particle (such as an electron or muon) emits Cherenkov light when it exceeds the speed of light in the medium in which it is moving. This motion does not violate Einstein's theory of relativity, for which the crucial velocity is *c*, the speed of light in a vacuum. In water, light propagates 25 percent slower than *c*, but other highly energetic particles can still travel almost as fast as *c* itself. Cherenkov light is emitted in a cone along the flight path of such particles.

In Super-K, the charged particle generally travels just a few meters and the Cherenkov cone projects a ring of light onto the wall of photon detectors [*see illustration on this page*]. The size, shape and intensity of this ring reveal the properties of the charged particle, which in turn tell us about the neutrino that produced it. We can easily distinguish the Cherenkov patterns of electrons from those of muons: the electrons generate a shower of particles, leading to a fuzzy ring quite unlike the crisper circle from a muon. From the Cherenkov light we also measure the energy and direction of the electron or muon, which are decent approximations to those of the neutrino.

Super-K cannot easily identify the third type of neutrino, the tau-neutrino. Such a neutrino can only interact with a nucleus and make a tau particle if it has enough energy. A muon is about 200 times as heavy as an electron; the tau about 3,500 times. The muon mass is well within the range of atmospheric neutrinos, but only a tiny fraction are at tau energies, so most tau-neutrinos in the mix will pass through Super-K undetected.

One of the most basic questions experimenters ask is, "How many?" We have built a beautiful detector to study neutrinos, and the first task is simply to count how many we see. Hand in hand with this measurement is the question, "How many did we expect?" To answer that, we must analyze how the neutrinos are produced.

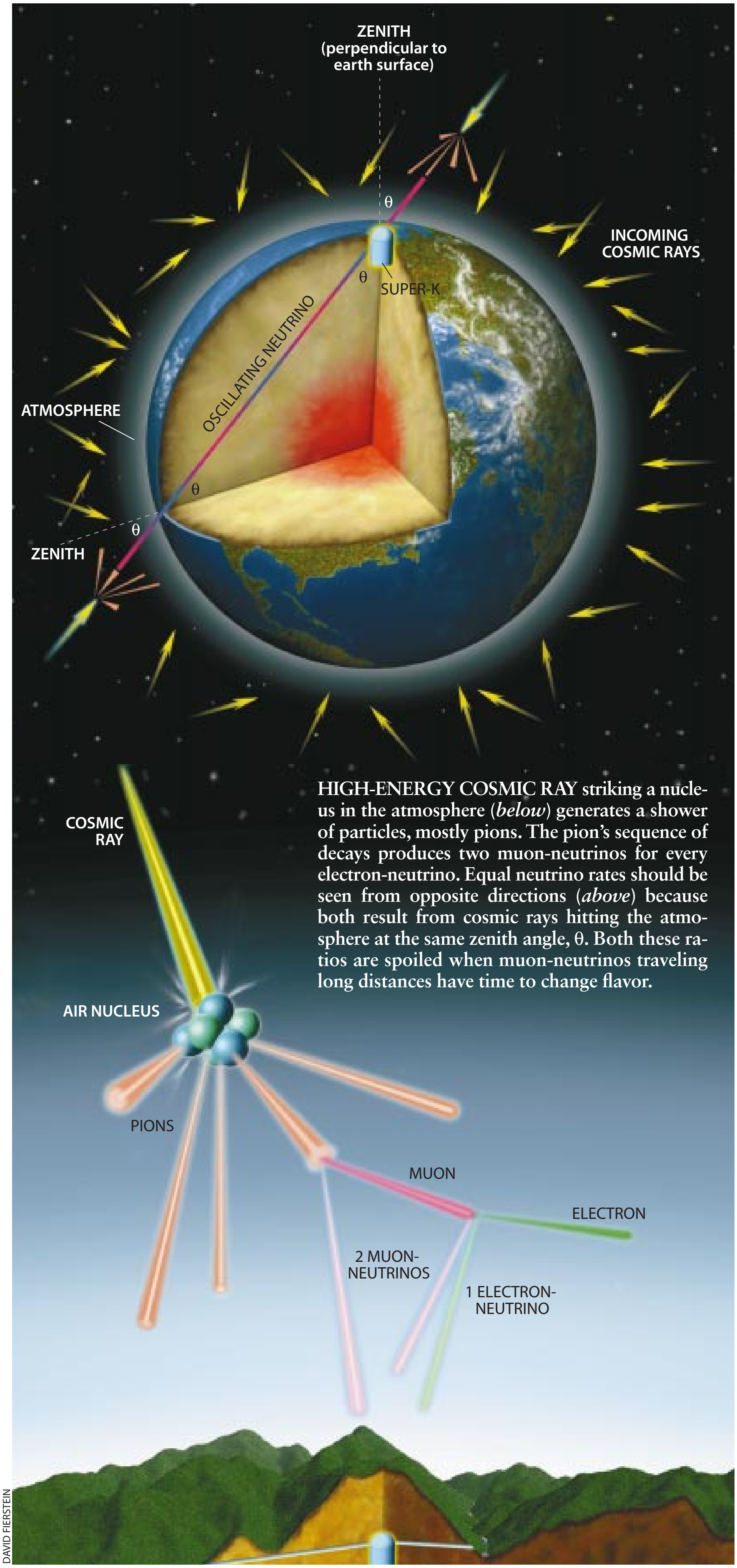
Super-K monitors atmospheric neutrinos, which are born in the spray of particles when a cosmic ray strikes the top of our atmosphere. The incoming projectiles (called primary cosmic rays) are mostly protons, with a sprinkling of heavier nuclei such as helium or iron. Each collision generates a shower of secondary particles, mostly pions and muons, which decay during their short flight through the air, creating neutrinos [*see illustration at right*]. We know roughly how many cosmic rays hit the atmosphere each second and roughly how many pions and muons are made in each collision, so we can predict how many neutrinos to expect.

