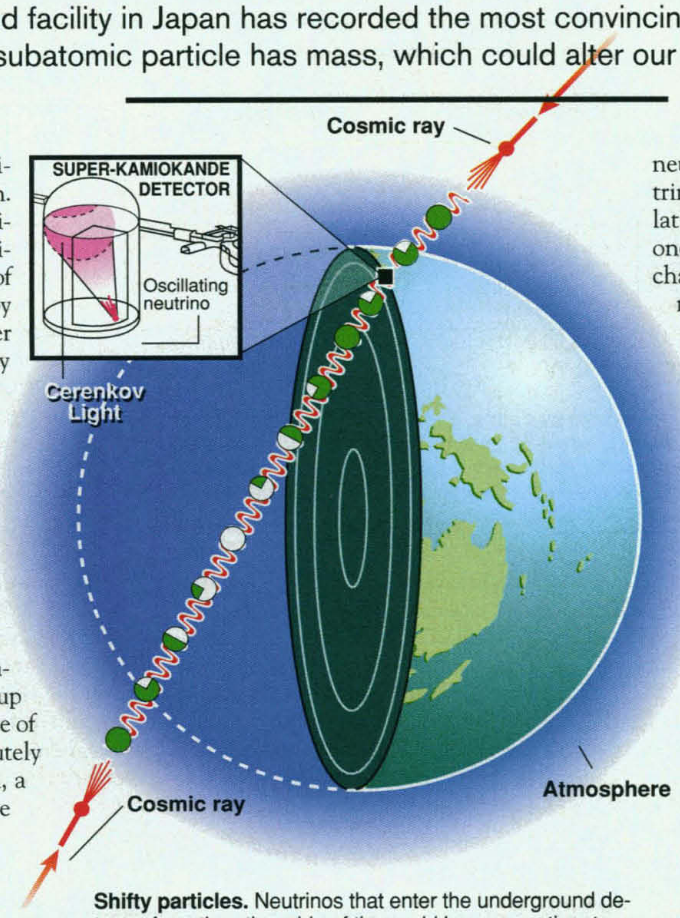
Weighing In on Neutrino Mass

An underground facility in Japan has recorded the most convincing evidence yet that this ephemeral subatomic particle has mass, which could alter our view of the universe



Shifty particles. Neutrinos that enter the underground detector from the other side of the world have more time to oscillate to another flavor than those coming straight down.

TAKAYAMA, JAPAN—Neutrinos are in the headlines—again. Every few years, a group of physicists announces preliminary evidence that, contrary to decades of theoretical prejudice, this wispy particle may have mass. Other physicists react to the news by scrutinizing the data or trying to replicate the experiment. As doubts set in, neutrino mass goes back to being no more than a tantalizing possibility.

But to many observers, last week's announcement by a Japanese–U.S. collaboration looks like the real thing. Their giant detector beneath a mountain in central Japan, they said, had picked up strong, albeit indirect, evidence of neutrino mass. "I'm absolutely convinced," says John Bahcall, a neutrino expert at the Institute for Advanced Study in Princeton, New Jersey. Theorist Wick Haxton of the University of Washington, Seattle, calls the results "incredibly impressive" and an example of "perfect physics."

Their faith rests largely on the size and sensitivity of the group's $100 million detector, Super-Kamiokande, operated by a collaboration of 120 physicists from 23 institutions headed by the University of Tokyo's Institute for Cosmic Ray Research (ICRR). Its 50,000-ton water tank and 13,000 photomultiplier tubes allow it to collect enough data to provide strong evidence that a certain type of neutrino from the atmosphere is "disappearing" by changing, or oscillating, into another type of neutrino the detector can't see. That can only happen if the particle has at least a trace of mass.

The actual mass of the neutrino has yet to be determined and is likely to be a minute fraction of the mass of the electron. But there is nothing lightweight about the implications of the findings, presented at a conference last week that brought some 350 neutrino experts from 24 countries to this small town just 50 kilometers down the road from Super-Kamiokande.

"It is one of the most important discoveries in particle physics of the last few decades," says Sheldon Glashow, a theorist at Harvard University. It will force a revision in the Standard Model, the established theory of particles and forces that has served as the basis of modern physics, which assumes a massless neutrino. The results also may affect calculations of the total mass of the universe, with implications for understanding its origin and eventual fate.

