Beam Me Up to the New Physics!

Laboratories around the world plan to send beams of neutrinos on journeys to distant detectors in an effort to find out whether these elusive particles have mass

Neutrinos are easy to dismiss as a useless accident of creation. Copiously produced in the sun and other stars but nearly indifferent to the forces of nature, these ghostly particles drift through the earth with almost no effect on the world of ordinary matter. But physicists can't afford to overlook these reclusive particles. They may, for example, exist without consequence in the universe, or they may control its fate, putting the brakes on infinite expansion through their collective gravitational power. It all depends on one question: What is the neutrino's mass? So far, physicists can't tell. After years of trying to measure it, largely by studying the debris from radioactive decays, they have been able to conclude only that if neutrinos have any mass, it is vanishingly small.

But the stakes here are too large for physical scientists to give up. Finding a mass for the neutrino would not only help answer the biggest questions of cosmology, it would also provide a clue to physics beyond the well-worn picture of matter and forces known as the "Standard Model"—something physicists once hoped for from the Superconducting Super Collider. Because so much is at stake, groups around the world are gearing up for a new assault on the question of neutrino mass. To increase the chance of success, the upcoming experiments are based on a new strategy: generating beams of neutrinos at existing accelerator facilities, sending them through anything from a kilometer to thousands of kilometers of solid rock, and, at the far end, capturing a tiny fraction of the neutrinos in giant detectors.

These experiments will begin over the next two years at the European Laboratory for Particle Physics (CERN), Fermilab, and Brookhaven National Laboratory. What researchers will be looking for in the data, which will take a year or more to gather, is evidence that neutrinos can switch identities among the three types (electron, muon, and tau). Evidence of identity changes, known to physicists as oscillations, would imply a mass for at least one of the neutrino types, because the rules of quantum mechanics forbid oscillations unless the two oscillating types have different masses. How often those oscillations take place could pin down that mass difference, implying at least a minimum value for the neutrino's mass. As CERN physicist Klaus Winter phrases it: "These experiments can be seen as an elegant way of weighing the neutrino."

Earlier hints that neutrinos may be capable of this shape shifting have physicists like Maury Goodman of Argonne National Laboratory saying, "I'm excited about the possibility of finding oscillations." But Goodman, the leader of one of the new experiments, cautions that many particle physicists consider the hints so far to be sketchy and speculative. "There is no guarantee that oscillations happen." And even if they do, he says, they may be too rare to detect. Still, the potential payoff is high, and the cost is small (by the lofty standards of particle physics). Speaking about his laboratory's $20-million experiment, Melvin Schwartz of Brookhaven says, "This project is not terribly expensive and it fits in a natural way into the existing program."

Mix and match

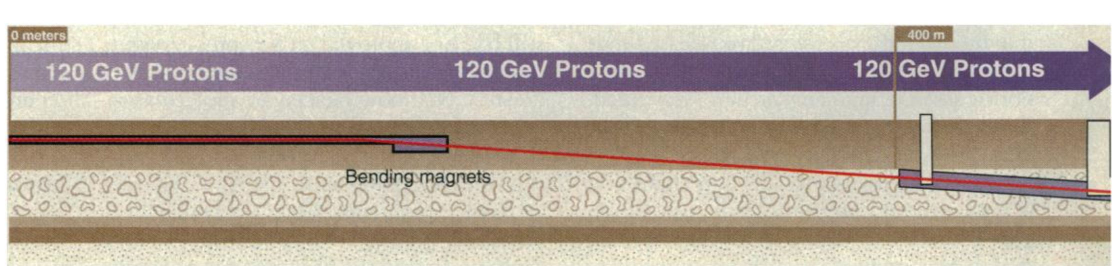
Most of the other neutrino beam experiments are similarly thrifty because they rely on existing accelerators, which generate the neutrinos by smashing protons into a target; many also exploit existing detectors, built to catch neutrinos from the sun or from cosmic rays. One is in a mine in Minnesota; physicists at Fermilab have plans to send a beam there. CERN researchers are discussing the possibility of beaming neutrinos to the detectors in Italy's Gran Sasso tunnel, and researchers at the KEK accelerator facility in Japan would like to aim neutrinos at a newly built detector called Super Kamiokande.