Tricks with Ratios

Unfortunately, this estimate is only accurate to 25 percent, so we take advantage of a common trick: often the ratio of two quantities can be better determined than either quantity alone. For Super-K, the key is the sequential decay of a pion to a muon and a muon-neutrino, followed by the muon's decay to an electron, an electron-neutrino and another muon-neutrino. No matter how many cosmic rays are falling on the earth's atmosphere, or how many pions they produce, there should be about two muon-neutrinos for every electron-neutrino. The calculation is more complicated than that and involves computer simulations of the cosmic ray showers, but the final predicted ratio is accurate to 5 percent, providing a much better benchmark than the individual numbers of particles do.

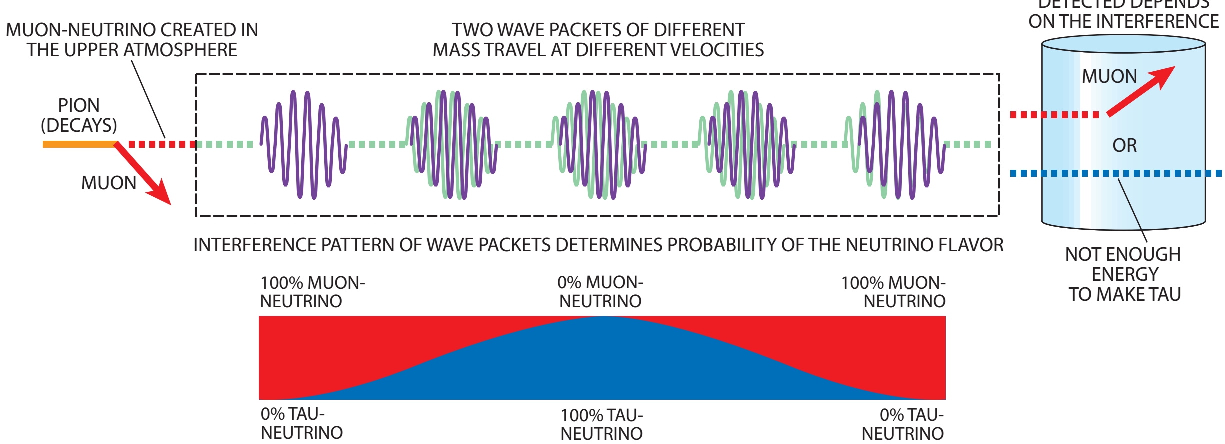
After counting neutrinos for almost two years, the Super-K team has found that the ratio of muon-neutrinos to electron-neutrinos is about 1.3 to 1 instead of the expected 2 to 1. Even if we stretch our assumptions about the flux of neutrinos, how they interact with the nuclei and how our detector responds to these events, we cannot explain such a low ratio—unless neutrinos are changing from one type into another.