The evidence for mass is the latest twist in the strange saga of the neutrino, a particle posited in 1930 by the Austrian physicist Wolfgang Pauli. Created in staggering numbers by the big bang and by the nuclear processes driving the sun and stars, the chargeless neutrinos flow through matter like sunlight through glass. As a result, the detectors do not record neutrinos directly. Rather, they capture charged particles formed in the aftermath of rare neutrino interactions with a nucleus or proton. But even after investigators allow for the inefficiency of their detectors, they often find fewer neutrinos than theorists predict.

The problem first arose with neutrinos from the sun. Because detectors can see only one or two of the three neutrino types, or flavors (electron, muon, and tau), this solar neutrino deficit led to speculation that neutrinos were changing back and forth, or oscillating, from a flavor the detector could see to one it could not. The laws of quantum mechanics require oscillating particles to have mass. And a neutrino with mass would not conform to the Standard Model.

The whiff of possible new physics was irresistible. Dozens of experiments examined neutrinos from the sun, from the upper atmosphere, and from nuclear reactors and particle accelerators. Many of these experiments reported evidence for neutrino mass, but most of the claims fared poorly. Some were retracted, others disproven, and still others ignored. One currently controversial claim comes from the LSND experiment at Los Alamos National Laboratory in New Mexico, which reported that neutrinos generated by an accelerator were oscillating on their way to a detector a few meters away (*Science*, 10 May 1996, p. 812). The LSND results cannot be checked against the Super-Kamiokande results, however, because the two experiments are looking for different types of oscillations. And many other experiments simply yielded data samples too small to rise above statistical uncertainties.

Super-Kamiokande, which opened in 1996, was designed to overcome these limitations. Sitting in a cavern in a working zinc mine 1000 meters beneath the surface to screen out background radiation, the detector holds nearly 20 times the volume of highly purified water as its predecessor, built in the early 1980s, and has a daily detection rate some 100 times greater. The charged particles resulting from neutrino interactions in the water generate a flash of light known as Cerenkov radiation, and analyzing the pattern of the light signals can yield the energy and direction of the incoming neutrino and identify it as a muon or electron neutrino.

Although Super-Kamiokande is also gathering data on solar neutrinos, its claim of neutrino mass comes from data on atmospheric neutrinos, which result from cosmic rays bombarding Earth's upper atmosphere. At present, scientists know only to a rough approximation how many cosmic rays hit the atmosphere at any given time. But because the process through which cosmic rays produce the different flavors of neutrinos is well understood, the ratio of muon to electron neutrinos generated in the atmosphere can be predicted with confidence. The ratio detected by Super-Kamiokande and several other experiments, however, differs from these predictions.

The difference, known as the atmospheric neutrino anomaly, suggests that one or both of the neutrinos are oscillating and thus changing the ratio. But Super-Kamiokande can go a step further by tracking the direction of the incoming neutrinos. In particular, the Super-Kamiokande team compared neutrinos coming down from the sky with those coming upward through Earth. Because the cosmic rays and their resulting neutrinos rain down equally from all directions, the ratio should be 1. But if oscillation can occur, the neutrinos coming the 13,000 kilometers from Earth's far side have more time to oscillate than the neutrinos traveling only 20 kilometers down from above.

For electron neutrinos, Super-Kamiokande caught equal numbers going up and coming down. But for muon neutrinos there was a big difference. In 535 days of operations, Super-Kamiokande counted 256 downward muon neutrinos and just 139 upward ones. The large number of observed neutrinos and the magnitude of the difference reduces the chances of the finding being a statistical fluke, say team members. Taken together, the data indicate that the muon neutrinos are oscillating, perhaps to tau neutrinos, which the detector cannot pick up. "From these data we conclude that we have strong evidence for muon neutrino oscillations," says Takaaki Kajita, an ICRR physicist who presented the Super-Kamiokande results.

Despite the awe that greeted the presentation—Bahcall called it "one of the most thrilling moments of my life"—the results were anything but surprising. "We have been releasing data all along," says Henry Sobel, a University of California, Irvine, physicist who heads the American side of the collaboration. "And we started seeing [evidence of oscillation] from the first data set." Late this spring, the group decided that the latest data had put them over the top. "Everyone was convinced we had done everything possible to find artifacts or misunderstandings," says Yoji Totsuka, ICRR director and head of the collaboration.

Now neutrino experts will begin pondering new questions. Measuring oscillations can only yield the difference between the masses of the two flavors being measured, not their absolute mass. In this case, the mass difference is about 0.07 electron volt, or about one 10-millionth of the mass of the electron. That figure serves as a lower limit for neutrino mass.

