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Although deep underground in an active nickel mine, workers build the detector for Canada's Sudbury (Ottawa) Neutrino Observatory to cleanliness standards that allow less than a gram of dust on the detector's interior surfaces.

A Little Mass Goes a Long Way

Fresh evidence for neutrino mass may open a new frontier in physics

By PETER WEISS

Aging particle physicists can relive the 1960s without squeezing into old bell-bottoms or blaring dusty Jimi Hendrix albums. Who needs mass protests to feel alive when neutrino mass may be sparking an upheaval in particle physics unlike anything seen since the Vietnam War era?

Until last year, the possibility that the wispy neutrino—a barely detectable subatomic particle—has some substance was considered intriguing but speculative. The standard model of physics, which accounts for elementary particles and the forces that act between them, holds that neutrinos have no mass. Evidence of neutrino mass would pose the first real challenge to the model, which has existed in roughly its current form since the late 1970s.

For the past 2 decades, particle physicists have occupied themselves mostly with minor repairs to the standard model. That's been a far cry from the ferment of earlier years, when new particle accelerators spawned a zoo of exotic particles that theorists scrambled to explain.

Then in June 1998, the prospects for neutrino mass changed. Researchers from the Super-Kamiokande neutrino detector in Kamioka, Japan, unveiled two years of data that carried a striking message. Many neutrinos produced by high-energy particle collisions in Earth's upper atmosphere were failing to appear at the detector a thousand meters underground (SN: 6/13/98, p. 374). The most likely explanation, physicists say, is that muon neutrinos, the type produced on high, were changing into tau neutrinos, which the detector can't pick up. For neutrinos to make such transformations, or oscillations, they must, by the rules of quantum mechanics, have mass.

The idea of neutrino oscillations first surfaced in the late 1950s, a brainstorm of theorist Bruno Pontecorvo. Also, experiments dating back decades have found evidence of the phenomenon. For the first time, however, the Super-Kamiokande group had gathered enough measurements with enough precision to make most physicists sit up and take notice. Now, their colleagues say that the discovery of neutrino mass may open a new frontier for physics, the way Sputnik did for space exploration.

"It's as though we are now back in the '60s, in the period before the standard model, when the experiments were giving hints to what direction the theory should go," says Carl H. Albright of Northern Illinois University in DeKalb and the Fermi National Accelerator Laboratory in Batavia, Ill.

"This is a good time to be alive if you are a neutrino experimenter," says John N. Bahcall of the Institute for Advanced Study in Princeton, N.J. "There are things out there to be measured that will change the way we look at physics."

Knowing the heft of neutrinos may help scientists account for the cosmological dark matter, invisible material thought to constitute a large fraction of the mass of the universe (SN: 1/16/99, p. 38). It may also help astrophysicists solve the riddles of how uranium and other heavy elements originated in stellar explosions called supernovas and why the universe has more matter than antimatter.

More fundamentally, recent findings hint at some "new physics," the scientists say. The results suggest the possibility of new types of subatomic particles, such as a superheavy neutrino and a neutrino so ghostlike and unable to interact with other matter that physicists describe it as "sterile."

Eventually, by weighing neutrinos, physicists may also gain their first experimental toehold on one of the central questions of modern physics that continually frustrated Albert Einstein and remains unanswered: Do the basic forces in nature originate from a single fundamental superforce?

"It's felt that there must be some simpler, more elegant underlying theory that explains everything," says theorist Paul G. Langacker of the University of Pennsylvania in Philadelphia. "The time wasn't ripe for Einstein, but it may be ripe now."

Catching a whiff of these possibilities, theorists have published articles about neutrinos at a frenzied pace during the past 7 months. Experimentalists have been rushing ahead with planned experiments and dreaming up new ones.

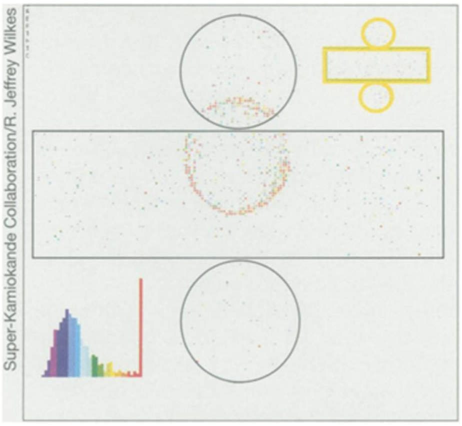
By summer, Canada's Sudbury (Ontario) Neutrino Observatory (SNO) is expected to finish the process begun last September of filling the detector tank with heavy water, which contains deuterium instead of hydrogen. Researchers will then start recording neutrinos from the sun.