We can play the ratio trick again to



HIGH-ENERGY COSMIC RAY striking a nucleus in the atmosphere (*below*) generates a shower of particles, mostly pions. The pion's sequence of decays produces two muon-neutrinos for every electron-neutrino. Equal neutrino rates should be seen from opposite directions (*above*) because both result from cosmic rays hitting the atmosphere at the same zenith angle, θ. Both these ratios are spoiled when muon-neutrinos traveling long distances have time to change flavor.

How Quantum Waves Make a Neutrino Oscillate



When a pion decays (*top left*), it produces a neutrino. Described quantum-mechanically, the neutrino is apparently a superposition of two wave packets of different mass (*purple* and *green; top middle*). The wave packets propagate at different speeds, with the lighter wave packet getting ahead of the heavier one. As this proceeds, the waves interfere, and the interference pattern controls what flavor neutrino—muon (*red*) or tau (*blue*)—one is most likely to detect at any point along the flight path (*bottom*). Like all quantum effects, this is a game of chance, with the chances heavily favoring a muon-neutrino close to where it was produced. But the probabilities oscillate back and forth, favoring the tau-neutrino at just the right distance and returning to favor the muon-neutrino farther on. When the neutrino finally interacts in the detector (*top right*), the quantum dice are rolled. If the outcome is muon-neutrino, a muon is produced. If chance favors the tau-neutrino, and the neutrino does not have enough energy to create a tau particle, Super-K detects nothing. —*E.K., T.K. and Y.T.*

LAURIE GRACE

test this surprising conclusion. The clue to our second ratio is to ask how many neutrinos should arrive from each possible direction. Primary cosmic rays fall on the earth's atmosphere almost equally from all directions, with only two effects spoiling the uniformity. First, the earth's magnetic field deflects some cosmic rays, especially the low-energy ones, skewing the pattern of arrival directions. Second, cosmic rays that skim the earth at a tangent make showers that do not descend deep into the atmosphere, and these can develop differently from those that plunge straight in from above.

But geometry saves us: if we "look" up into the sky at some angle from the vertical and then down into the ground at the same angle, we should "see" the same number of neutrinos coming from each direction. Both sets of neutrinos are produced by cosmic rays hitting the atmosphere at the same angle; it is just that in one case the collisions happen overhead and in the other they are partway around the world [*see illustration on preceding page*]. To use this fact, we select neutrino events of sufficiently high energy (so their parent cosmic ray was not deflected by the earth's magnetic field) and then divide the number of neutrinos going up by the number going down. This ratio should be exactly 1 if no neutrinos are changing flavor.

We saw essentially equal numbers of high-energy electron-neutrinos going up and down, as expected, but only half as many upward muon-neutrinos as downward ones. This finding is the second indication that neutrinos are changing identity. Moreover, it provides a clue to the nature of the metamorphosis. The upward muon-neutrinos cannot be turning into electron-neutrinos, because there is no excess of upward electron-neutrinos. That leaves the tau-neutrino. The muon-neutrinos that become tau-neutrinos pass through Super-K without interaction, without detection.

