PHYSICS

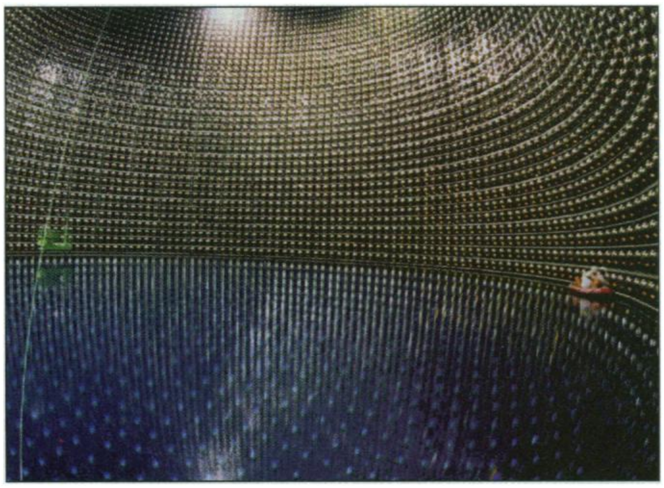
Neutrinos Throw Their Weight Around

The discovery that these ghostly particles have a trace of mass raises startling possibilities about the universe on the smallest and largest scales

From the beginning, neutrino physics has been a slow-motion drama. Wolfgang Pauli reluctantly postulated the elusive particles in 1930, but it was another 25 years before the late Frederick Reines and his colleague Clyde Cowan succeeded in detecting one. And the crucial question of whether these tiny particles have a small mass, or no mass at all, has endured for half a century. "Neutrino mass has been discovered about four times," says Oxford University physicist Donald Perkins, "and undiscovered about twice."

This summer, however, the plot took a decisive twist when physicists working with the giant Super-Kamiokande detector in Japan announced that they had seen solid evidence for neutrino mass: There were too few muon neutrinos streaming in from the upper atmosphere, presumably because they were switching to a different, undetectable kind. The switching, and the way it varied depending on the path from the upper atmosphere to the detector, was a trick only neutrinos with a tiny allotment of mass could pull off (*Science*, 12 June, p. 1689). The Super-Kamiokande data are "quite convincing," says Perkins. "For the first time," agrees Harvard University physicist Sanjib Mishra, "one of these flimsy [pieces of evidence] has become extremely compelling." And now comes the second act: working out what this trace of mass could mean for how the universe is put together on the very largest and smallest scales.

Theorists are speculating, for example, about how the gravitational pull of swarms of neutrinos might have gently sculpted the distribution of galaxies in the early universe. They are also puzzling over the peculiar fact that neutrinos are so light, which may hint at the existence of unseen, heavier particles that could help sew up some holes in the so-called Standard Model—physicists' current picture of subatomic particles and how they interact. And they are worrying about how to reconcile the Super-Kamiokande result with the weaker hints of mass from other experiments—a picture, say some, that could only be made consistent by assuming the existence of another neutrino, even more ghostlike than known neutrino types. The papers are appearing at a pace rarely seen in the slow-moving world of neutrino physics. "I can't even keep up with them all," says Edward Kearns, a Boston University physicist and Super-Kamiokande collaborator.



Neutrino weigh station. The Super-Kamiokande detector, where an occasional neutrino triggers a flash detected by an array of photomultipliers.

INSTITUTE FOR COSMIC RAY RESEARCH, THE UNIVERSITY OF TOKYO

The unreasonable lightness of neutrinos

The Standard Model, it is sometimes said, predicts that neutrinos should weigh exactly nothing. But that was purely to save ink, says Lincoln Wolfenstein, a physicist at Carnegie Mellon University. "We knew the mass was very small," he says, noting that experiments would have revealed a sizable electron neutrino mass decades ago. "And zero is a very nice small number. That's really the level at which it was done." It's easy to expand the Standard Model's equations to embrace the neutrino's newfound heft, but that doesn't explain the deeper questions. "The real mystery is why neutrinos are so light" compared to other particles, says physicist Paul Langacker of the University of Pennsylvania, Philadelphia. "That's what I'm dying to know."