If the experiments using these existing detectors do catch neutrinos in the act of changing their personae, they will be confirming hints that first came from studies of the sun. The nuclear reactions at the sun's core churn out neutrinos, and in the 1960s physicists realized that because these particles interact so rarely with other matter, they can slip freely out of the sun, carrying messages about processes at its very heart. But detectors set up to capture solar neutrinos produced a puzzling result: They registered far fewer neutrinos than they should have according to the current model of the sun's inner workings. That shortage led some physicists to speculate that the electron neutrinos generated by the sun were oscillating into one of the other types, which the detector couldn't pick up.

Further hints of strange neutrino behavior came two years ago from the neutrinos created when cosmic rays bombard our atmosphere (*Science*, 25 September 1992, p. 1862). Two underground detectors, one near Cleveland, the other in Japan, detected fewer muon neutrinos than were predicted by theoretical calculations. Like the "solar neutrino problem," this shortfall hinted at oscillations—in this case from muon to tau neutrinos.

This evidence "was suggestive, but one didn't really know what to do with it," says University of Pennsylvania physicist Al Mann, because of uncertainties in models of the sun and of cosmic-ray physics. No one could conclude definitively that neutrino oscillation had been seen. Still, says Mann, "the results of these experiments have been so tantalizing that we kept trying to think of [other] experiments to do."

In order to detect oscillations definitively, the researchers needed to know exactly how many neutrinos come out of their source as well as how many show up in the detector. And that meant following up on an idea first proposed in the 1970s by the Italian physicist Bruno Pontecorvo: replacing the sun or the upper atmosphere as a neu-



A long road for neutrinos. In a scheme for directing neutrinos from Fermilab's Tevatron through the earth to an underground detector in Minnesota, high-energy protons collide with a target and give rise to unstable particles called pions and kaons, which decay to produce neutrinos. A nearby detector samples the beam *(red)*.

SOURCE: GOODMAN ILLUSTRATION: C. FABER SMITH trino source with a controlled, calibrated beam from an accelerator.

The first such efforts will begin this summer at CERN (see box) and a year later at Fermilab. The Fermilab experiment, like CERN's initial effort, will send neutrinos a relatively short distance: less than a kilometer, from the Tevatron accelerator to a specially-designed detector made of stacked photographic plates. The neutrino source will generate only muon neutrinos, according to University of Kansas physicist Bill Reay, who heads the experiment. The detector will be sensitive only to tau neutrinos, hence any taus that show up must have been produced en route by oscillations from muon to tau. But the short baseline will also limit the range of neutrino masses the experiment can detect, because theory predicts that neutrinos with lower masses take more time to oscillate.

In fact, the short span of Reay's experiment allows enough time for oscillations only if one of the neutrino types carries a mass of about 10 electron volts, which fits nicely with some—but not all—of the observational data. It's more than a hundred times the mass that is required to explain the solar and atmospheric neutrino results. But a mass in that range is exactly what would be needed to satisfy cosmologists searching for sources of invisible mass, says Reay.

The other planned neutrino beam experiments could search for neutrino masses that Reay's experiment would overlook, since they span much longer distances and could pick up the oscillations of a neutrino weighing as little as a tenth of an electron volt. Although evidence of oscillations from these experiments might explain the solar neutrino problem, their immediate target is the atmospheric neutrino problem, says Penn's Mann. He explains that physicists think the case for oscillations is more secure for atmospheric neutrinos; what's more, muon neutrinos like those from the atmosphere are easier to generate in the laboratory than electron neutrinos like those born in the sun.

Nomadic neutrinos

Scientists at Brookhaven National Laboratory plan to start the first of these longer-baseline experiments next year. The Brookhaven group, collaborating with the TRIUMF laboratory in Canada and Los Alamos National Laboratory, will send a beam of muon neutrinos about 24 kilometers from the Advanced Gradient Synchrotron across Long Island to a giant tank of water rigged to pick up the flash of light generated when an occasional neutrino tangles with a water molecule. As in the other experiments, identity-shifting will be detected by differences between source and detector. Here, however, the evidence will be indirect, rather than direct.