Fickle Flavor

The above two ratios are good evidence that muon-neutrinos are transforming into tau-neutrinos, but why should neutrinos switch flavor at all? Quantum physics describes a particle moving through space by a wave: in addition to properties such as mass and charge, the particle has a wavelength, it

1930 Wolfgang Pauli rescues conservation of energy by hypothesizing an unseen particle

1933 Enrico Fermi formulates the theory of beta-decay incorporating Pauli's particle,

1956 Frederick Reines (*center*) and Clyde Cowen first detect the neutrino using the Savannah

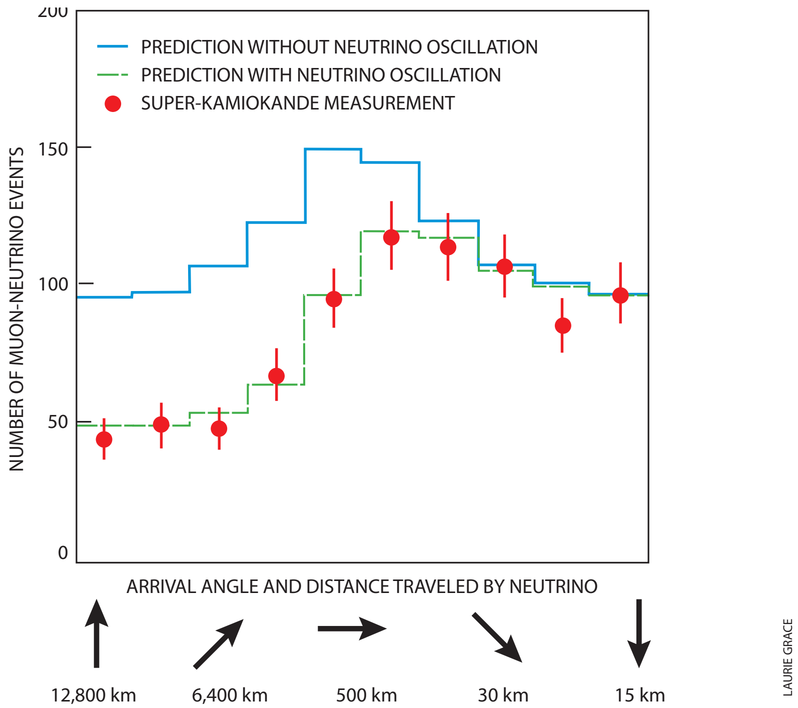
1962 At Brookhaven, the first accelerator beam of neutrinos proves the distinction

1969 Raymond Davis, Jr., first measures neutrinos from the sun, using 600 tons of can diffract, and so on. Furthermore, a particle can be the superposition of two waves. Now suppose that the two waves correspond to slightly different masses. Then, as the waves travel along, the lighter wave gets ahead of the heavier one, and the waves interfere in a way that fluctuates along the particle's trajectory [*see box on opposite page*]. This interference has a musical analogue: the beats that occur when two notes are almost but not exactly the same.

In music this effect makes the volume oscillate; in quantum physics it is the probability of detecting one type of neutrino or another that oscillates. At the outset the neutrino appears as a muon-neutrino with a probability of 100 percent. After traveling a certain distance, it looks like a tau-neutrino with 100 percent probability. At other positions, it could be either a muon-neutrino or a tau-neutrino, depending on the roll of the dice.

This oscillation sounds like bizarre behavior for a particle, but another familiar particle performs similar contortions: the photon, the particle of light. Light can occur in a variety of polarizations, including vertical, horizontal, left circular and right circular. These do not have different masses (all photons are massless), but in certain optically active materials, light with left circular polarization moves faster than right circular light. A photon with vertical polarization is actually a superposition of these two alternatives, and when it is traversing an optically active material its polarization will rotate (that is, oscillate) from vertical to horizontal and so on, as its two circular components go in and out of sync.

For neutrino oscillations of the type we see at Super-K, no "optically active" material is needed; a sufficient mass difference between the two neutrino components will cause flavor oscillations whether the neutrino is passing through air, solid rock or pure vacuum. When a



NUMBER OF HIGH-ENERGY MUON-NEUTRINOS seen arriving on different trajectories at Super-K clearly matches a prediction incorporating neutrino oscillations (*green*) and does not match the no-oscillation prediction (*blue*). Upward-going neutrinos (*plotted toward left of graph*) have traveled far enough for half of them to change flavor and escape detection.

neutrino arrives at Super-K, the amount it has oscillated depends on its energy and the distance it has traveled since it was created. For downward muon-neutrinos, which have traveled at most a few dozen kilometers, only a small fraction of an oscillation cycle has taken place, so the neutrinos' flavor is only slightly shifted, and we are nearly certain to detect their original muon-neutrino flavor [*see illustration on page 67*]. The upward muon-neutrinos, produced thousands of kilometers away, have gone through so many oscillations that on average only half of them can be detected as muon-neutrinos. The other half pass through Super-K as undetectable tau-neutrinos.

