US and Japan Plan to Create Cross-Country Neutrino Beams

Deep inside the Kamioka zinc mine, in the mountains west of Tokyo, the just-completed Super Kamiokande proton-decay and neutrino detector is now being filled with 50 000 tons of highly purified water. (Fifty thousand tons is the displacement of a large battleship.) Super Kamiokande is a Japan–US collaboration. In a few months this newest, and largest by far, of the water-Čerenkov detectors will be recording neutrinos from the Sun and from collisions of cosmic rays in the atmosphere. It will also be keeping its 11 200 photomultiplier eyes peeled for neutrino bursts from distant supernova explosions and for evidence that one of the detector's 10^{34} nucleons has decayed. (See the photograph on this page).

Neutrino beams running hundreds of kilometers through the Earth, from accelerator to detector, would provide sensitive tests of neutrino flavor oscillation.

But it was the longer-term plans for Super Kamiokande that were of particular interest to the High Energy Physics Advisory Panel's recent subpanel on accelerator-based neutrino oscillation experiments. The subpanel's report, commissioned early last year by Martha Krebs, director of the Department of Energy's Office of Energy Research, was submitted to her in October with HEPAP's blessing. Krebs had asked that HEPAP advise her office "on the optimal planning of accelerator-based neutrino oscillation experiments in a [US] national program."

The most ambitious of the proposed neutrino-oscillation experiments, in the US and abroad, involve "long baseline" neutrino beams that would travel through the Earth from a high-energy proton accelerator to a massive neutrino detector far away. The two principal long-baseline proposals in the US were from Brookhaven (for a 68-km beam) and Fermilab (for a 740-km beam). Neutrinos interact so weakly that the fraction scattered en route through the Earth would be negligible. By the end of 1998, before any such facility in the US or Europe would be ready, the Super Kamiokande collaboration hopes to begin taking data with a neutrino beam directed at Super Kamiokande from the old 12-GeV KEK proton synchrotron in Tsukuba, 250 km away. So an important issue that the HEPAP subpanel had to address was the prospect that, "under any realistic scenario," Super Kamiokande would get the first crack at the most probable neutrino oscillation parameters suggested by anomalous cosmic-ray data in recent years. (See PHYSICS TODAY, October 1994, page 22.)

The atmospheric anomaly

Neutrinos come in three varieties, associated respectively with the three charged leptons—the electron, the muon and the tau. Since the late 1980s various underground-neutrino-detector groups have been reporting a shortfall in the ratio of muon neutrinos (ν_μ and $\bar{\nu}_\mu$) to electron neutrinos (ν_e and $\bar{\nu}_e$) in atmospheric cosmic-ray showers. If this atmospheric anomaly is real, neutrino oscillation is the only explanation readily at hand. That is to say, muon neutrinos created in the decays of cosmic-ray shower particles appear to be changing into ν_e or ν_τ with a probability that varies with distance traveled.

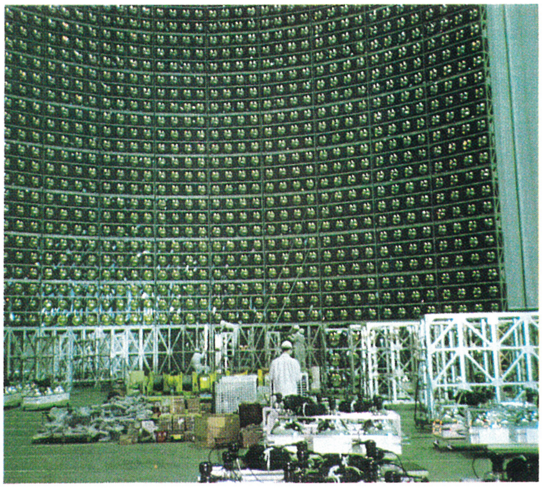
A key parameter of neutrino oscillation, if the phenomenon exists, is Δm^2, the difference between the squared masses of the two oscillating neutrino flavors. (If there is neutrino oscillation, at least one of the neutrino varieties must have a nonvanishing mass.) The most persuasive atmospheric-anomaly data (from Super Kamiokande's 3-kiloton predecessor) suggest a Δm^2 on the order of 0.01 eV^2. That is precisely the regime for which the long-baseline experiments are optimal. Accelerator neutrino beams consist almost entirely of ν_μ and $\bar{\nu}_\mu$ from meson decay, and one looks downstream for the disappearance of muon neutrinos and the appearance of other neutrino flavors.