In Japan, an experiment known as K2K was slated to fire up its neutrino beam for the first time this week. The acronym stands for KEK-to-Kamioka, because neutrinos generated at Japan's High Energy Accelerator Research Organization (KEK) in Tsukuba will zip unimpeded through earth and rock before reaching the Super-Kamiokande detector 250 kilometers away.

This week, neutrino experts from around the world were to meet in South Africa to review experimental progress and to discuss other aspects of the neutrino-mass hunt. The enterprise of pursuing neutrino mass has grown so large and diverse that Maury Goodman of Argonne (Ill.) National Laboratory, an experimentalist and author of a monthly Internet newsletter about the various efforts, refers to them collectively as the "neutrino oscillation industry."

In the standard model of physics, neutrinos come in three flavors: electron neutrino, muon neutrino, and tau neutrino. They all lack mass and charge, and they scarcely ever interact with other matter. Some 300 of these particles, remnants of the Big Bang, course through every cubic centimeter of space at any moment. Others pour out of the sun as products of nuclear fusion, and some come from human-made nuclear fission reactors. Some rain down on Earth when ultrahigh-energy protons, known as cosmic rays, smash into atoms in our planet's upper atmosphere.

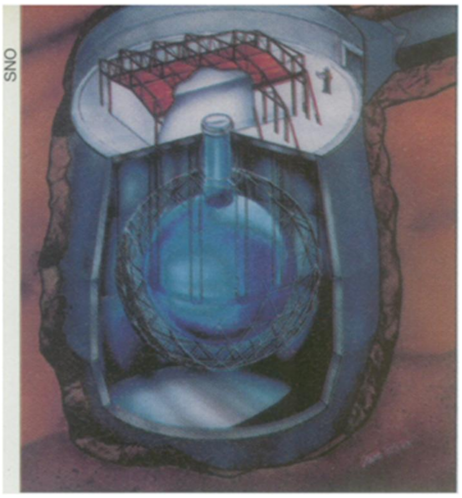
Neutrino observers use large underground detectors—a liquid-filled tank surrounded by photodetectors, for instance, or a stack of charged metal plates—to measure the light or current produced by reactions between neutrinos and detector materials.


Super-Kamiokande Collaboration/R. Jeffrey Wilkes

A circular light flash is detected on the inner wall of the Super-Kamiokande neutrino detector after a muon neutrino plows into an atom's nucleus in a 40-meter-deep underground tank of water. This display represents the detector as a flattened cylinder, with each photomultiplier tube on the wall as a dot.

For more than 30 years, theorists have proposed that neutrinos of different flavors might be able to metamorphose into each other. Counts of solar and atmospheric neutrinos have for decades revealed shortfalls from theoretical expectations, indicating experimentally that neutrino oscillations might be taking place and that neutrinos might have mass.

Until now, those investigations have taken place in their own special niche, but the Super-Kamiokande detector has pushed the neutrino onto a larger stage. Before last June, "only 5 to 10 percent of the particle-physics community was really intimately aware of what was going on with the neutrinos," Langacker says. The Super-Kamiokande results "convinced the other 90 percent that this is for real and it's worthy of being taken seriously."


SNO

Kilometers of rock shield the Sudbury Neutrino Observatory from unwanted radiation. The neutrino detector, the blue bottle surrounded by a geodesic sphere, is suspended in a 10-story cavern.

More curious than ever about every little nuance of neutrinos, researchers demand firmer evidence that the particles oscillate. The scientists also want answers to a host of questions: How many neutrino types are there after all? What is the mass of each? Which oscillates into which, how often, and why?

Both theory and experiment so far suggest that any neutrino masses would be so peculiarly small as to be far out of line with the masses of all other forms of matter. Physicists again ask: Why?

Shadowy answers have emerged from the experimental data—at least to the question of how massive each of the neutrino flavors is—and physicists are struggling to make sense out of them. It all depends on which experiments the researchers consider. Knowing neutrino energies and the distances they travel, physicists can roughly gauge the differences in mass between oscillating flavors.