Super-Kamiokande's measurement pins down only the difference in mass between two neutrino types and so indicates only that one of them must have a mass of at least 0.07 electron volts, less than a millionth of the puny electron's mass. But earlier experiments had set an upper limit, showing that the electron neutrino, for instance, must have a mass less than 1/30,000 of the electron's.

Despite years of contemplation, physicists have come up with only one good way to explain why neutrinos should have a mass so close to zero. The idea, called the "seesaw mechanism," requires the existence of an elusive superheavy neutrino, sometimes called the "N" particle. Without this particle, the three ordinary neutrinos (the electron, muon, and tau neutrinos) would be massless. But the N, if present, could mingle with them and, in a sense, share a bit of its mass. Mathematically, the heavyweight leverages the three neutrinos out of masslessness as on a seesaw. The heavier the fourth neutrino, the lighter the three everyday ones.

Some physicists see this hint of a superheavy neutrino as the first step to a long-sought grand unified theory (GUT) that would unite all the forces and particles in a single framework. (Current theories have yet to yoke the strong nuclear force to the electromagnetic force and the weak force responsible for radioactive decays.) The unification plans inevitably invoke heavy particles to pull everything together.

"It's fantastically exciting," says Pierre Ramond, a theorist at the University of Florida, Gainesville. "This is the first time in 20 years that we've had something beyond the Standard Model." Others are less willing to let light neutrinos catapult them so far into the unknown. "It's a beautiful idea," says Mishra, "but the predictions are about as accurate as the military's bookkeeping. ... Which is to say, poor."

The seesaw has a number of fearless advocates, however. "It fits like a glove," says Frank Wilczek, a theorist at the Institute for Advanced Study in Princeton, New Jersey. Wilczek champions a particular GUT that goes by the name of SO(10). In this framework, the heavy neutrino appears naturally and gives light neutrino masses in line with the data from Super-Kamiokande, he says. "All the ugly ducklings turn into beautiful swans."

Others complain that SO(10) introduces some ugly ducklings of its own. In its simplest form, SO(10) predicts over 100 weighty new particles. "You get a ridiculous number of particles," says physicist Joseph Lykken of Fermi National Accelerator Laboratory in Batavia, Illinois. Although these heavy particles would have been seen routinely only in the first superhot instants after the big bang, they would pop up at awkward moments even today. In particular, under the uncertainty principle of quantum mechanics, one could momentarily appear at any time and catalyze the decay of the normally stable proton. Super-Kamiokande and other experiments have looked for the telltale flash of light that would signal a proton's demise in their underground tanks of water but have seen nothing. Wilczek is undaunted: "It would be churlish not to take [neutrino mass] as a hint that these wild ideas are right on track."

One puzzle, too many pieces

The superheavy neutrino isn't the only strange guest that the discovery of neutrino mass is introducing to physics. Physicists are also toying with an additional lightweight neutrino, inspired by what may be a conflict between the Super-Kamiokande results and other, weaker hints of neutrino mass. These come from two other kinds of experiments—one looking at neutrinos from the sun and another studying neutrinos generated by particle accelerators. Both kinds of experiments, like Super-Kamiokande, look for signs that neutrinos experience a periodic identity crisis and transform back and forth from one type to another as they travel.

The shifting can happen because neutrinos as we observe them are actually mixtures of quantum mechanical waves—musical chords, in effect—in which each wave corresponds to a different neutrino type. Mass differences between the neutrino types result in wavelength differences, so the notes in the chord beat against each other. The result is that the identity of the observed neutrino can switch back and forth, in time with the beating. Thus the frequency of this "oscillation," and hence the probability of observing an identity switch at a particular point, depends in part on the mass difference between neutrino types.

Because there are three kinds of neutrinos, it's only possible to form two independent differences. Unfortunately, the data from solar, atmospheric, and accelerator neutrinos together point to three mass differences. "I think nearly everyone agrees we can't explain all three experiments," says Wolfenstein. Either one experiment is wrong, or something very strange indeed is going on.