The oscillating probability, $P(L)$, that a neutrino of one flavor and energy E (in GeV) will have some other flavor after a flight of L kilometers is given by

$$P = A \sin^2 (1.27\, \Delta m^2 L/E)$$

where A, which can range from 0 to 1, is the mixing-strength parameter between those two neutrino flavors. The smaller the Δm^2 one wants to investigate, the greater is the required distance between the neutrino source and the detector.

More than 20 years of anomalous solar-neutrino data point to a Δm^2 on the order of 10^{-5} eV^2, much too small for purely terrestrial experiments with present techniques. At the other end of the scale, a recent short-baseline accelerator experiment at the Los Alamos Meson Physics Facility found tentative evidence of $\nu_\mu \rightarrow \nu_e$ oscillation with a Δm^2 on the order of 1 eV^2. (See PHYSICS TODAY, August, page 20.) To



INSIDE SUPER KAMIOKANDE, shown here before construction was finished last fall, 11 200 photomultiplier tubes will keep watch over 50 kilotons of purified water, looking for Čerenkov light from neutrino scattering or proton decay. The world's largest Čerenkov detector, it sits deep inside a Japanese mine. Filling with water began in December. Plans call for a neutrino beam from an accelerator 250 km away to be bombarding the detector by 1998.

investigate such relatively large mass-square differences, which are of particular interest to cosmologists, one wants neutrino beam lengths on the order of one kilometer. Therefore the Fermilab and Brookhaven long-baseline proposals include secondary detectors within 1 km of the accelerator. These "near" detectors would of course also serve to normalize any signal observed by the detectors farther downstream.

One should not be put off, the theorists tell us, by the fact that the Δm^2 suggested by the atmospheric anomaly is so much larger than what the solar-neutrino shortfall requires and so much smaller than what the cosmologists and the Los Alamos experimenters want. There are, after all, three active neutrino species that could pair up differently in these different observational regimes, and some theorists also make a case for the possible participation of additional "sterile" neutrino species impervious to the conventional weak interactions.

HEPAP recommendations

Arguing that "the discovery of neutrino oscillations would constitute a major breakthrough in particle physics and the first evidence of physics beyond the mininum standard model," the HEPAP subpanel's report made several explicit recommendations. It recommended that a long-baseline neutrino oscillation experiment be funded, but only one. Thus the subpanel had to choose between the Brookhaven and Fermilab proposals.

The subpanel, chaired by Frank Sciulli of Columbia University, comprised 12 physicists, 3 of them theorists. They unanimously chose the Fermilab proposal, giving a number of reasons. The Fermilab neutrino beam, produced by the collision products of 120-GeV protons from the new main injector now under construction at the Tevatron, would have much greater energy, flux and flexibility than the neutrino beam one could produce with the AGS, Brookhaven's venerable 28-GeV proton synchrotron.

The energy spectrum of the Brookhaven neutrino beam, peaking at 1 GeV, would not reach the 3.5-GeV kinematic threshold for producing the 1.8-GeV charged tau leptons that would be the most direct evidence of the appearance of tau neutrinos. Neither would the KEK neutrino beam in Japan. The Fermilab scheme, on the other hand, provides both a high-flux, broad-band neutrino beam ranging up to 40 GeV and a narrow-band beam of tunable energy. That would let the experimenters search over a very large range of L/E when Δm^2 is unknown and then home in on the optimal beam energy if and when neutrino oscillation is discovered. Higher neutrino energies also offer the advantages of larger neutrino-interaction scattering cross sections and easier differentiation between muons and electrons.

MINOS and COSMOS

One of the attractive features of the Fermilab proposal is that it offers two distinct detector facilities—MINOS and COSMOS—with a single neutrino beam. The subpanel report recommends that both facilities be supported. MINOS would actually be a pair of fine-grained conventional neutrino detectors at the near and far ends of the beam. The 10-kiloton far detector is to be located 740 km northwest of Fermilab, in the disused Soudan iron mine in northern Minnesota that already houses a 1-kiloton atmospheric-neutrino detector. The neutrino beam, whose transverse profile is shaped by focusing and collimating the decaying mesons that produce it, would be about 500 meters wide by the time it reaches Soudan.

The far detector would be a sequence of 8-meter-wide magnetized steel plates interspersed with charged-particle tracking arrays. The near MINOS detector, essentially a small-scale replica of the far detector, would be about a kilometer from the Tevatron. The purpose of both MINOS detectors is to scatter neutrinos and record enough information about the collision products to determine the neutrino flavor.