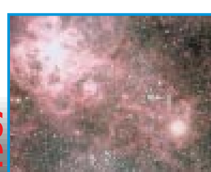
This description is just a rough picture, but the arguments based on the ratio of flavors and the up/down event rate are so compelling that neutrino oscillation is now widely accepted as the most likely explanation for our data. We also have done more detailed studies of how the number of muon-neutrinos varies according to the neutrino energy and the arrival angle. We compare the measured number against what is expected for a wide array of possible oscillation scenarios (including no oscillations). The data look quite unlike the no-oscillation expectation but match well with neutrino oscillation for certain values of the mass difference and other physical parameters [*see illustration above*].

With about 5,000 events from our first two years of running the experi-

1975–1977
The tau lepton and b quark are discovered, revealing a third generation of quarks

1983
W and Z^0 bosons are discovered at CERN: they are the carriers of the weak force, which

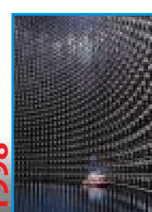
1987



Neutrino astronomy: the IMB and Kamiokande proton decay experiments detect 19 neutrinos

1989
The Z^0 decay rate is precisely measured at SLAC and CERN, showing

1998



Super-K assembles evidence of neutrino oscillation using

TIMELINE BY HEIDI NOLAND; AIP EMILIO SEGRÈ VISUAL ARCHIVES (*Pauli and Reines*); COURTESY OF THE INSTITUTE FOR ADVANCED STUDY, PRINCETON (*Davis*); DAVID MALIN *Anglo-Australian Observatory (SN1987A)*; ICRR (*Super-Kamiokande*) ment, we have eliminated any speculation that the anomalous numbers of atmospheric neutrinos could be just a statistical fluke. But it is still important to confirm the effect by looking for the same muon-neutrino oscillation with other experiments or techniques. Different detectors in Minnesota and Italy have provided some verification, but with fewer events measured they do not have the same statistical certainty.

Corroborating Evidence

Further corroboration comes from studies of a different variety of atmospheric neutrino interaction: their collisions with nuclei in the rock around our detector. Electron-neutrinos again produce electrons and subsequent showers of particles, but these are absorbed in the rock and never reach Super-K's cavern. High-energy muon-neutrinos make high-energy muons, which can travel through many meters of rock and enter our detector. We count such muons from upward-traveling neutrinos—downward muons are masked by the background of cosmic-ray muons that penetrate Mount Ikenoyama from above.

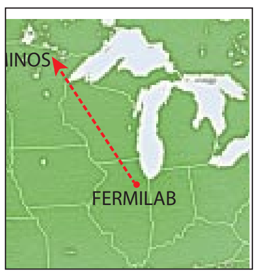
We can count upward-traveling muons arriving on trajectories that range from directly up to nearly horizontal. These paths correspond to neutrino travel distances (from production in the atmosphere to the creation of a muon near Super-K) as short as 500 kilometers (the distance to the edge of the atmosphere when looking horizontally) and as long as 13,000 kilometers (the diameter of the earth, looking straight down). We find that the numbers of muon-neutrinos of lower energy that travel a long distance are more depleted than higher-energy muon-neutrinos that travel a short distance. This behavior is just what we expect from oscillations, and careful analysis produces neutrino parameters similar to those from our first study.

If we consider just the three known neutrinos, our data tell us that muon-neutrinos are changing into tau-neutrinos. Quantum theory says that the underlying cause of the oscillation is almost certainly that these neutrinos have mass—although it has been assumed for 70 years that they do not. (The box on the opposite page mentions some other scenarios.)