A now discontinued project known as the Liquid Scintillator Neutrino Detector (LSND) experiment at Los Alamos (N.M.) National Laboratory (SN: 5/18/96, p. 319) indicated a relatively large mass difference between muon and electron neutrinos. The Los Alamos researchers used an accelerator to fire neutrinos into a tank of mineral oil, finding that muon neutrinos changed into electron neutrinos en route. The mass-difference estimate they came up with was about 1 electron volt. (Physicists habitually use the electron volt, an energy unit, to describe particle mass. In so doing, they rely on the equivalence of mass and energy established by Einstein.)

However, solar and atmospheric experiments indicate mass differences among neutrinos incompatible with the LSND findings. Enter the sterile neutrino. "You really need four neutrinos to explain such effects," Albright says. Theorists resolve the conflicting results by having electron neutrinos in the solar experiments oscillate into sterile neutrinos.

Yet, there is no direct evidence for a fourth neutrino. So, many physicists suspect the LSND results are wrong. An ongoing experiment in England called the Karlsruhe-Rutherford Medium-Energy Neutrino Experiment, or KARMEN, has tried unsuccessfully so far to reproduce them.

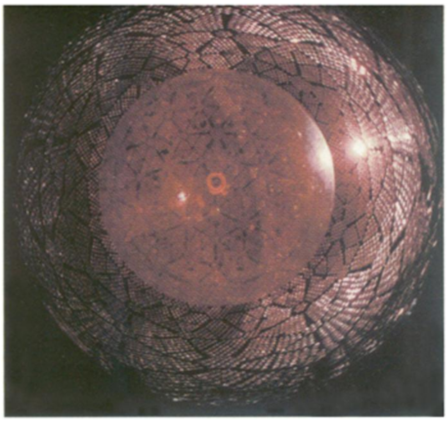
Postulating a new, lightweight particle so evanescent that it can't be detected rubs some physicists the wrong way. "It's not the most elegant and attractive hypothesis you can invent. In fact, it's rather ugly," Bahcall says.

Many scientists believe that neutrino mass will be in the same size range as the estimated differences. At the weightiest figure, 1 eV from LSND, these extraordinarily plentiful particles could make up a significant chunk of the presumed dark matter in the universe. If neutrinos prove to have lower mass, they would still likely contribute to the dark matter but not in a decisive way, researchers say.

Beyond details of which particle has how much mass, physicists also hope to determine what theoretical mechanism causes neutrinos to have mass at all. Experimental results such as Super-Kamiokande "open things wide to theoretical speculation as to what could be causing these mass differences," says theorist William J. Marciano of Brookhaven National Laboratory in Upton, N.Y.

For now, speculation centers on another possible new type of particle: superheavy neutrinos. In equations that relate these postulated heavyweights to the known neutrinos, the mass of ordinary neutrinos becomes lower if the mass of their superheavy partners is made higher. Physicists describe the link as a quantum-mechanical "see-saw."

The physics community itches for answers to neutrino questions, and experimenters are moving ahead on many fronts to find them. Many scien-



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An acrylic sphere 12 meters across hangs inside a shell of photomultiplier tubes in Canada's Sudbury (Ottawa) Neutrino Observatory. Shown empty, the sphere will hold 1,000 tons of heavy water. When neutrinos hit the water, buried more than two kilometers deep, the tubes will detect faint flashes.

tists see Canada's SNO as the best bet for quick proof of neutrino oscillations.

The great promise of SNO lies in its detector's unique use of deuterium, an isotope of hydrogen with an extra neutron, which reacts with neutrinos in two ways. One reaction takes place only with electron neutrinos, the sole type that the sun emits. The other occurs equally for all three neutrino flavors. Comparison of the rates of the two reactions should allow scientists to know with unprecedented certainty whether electron neutrinos are transforming into muon or tau neutrinos.

Escaping the vagaries of using natural neutrino sources, K2K is the first of a new generation of accelerator-based experiments. These so-called long-baseline experiments will fire neutrinos hundreds of kilometers to verify independently the Super-Kamiokande results. Fermilab is building a detector, and physicists have proposed another similar experiment for Europe. The neutrino flight paths of each would extend about three times the distance of K2K. Because these experiments use accelerators to make their neutrinos, researchers expect to gain much greater control over what is headed for their detectors.