A neutrino of a given flavor colliding with a nucleon in the detector is generally transformed into a charged lepton of the same flavor. Muon neutrinos, for example, produce muons, but never electrons or taus. Sometimes, however, the neutrino scatters without acquiring electric charge. These so-called neutral-current collisions do not depend on or reveal the flavor of the colliding neutrino, but they can serve as a valuable means of calibrating the total neutrino flux, summed over all flavors, at each detector.

The COSMOS detector, designed to share the near MINOS detector's experimental hall and beam, would be essentially a ton of photographic emulsion interspersed with a high-precision magnetic spectrometer. COSMOS is intended to look carefully for tau-lepton production. In the emulsion, a highly automated scanning system would search for a telltale kink a fraction of a millimeter from the start of a charged track. Such a kink would signal the decay of a short-lived tau to a charged pion plus one or more neutral particles. One wants the fine spatial resolution of photographic emulsion because the short-lived tau decays so quickly after its creation. With its special sensitivity for finding taus, COSMOS would be much more sensitive than MINOS alone to neutrino oscillation with a very small mixing-strength parameter and Δm^2 above 1 eV^2. It would also be more sensitive than CHORUS or NOMAD, two similar short-baseline experiments now looking for $\nu_\mu \rightarrow \nu_\tau$ oscillation with such large Δm^2 at CERN's Super Proton Synchrotron. CHORUS, which has already been running for two years, is the prototype for the COSMOS design. The 2.6-ton NOMAD detector, a more traditional array of drift chambers, calorimeters and muon detectors, seeks to identify taus purely by kinematics.

Super Kamiokande

The estimated cost of the Fermilab proposal, including the three detectors and the new neutrino beam, would be about $130 million in 1995 dollars. The proposed construction schedule, given timely funding, would have the far detector operating at about a third of its design capacity by the time the neutrino beam is ready in 2001. The detector system would then be completed while the facility is running, during the two following years.

Can one justify this effort if the Super Kamiokande long-baseline facility is likely to be taking data by 1999? The HEPAP subpanel concluded that "first exploration of the central part of the oscillation parameter space indicated by the atmospheric anomaly will likely be done by Super Kamiokande," first with atmospheric neutrinos and then with the neutrino beam from KEK. But the subpanel report argues that the Fermilab proposal makes sense whether or not the Super Kamiokande can confirm the atmospheric anomaly: "If the anomaly is confirmed as neutrino oscillation, it will be imperative to explore fully the parameter space with high precision. The much greater sensitivity of either [the Fermilab or Brookhaven proposal] would uniquely allow such measurement." If, on the other hand, neutrino oscillation has not been demonstrated before the Fermilab–Soudan facility turns on, its "large increase in parameter space . . . as well as its larger number of redundant checks . . . lead us to conclude that the [proposed] US program could provide an important and unique contribution . . . to the study of neutrino oscillations."

Apropos of the looming Japanese competition, Brookhaven's proponents had pointed out that their facility could already be taking data, with two of its four detectors, in 1999. In fact, in response to the subpanel's decision to support only the Fermilab proposal, the Brookhaven adminstration pointed out that the laboratory could mount a stripped-down long-baseline experiment even faster (and cheaper) than their original proposal by using an existing neutrino beam line that points roughly in the direction of New Haven instead of the new beam line that would have been directed at Plum Island, off the eastern end of Long Island. "But that would just be a single experiment, as distinguished from the costly, long-term research programs the subpanel was asked to consider," counters chairman Sciulli. "If you're going to spend large amounts of money, it shouldn't just be for a race that you might well lose. Fermilab–Soudan will have an order of magnitude greater sensitivity and flexibility than the KEK–Super Kamiokande scheme. The panel has opted for a facility that would have the range to explore all the possible flavor transformations thoroughly, whether or not someone else has already confirmed some variety of neutrino oscillation."

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LEP Collider Moves Beyond the Z^0

Last November, CERN's LEP collider looked at the highest-energy e^+e^- collisions yet achieved and saw no serious challenges to the standard model.