The Brookhaven accelerator's relatively low energy means that any tau neutrinos spawned by oscillations won't have enough energy to trigger the detector themselves; as a result, the detector can pick up only muon neutrinos. Therefore, the evidence of oscillations from muon to tau neutrinos, if any, will take the form of a shortage of muon neutrinos captured over the experiment's 4-month run. That strategy makes it especially important to know how many neutrinos are in the original beam, says Penn's Mann, the experiment's principal investigator, and so the researchers will use two additional detectors to sample the neutrino beam closer to the source—1 and 3 kilometers away, respectively. "I will know precisely what to expect in the far detector from having looked at the closer ones," says Mann.

A proposed long-range experiment at Fermilab, in contrast, would generate a beam energetic enough for any tau neutrinos to be detected directly. On the other hand, the high energy of the beam means the neutrinos wouldn't have enough time to oscillate if they travelled only a few tens of kilometers. To be sensitive to very small neutrino masses, the experiment has to unleash the neutrinos for hundreds of kilometers. Argonne's Goodman, the experiment's principal investigator, would like to aim the beam at an existing detector called Soudan II, in Minnesota, 730 kilometers away. But that long baseline raises a new problem: By the time the beam reached the detector, it would have fanned out to a width of several kilometers, and most of the neutrinos would miss the detector completely.

To have a chance of catching even a few thousand neutrinos—the minimum needed to say anything about oscillation frequency and neutrino mass—Goodman and his colleagues would have to start with a far more intense beam than the Tevatron can now generate. And that means their experiment could only be done if the Tevatron gets a boost from the proposed $230 million Main Injector, which is due to be up and running by 1998.

The long-baseline experiments proposed at CERN and KEK won't be immune to such tradeoffs, either; compromises are inevitable when you are trying to make the best of existing equipment, says Fermilab neutrino theorist Steve Parke. "Brookhaven has a lower energy accelerator, so they try to justify a lower energy experiment, while Fermilab has a higher energy beam, so they try to justify that." Which plan is best? Parke says he doesn't want to take sides. Humbled by the loss of the Super Collider, he and many of his fellow physicists now hesitate to criticize any proposed experiment, even their competitors', if it promises a way out of the impasse in which their field is, for the moment, trapped.

–Faye Flam

ECOLOGY

Is Marine Biodiversity At Risk?

In the early 1970s, marine biologist Kerry Clark of the Florida Institute of Technology discovered a new species of sea slug in sea grasses in the Indian River lagoon on the Atlantic coast of Florida. Sea slugs are small, graceful creatures with brilliant coloring, and many species are rare. But at first this bright green species, which Clark named *Phyllaplysia smaragda*, the emerald sea slug, was relatively common. However, as the lagoon's shores were developed, the sea grasses shrank into the shallows and the slug's numbers dwindled. Clark hasn't seen one since 1982 and fears they're gone for good.

This tale of species found, then lost, is all too familiar to terrestrial ecologists, especially those in tropical rainforests, who have watched species vanish or hover at the edge of extinction. But it's a new story for many marine biologists. Except for large vertebrates like mammals and birds, marine organisms rarely appear on lists of extinct and endangered species. Indeed, although the fossil record is full of such extinctions, marine organisms were believed to be resistant to human-caused extinction, because many sea creatures have larvae that can drift long distances and most are thought to have large geographic ranges.

Now, a small but growing band of marine ecologists is sounding the alarm. The resilience of marine species may have been overestimated, they say, and human modifications of coastal environments, along with overfishing, may threaten marine biodiversity. These researchers are taking a new look at the question of extinctions in the sea, and some conclude that such extinctions may be common—but overlooked. "There's a perception of fewer extinctions in the ocean and I'm not sure the perception is right," says James Carlton, director of maritime studies at Williams College and Mystic Seaport (a program of marine studies in Mystic, Connecticut). Furthermore, ecologists argue, even if oceanic species are being lost more slowly than those on land, the marine environment operates differently. Other signs of decline, such as the shrinking percentage of coral cover seen on some reefs, may be more relevant indicators of deterioration in marine ecosystems.

Still, studies of marine biodiversity are in their infancy, and many biologists remain skeptical about marine extinctions. The