Aside from SNO and long-baseline projects, many other experiments of various types are expected to contribute pieces to the puzzle. Some researchers use nuclear reactors to fire neutrinos over relatively short distances. Others are studying the decay of neutrons, which release the antimatter partners of neutrinos, to more deeply probe the nature of neutrinos.

Data from astronomical observations may also shed some light. Two upcoming satellite studies of the cosmic background radiation could yield evidence for or against a fourth neutrino's existence. Also, a recently inaugurated telescope survey of the distribution of galaxies in space could provide a new estimate of neutrino mass. "It looks like astronomers will actually be able to say something about neutrino physics," says Subir Sarkar of the University of Oxford in England.

With so many voices expected to chime in during the next few years, Albright predicts a rapid denouement to the hunt for neutrino mass. "We'll have the mystery pretty much unraveled in a 5-to-7-year period," he predicts.

Langacker senses that neutrino oscillations may be the first step toward an even bigger prize, a theory of everything, which could unite all the forces in the universe, including gravity, in a single framework—perhaps within the next 20 years.

"We will have the new ideas, the new probes, the neutrino masses, and the new accelerators," he says. "It's a very, very exciting time for understanding nature at the most fundamental level." The promise of his utopian vision hints that more than just the uncertainty of the '60s is back. ☐

Biology

Night life discovered for bumblebees

Bumblebees, supposedly your basic daylight travelers, can navigate outside their nests in the dark, researchers have accidentally discovered.

One night last year, someone left on an infrared monitoring system in a bumblebee colony in the darkened lab of James D. Thomson at the State University of New York at Stony Brook. The next morning, researchers were startled to realize that the bees had slipped out of their nest to visit a feeding station after hours.

Bees must be able to get around in the dark since they live in underground nests, Thomson points out. Yet researchers know little about the dark side of navigation.

Outdoors, some bees will fly in bright moonlight, but they don't buzz over the landscape in pitch blackness. The lab bees didn't fly, either. They walked.

Subsequent studies of their late-night hikes suggest they use odor and perhaps some kind of magnetic compass, report Lars Chittka of the University of Würzburg in Germany, Thomson, and their colleagues. The analysis appears in the Jan. 7 Proceedings of the Royal Society of London B.

Bees respond to scents once they reach a flower, but previous studies had not turned up evidence that scent guided foragers. The researchers let bees troop out to the feeder, then removed it and reoriented the surface they walked on. In the next forays, bees headed in the wrong direction, as if still following the scent trails laid down on earlier treks.

When researchers cleaned the surface, the bees headed in the compass direction of the feeder's original location. Other research has suggested that honeybees and a few other arthropods have internal magnetic compasses, but this evidence is new for bumblebees.

In another novel finding, the lab bees going out to forage showed two rush-hour peaks: one in full light at midday and one in the dark at midnight. *—S.M.*

Do parasites explain female promiscuity?

An experiment with bumblebees provides the most direct evidence yet for a theory explaining why females of so many species go to the trouble of mating with more than one male.

Such behavior has puzzled biologists because of "the obvious costs of time, energy, and exposure to predation," as Boris Baer and Paul Schmid-Hempel put it in the Jan. 14 Nature. The researchers, from ETH Zurich in Switzerland, point out that some social insects "carry this behavior to extremes." Virgin honeybee queens mate with 10 to 20 males during a once-in-a-lifetime round of midair sex.

Female insects can give birth to broods with multiple fathers, and theorists have proposed that boosting the genetic diversity of a brood should make the colony better able to withstand parasites.

Baer and Schmid-Hempel artificially inseminated bumblebee queens with either low- or high-diversity sperm. The colonies that the queens founded foraged outdoors, where workers encounter all sorts of menaces. The seven high-diversity colonies ended up with fewer parasites and greater reproductive success, on average, than the low-diversity colonies.

William D. Hamilton of the University of Oxford in England, one of the theorists who proposed the parasite idea, greeted the work warmly. Besides helping explain the forces behind insect orgies, he says, the paper may also help resolve another mystery, "perhaps the very greatest of the subject—that of why sexual reproduction so often prevails over its obviously far more efficient alternative, female-female parthenogenesis."

Would female animals be more likely just to give birth without male input if it weren't for the risks of parasites? The new study, Hamilton muses, "reflects on a lot that we all care about—on love, for example, and all its troubles, and on all the rest of the wonderful, yet confusing, patterns that sex creates." *—S.M.*