Last year, after six years of precisely mapping out the physics of Z^0-boson production and decay, CERN's Large Electron–Positron collider completed its role as the Z^0 factory called LEP 1 and began to metamorphose into LEP 2—a W^+W^- or W-pair factory. The transformation, scheduled for completion in June, involves replacing 32 of the conventional copper 1.4-megavolt/meter accelerating elements in the 27-km-circumference collider with superconducting cavities having an accelerating gradient of 6.0 MV/m.

As CERN neared the halfway point in the upgrade last November, accelerator scientists got their first glimpses of the new cavities' performance and experimenters got a chance to look at physics at the highest energies ever achieved in e^+e^- collisions. This was the first and only run of "LEP 1.5", so-called because its 130–140-GeV center-of-mass energy is midway between the thresholds of the Z^0 and W-pair production—about 91 and 161 GeV, respectively. From the point of view of accelerator physicists and experimenters, the run was an unqualified success. Even individuals not given to hyperbole were saying the machine performed nearly perfectly. The four LEP detectors—Aleph, DELPHI, L3 and Opal—also performed well.

For theorists, however, there was good news and bad news: The good news was that the preliminary results reported on 12 December at CERN[1] pose no serious challenge to the standard model of particle physics. (Aleph saw more events in one interesting topology than would be predicted given known processes. Opal saw an excess in a different topology. However, the numbers of events involved are small, and more statistics will be needed to tell whether the excesses are attributable to new physics or to statistical fluctuations.) The bad news is the obverse of the good news: There is no convincing evidence from LEP 1.5 of supersymmetric particles, of composite leptons or quarks or any other physics beyond the standard model. As the last slide of the talk given by DELPHI member Hans Dijkstra put it, "Yes, we have no anomalies."

Looking beyond

For a variety of reasons, many particle physicists had hoped LEP 1.5's intermediate energies would prove fruitful hunting grounds for physics beyond the standard model. For experimentalists, light supersymmetric particles would be more easily seen at LEP 1.5 than at the LEP-2 W-pair factory, because decays of W bosons resemble the expected decays of supersymmetric particles. On the theoretical side, various papers[2] have suggested that supersymmetry might explain why LEP 1 and the Stanford Linear Collider see slightly fewer Z^0 bosons decaying into b quarks than predicted by the standard model, provided supersymmetric particles exist with masses less than 50 GeV/c^2. Supersymmetry postulates an additional symmetry in nature, with each fundamental fermion or boson having a supersymmetric partner whose spin differs by half a unit. Theorists have found supersymmetry useful in problems ranging from grand unification to quark confinement to quantum gravity. (See PHYSICS TODAY, March 1995, page 17.) Light supersymmetric particles would decay in a distinctive manner, and LEP 1.5 should have been able to see them if they existed within its kinematical range. Theoretical calculations[3] suggest that the failure to observe any sign of supersymmetry at LEP 1.5 makes it unlikely that supersymmetry can explain the putative Z^0-decay anomalies seen at SLC and LEP 1. It does not, however, mean the end of supersymmetry.

With the end of the LEP-1.5 run, attention at LEP is now focused on the energy upgrade for next June's LEP-2 run. A primary physics goal of this run is a precise measurement of the W mass. Such a measurement would tighten the mass range predicted for the Higgs particle, which is thought to be responsible for breaking electroweak symmetry and generating the masses of fundamental particles. Other LEP-2 goals include determining the production and decay characteristics of W pairs and further refinements of the standard model. All four LEP experiments will also be actively hunting for physics beyond the standard model. The same searches will continue as LEP's center-of-mass energy moves upward—to 172 GeV in November, 188 GeV in 1997 and 192 GeV in 1998 (approved last December).

In principle LEP could handle center-of-mass energies as high as 208 GeV, but energy losses resulting from synchrotron radiation would make such an upgrade very expensive. As such, how much higher LEP's energy will climb depends to a great degree on whether future runs reveal any interesting new physics. Hope for supersymmetry springs eternal in the hearts of many theorists, and if the Higgs boson is sufficiently light, as favored by some theorists, it could also be within the range of LEP 2. According to CERN's Carlo Wyss, the 192 GeV at LEP will be sufficient to ensure the Higgs boson, if it exists, will be seen either at LEP or at CERN's proposed Large Hadron Collider, which will displace LEP from its 27-km tunnel by the year 2000. During the latter half of the next decade, the LHC is scheduled to begin colliding protons to yield 14 TeV in the center of mass. As Wyss says, "One of the strengths of CERN is that we are able to exploit the infrastructure of previous machines for new machines. Being on the same site for so long allows us to make the best use of our facilities."

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