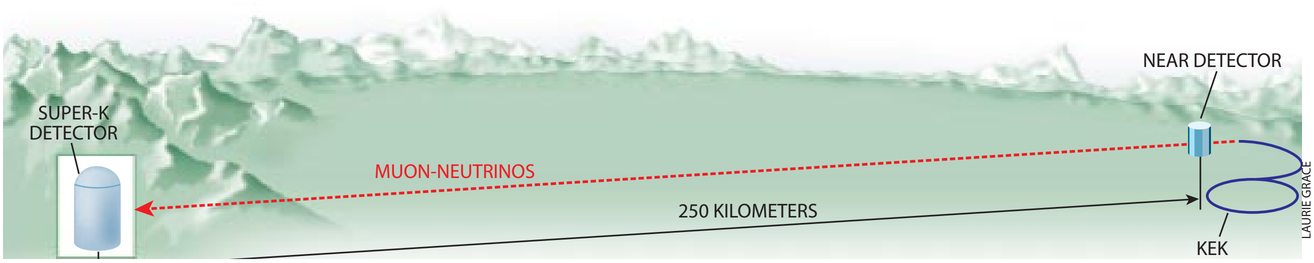
Unfortunately, quantum theory also limits our experiment to measuring only the difference in mass-squared between the two neutrino components, because that is what determines the oscillation wavelength. It is not sensitive to the mass of either one alone. Super-K's data give a mass-squared difference somewhere between 0.001 and 0.01 electron volt (eV) squared. Given the pattern of masses of other known particles, it is likely that one neutrino is much lighter than the other, which would mean that the mass of the heavier neutrino is in the range of 0.03 to 0.1 eV. What are the implications of this result?

First, giving neutrinos a mass does not wreck the Standard Model. The mismatch between the mass states that make up each neutrino requires the introduction of a set of so-called mixing parameters. A small amount of such mixing has long been observed among quarks, but our data imply that neutrinos need a much greater degree of mixing—an important piece of information that any successful new theory must accommodate.

Second, 0.05 eV is still very close to zero, compared with the masses of the other particles of matter. (The lightest of those is the electron, with a mass of 511,000 eV.) So the long-held belief that neutrinos had exactly zero mass is understandable. But theoreticians who wish to build a Grand Unified Theory, which would elegantly combine all the forces except gravity at enormously high energies, also take note of this relative lightness of neutrinos. They often employ a mathematical device called the seesaw mechanism that actually predicts that such a small but nonzero neutrino mass is very natural. Here the mass of some very heavy particle, perhaps at the Grand Unified mass scale, provides the leverage to separate the very light neutrinos from the quarks and leptons that are a billion to a trillion times heavier.



LONG-BASELINE neutrino oscillation experiments are planned in Japan and the U.S. Beams of neutrinos from accelerators will be detected hundreds of kilometers away. The experiments should confirm the oscillation phenomenon and precisely measure the constants of nature that control it.



Another implication is that the neutrino mass should now be considered in the bookkeeping of the mass of the universe. For some time, astronomers have been trying to tabulate how much mass is found in luminous matter, such as stars, and in ordinary matter that is difficult to see, such as brown dwarfs or diffuse gas. The total mass can also be measured indirectly from the orbital motion of galaxies and the rate of expansion of the universe. The direct accounting falls short of these indirect measures by about a factor of 20. The neutrino mass suggested by our result is too small to resolve this mystery by itself. Nevertheless, neutrinos created during the big bang permeate space and could account for a mass nearly equal to the combined mass of all the stars. They could have affected the formation of large astronomical structures, such as galaxy clusters.

Finally, our data have an immediate implication for two experiments that are soon to commence. Based on the earlier hints from smaller detectors, many physicists have decided to stop relying on the free but uncontrollable neutrinos from cosmic rays and instead are creating them with high-energy accelerators. Even so, the neutrinos must travel a long distance for the oscillation effect to be observed. So the neutrino beams are aimed at a detector hundreds of kilometers away. One such detector is being built in a mine in Soudan, Minn., optimized to study neutrinos sent from the Fermilab accelerator near Batavia, Ill., 730 kilometers away on the outskirts of Chicago.