Many physicists say that of the three, the accelerator-based work by the LSND collaboration at Los Alamos National Laboratory in New Mexico is the most vulnerable. LSND watches for muon antineutrinos to switch to electron antineutrinos. By 1996 the team had captured what looked like 20 or so such events. More recently, however, a similar experiment, Karmen in England, looked but saw no evidence for such a transition. The Karmen team now claims to have largely ruled out the possibility that LSND has seen oscillations. "[Karmen] sees no hint at all," says Langacker. But many observers interviewed by *Science* felt that Karmen's limited data did not support such strong conclusions. "I think the jury is still out," says Harvard's Mishra.

"The LSND issue is pivotal," says George Fuller of the University of California, San Diego. If the result holds up, he and others say, it points somewhere no one wants to go—to the existence of an extra, lightweight "sterile" neutrino. "There's no alternative," Fuller says. Some of the neutrinos from the sun or the upper atmosphere could then transform into sterile neutrinos, so called because they essentially never interact with matter. With that extra outlet, all the data could be accommodated. "I think we'd best tread lightly in that direction," Fuller cautions. "This is a totally made-up particle." And it's one that could never be detected.

A PARTIAL MENU OF NEUTRINO MASS EXPERIMENTS

Name	Location	Date
Long-Baseline*		
Minos	Fermilab, U.S.	2002
K2K	KEK, Japan	1999
Noe, AquaRich, Opera, Nice	CERN, Switzerland, and Gran Sasso, Italy	proposed
Solar†		
SNO	Ontario, Canada	1998
Icarus, Borexino, GNO	Gran Sasso	under construction
Homestake	South Dakota	running
SAGE	Baksan, Russia	running
Atmospheric‡		
Soudan 2	Minnesota	running
Super-Kamiokande	Japan	running
Short-Baseline§		
Nomad, Chorus	CERN	running
Karmen	ISIS, England	running
LSND	Los Alamos, U.S.	running
Boone	Fermilab	approved
Tosca, I-216	CERN	proposed

* High-energy neutrinos produced by accelerators 100+ kilometers away. † Low-energy neutrinos produced ~100 million km away. ‡ High-energy neutrinos produced ~30 km away. § Moderate-energy neutrinos traveling <1 km.

Cosmic ovens

Sterile neutrinos might, however, act as an unseen hand shaping the abundance of heavy elements in the cosmos. Some astrophysicists speculate they may be necessary to explain how the stellar explosions called supernovae can cook up heavy nuclei in the observed quantities. "It works extremely well," says Baha Balantekin, a physicist at the University of Wisconsin, Madison, who studies supernovae. "It's almost too convenient."

A supernova begins as a heavy star that runs out of fuel and collapses under its own weight. The enormous pressure is thought to force neutrons to join up with existing atoms and forge heavy elements such as gold. At the same time, a shock wave spawned by the collapse heats the material, creating a storm of neutrinos in the star's core. The neutrinos flee and carry away almost 99% of the energy of the explosion, says Balantekin. On their way out, however, some of the electron neutrinos would convert neutrons to protons and stall the formation of heavy elements. But if these neutrinos can oscillate into sterile neutrinos, models of the element-forming process more easily produce the observed abundances. He cautions, though, that the models are still too uncertain to make definite predictions.

One way out of some of these theoretical quagmires would be to get a firmer idea of exactly how massive ordinary neutrinos are. A raft of current or planned experiments should sharpen the picture of neutrino mass (see table). And Joel Primack, a physicist at the University of California, Santa Cruz, suggests an astrophysical gauge. He points out that because massive neutrinos would exert a gravitational tug, they should leave their imprint on the density and arrangement of galaxies. By charting galaxy clusters and the cosmic voids in between, the Sloan Digital Sky survey—a mapping effort that will take in a region more than a billion light-years across—may be able to roughly discern the average mass of the neutrinos. Their effect on cosmic structure would be small, however, because other kinds of invisible matter are also thought to have sculpted the universe.

A nearby supernova explosion could also yield clues to the mass, in the timing of the neutrino burst that would likely be picked up in Super-Kamiokande and other detectors. If neutrinos have mass, it should slow them down. Ejected at a variety of speeds from the supernova, the neutrinos would spread out as they crossed the galaxy, arriving over a period of time rather than in a single burst. But because such explosions only happen a few times a century, physicists will again have to be patient to learn new facts about the neutrino.

–DAVID KESTENBAUM