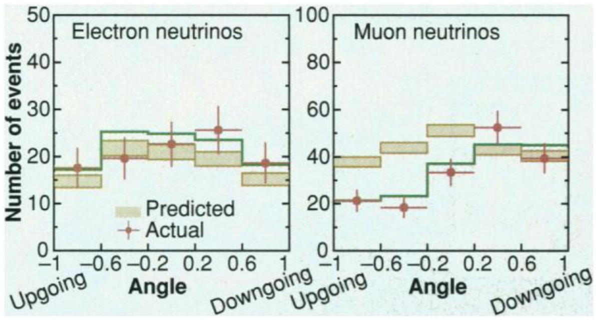
The uncertainty also leaves unresolved one fierce cosmological debate—whether neutrinos make up a significant part of the universe's dark matter, the mass theorists believe must be present for the universe to exist as we know it but which can't be accounted for by the observable stars and planets. John Learned, a Super-Kamiokande collaborator at the University of Hawaii, Manoa, says that the result implies that neutrinos are a significant fraction of the dark matter, but David Caldwell of the University of California, Santa Barbara, says the Super-Kamiokande evidence is irrelevant because that lower limit is "too low to be significant."

Theorists have other issues to address. Paul Langacker, a physicist at the University of Pennsylvania, says, "Standard Model theories will have to be extended" to accommodate a neutrino with mass. Others believe that the revisions could be major. Barry Barish of the California Institute of Technology in Pasadena says the massive neutrino "is the first empirical evidence providing a clue for what is beyond the Standard Model." In particular, a massive neutrino is one of the cornerstones of Grand Unified Theories, which seek to provide a unified explanation for all known particles and forces.

Experimentalists still have lots to do as well, including verifying the Super-Kamiokande results. Several groups are now readying long-baseline experiments in which a stream of neutrinos generated by an accelerator is aimed at a detector hundreds of kilometers away. Such experiments promise greater detail on oscillations by actually counting the number of neutrinos at the source, instead of relying on theory, as the atmospheric neutrino experiments do. But their range and energy levels don't fit the parameters; Harvard's Glashow gives them only a 50–50 chance of confirming the Super-Kamiokande findings.

More data will certainly be necessary to stitch the results into a consistent picture of neutrino masses. Whatever the outcome, this ephemeral particle seems likely to have a weighty impact on physics.

–Dennis Normile



Amassing evidence. The number of muon neutrinos detected coming up through Earth falls short of what theory predicts *(right)*, which suggests that they are transforming into some undetected neutrino type. Electron neutrinos follow the expected curve *(left)*.

SOURCE: SUPER-KAMIOKANDE COLLABORATION

COMBINATORIAL CHEMISTRY

The Fast Way to a Better Fuel Cell

Combinatorial chemistry—the shotgun approach to chemical discovery whereby researchers synthesize and test hundreds or thousands of different compounds simultaneously—is already revolutionizing the discovery of new drugs. Researchers are working to apply the strategy to finding hot new materials, such as catalysts, as well. But in many cases, testing hundreds or thousands of new catalysts at once can be a major obstacle. Now a team at Pennsylvania State University, University Park, and the Illinois Institute of Technology (IIT) in Chicago has found a way around this bottleneck, coming up with a method for quickly selecting the better catalysts for everything from fuel cells to batteries.

The technique, which signals the presence of an effective catalyst with a fluorescent glow, has already yielded a concrete result, as the researchers, led by Penn State chemist Tom Mallouk and IIT chemical engineer Eugene Smotkin, report on page 1735. They used it to discover a new catalyst for converting methanol to electricity in fuel cells—devices that are being hotly pursued by companies around the world as a clean alternative to combustion engines. The catalyst isn't ideal, Mallouk and others note: Among its ingredients are osmium—potentially toxic—and iridium, which is prohibitively expensive, along with platinum and ruthenium. Nevertheless, its discovery shows that in the search for better catalysts, the brute strength of combinatorial chemistry "is definitely worth pursuing," says Tom Fuller, a methanol fuel-cell expert at International Fuel Cells in South Windsor, Connecticut.

Current fuel-cell catalysts consist of an equal mix of platinum and ruthenium, which, with the help of a small electrical voltage, break down methanol into carbon dioxide, protons, and electrons. The electrons are routed through a wire to power a car or do other work and are eventually channeled to another electrode in the cell, where they meet up with the mobile protons. But these catalysts are inefficient, wasting about 25% of the energy stored in the fuel as heat instead of converting it to electricity. Researchers have searched for years to find an improved mixture of metals. Most of these efforts have concentrated on various mixtures of two metals or occasionally three, but few have tried four or more because so many different