Of course, a good atmospheric neutrino detector is also a good accelerator neutrino detector, so in Japan we are using Super-K to monitor a beam of neutrinos created at the KEK accelerator laboratory 250 kilometers away. Unlike atmospheric neutrinos, the beam can be turned on and off and has a well-defined energy and direction. Most important, we have placed a detector similar to Super-K near the origin of the beam to characterize the muon-neutrinos before they oscillate. Effectively, we are using the ratio (again) of the counts near the source to those far away to cancel uncertainty and verify the effect. As this article is being printed, neutrinos in the first long-distance artificial neutrino beam are passing under the mountains of Japan, with 50,000 tons of Super-K capturing a small handful. Exactly how many it captures will be the next chapter in this story.

Other Puzzles, Other Possibilities

There are other indications of neutrino mass that particle physicists are trying to sort out. For more than 30 years, scientists have been capturing some of the electron-neutrinos that are generated by nuclear fusion processes in the sun. These experiments have always counted fewer neutrinos than the best models of the sun predict [see "The Solar-Neutrino Problem," by John N. Bahcall; SCIENTIFIC AMERICAN, May 1990].

Super-K has also counted these solar neutrinos, finding only about 50 percent of what is expected. We are studying these data, hoping to find a clear signature of neutrino oscillations. In May the Sudbury Neutrino Observatory in Ontario detected its first neutrinos. It uses 1,000 tons of heavy water, which greatly enhances solar neutrino detection. Other new detectors will start up soon.

An experiment performed at Los Alamos National Laboratory provides a further hint of neutrino oscillation: it detects electron-neutrinos from a source that should produce only muon-neutrinos. The signal is mixed, however, with background processes. The result has not yet been independently confirmed, but some experiments will check it in the next few years.

Mass-induced oscillations between muon- and tau-neutrinos seem the most natural explanation for the Super-K neutrino data, but there are other possibilities. First, the most general scenario has mixing between all three neutrino flavors, and Super-K's data can accommodate some oscillations between electron- and muon-neutrinos at the energies it covers. Yet results from an experiment at the Chooz nuclear power station in Ardennes, France, greatly limit how much electron-muon oscillation could be occurring at Super-K.

Another possibility is that the muon-neutrinos are oscillating to a previously unseen flavor of neutrino. Still, studies of the so-called Z^0 particle at CERN, the European laboratory for particle physics near Geneva, clearly show that there are only three active flavors of neutrino. ("Active" means that the flavor participates in the weak nuclear interaction.) A new flavor would therefore have to be "sterile," a species of neutrino that interacts only through gravity. Some physicists favor this idea, because current evidence for three distinct effects (solar neutrinos, atmospheric neutrinos and the Los Alamos data) cannot be accounted for by one consistent set of masses for the electron-, muon- and tau-neutrinos.

Other oscillation mechanisms, relying on more esoteric effects than neutrino mass, have also been proposed. *—E.K., T.K. and Y.T.*

The Authors

EDWARD KEARNS, TAKAAKI KAJITA and YOJI TOTSUKA are members of the Super-Kamiokande Collaboration. Kearns, a professor of physics at Boston University, and Kajita, a professor of physics at the University of Tokyo, lead the analysis team that studies proton decay and atmospheric neutrinos in the Super-K data. Totsuka is spokesman for the Super-K Collaboration and is director of the Institute for Cosmic Ray Research at the University of Tokyo, the host institution for the experiment.

Further Reading

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THE ELUSIVE NEUTRINO: A SUBATOMIC DETECTIVE STORY. Nickolas Solomey. Scientific American Library, W. H. Freeman and Company, 1997.

The Official Super-Kamiokande Web site is available at www-sk.icrr.u-tokyo.ac.jp/doc/sk/

The K2K Long Baseline Neutrino Oscillation Experiment Web site is available at neutrino.kek.jp/

The Super-Kamiokande at Boston University Web site is available at hep.bu.edu/~superk/index.html