

SOLAR NEUTRINO EXPERIMENTS: THE NEXT GENERATION

In the next few years, three massive new solar neutrino detectors will generate large amounts of precise data that should have a major impact on our understanding of how the Sun shines and how neutrinos behave. They are Super Kamiokande,¹ in the mountains west of Tokyo; the Sudbury Neutrino Observatory (SNO) in a northern Ontario mine;² and Borexino, in the Apennines east of Rome.³ Each of these detectors was conceived and is being built by a sizable international collaboration. Each is housed in an underground laboratory shielded from cosmic ray products other than neutrinos and very energetic muons by a mile or so of earth. Super Kamiokande, the most massive of the three, is a 50-kiloton water-Čerenkov detector. (See figure 1 and the cover of this issue.) In all of these new detectors, sophisticated electronics will record and analyze the individual neutrino collision events. Each detector will register more neutrino interactions in two months than all of the previous solar neutrino experiments have detected in a quarter of a century.

Why are hundreds of physicists undertaking such difficult experiments in such hostile environments, with the most elusive elementary particles we know of? Most of them are excited by the possibility of discovering the first definitive evidence that neutrinos have mass and that lepton number is not conserved. The range of putative neutrino masses a given experiment can explore depends on the energy of the neutrinos, the distance between their source and the detector, and the material the neutrinos encounter on their journey. Solar neutrinos are born in the inner core of the Sun, 10^6 km below its surface and 10^8 km from the waiting detectors. These astronomical distances and the relatively low neutrino energies (a few MeV or less) dictate that experiments with solar neutrinos are uniquely sensitive to very small neutrino masses—from about 10^{-6} to 10^{-2} electron volts.

Any clear evidence of neutrino metamorphoses indicative of nonvanishing masses would be a crucial pointer toward a more comprehensive theory beyond the brilliantly

Three big new detectors are addressing the puzzle of the persistent solar-neutrino deficit. Is it the Sun, or the neutrino, that's behaving so strangely? We may soon know for certain.

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successful, but manifestly incomplete, “standard model” of the fundamental particles.

The original motivation for doing solar neutrino experiments was quite different.⁴ The aim 30 years ago was to use the neutrinos produced by nuclear reactions between light elements in the solar core to test the theory of stellar evolution and the general presumption

that the ultimate source of the Sun's energy is nuclear fusion. Stars are believed to shine and evolve by burning their nuclear fuel deep in their interiors. From the so-called standard solar models, one can calculate the neutrino fluxes terrestrial observers should see from fusion reactions in the core of the Sun.

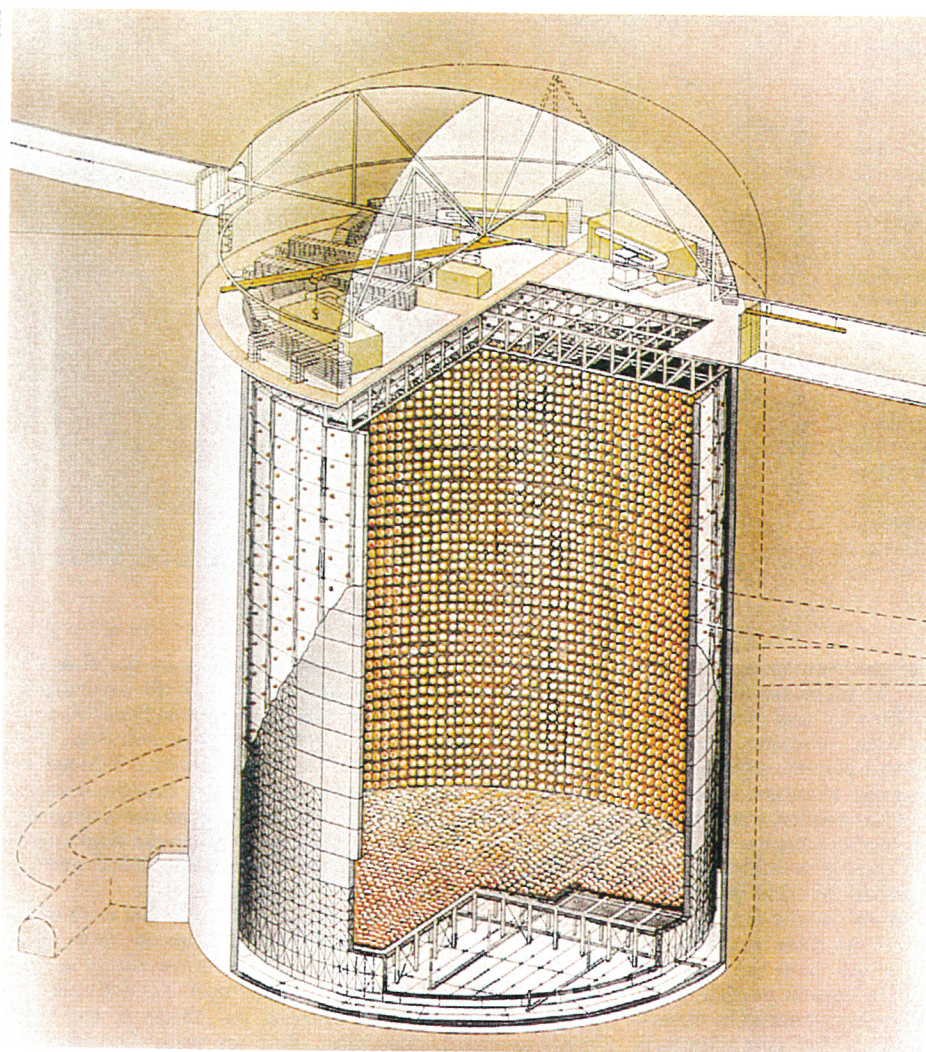
Traditionally, these calculations assume, as does the standard particle-physics model,⁵ that neutrinos do not engage in any exotic “mixing” metamorphoses once they have been created. Figure 2 shows the calculated energy spectrum of neutrino production predicted by one of the standard solar models.⁶ Conventional neutrino scattering in the outer reaches of the Sun and the Earth's atmosphere is negligible. If all these neutrinos experience no exotic metamorphoses between their creation and the detector, the experimenter should simply see the fluxes shown in figure 2. With two different kinds of “standard models” underfoot, we will avoid confusion by referring to figure 2 plus the default prediction of the standard particle-physics model simply as the standard model prediction.

The goal of observing solar neutrinos was achieved by four pioneering solar neutrino experiments. The oldest, Raymond Davis's chlorine radiochemical detector deep inside a South Dakota gold mine, has been recording solar neutrinos for more than 25 years.⁷ The other two radiochemical detectors, Gallex in the laboratory where Borexino is to be built⁸ and SAGE in the Caucasus,⁹ reported their first results in 1992. They both use gallium instead of chlorine. (See PHYSICS TODAY, April 1995, page 19.) The fourth is Kamiokande,¹⁰ Japan's water-Čerenkov precursor to Super Kamiokande. All four of these first-generation experiments have detected solar neutrinos at *approximately* the rates predicted by standard solar models.

Three solar-neutrino problems

There are, however, significant quantitative differences between the standard model predictions and the observations accumulated by the four first-generation detectors. Figure 3 summarizes these differences. The predicted contributions of the various neutrino production processes to the detector signals depend on the type of detector.

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SUPER KAMIOKANDE, the first and largest of the new generation of solar neutrino facilities, is a gargantuan water-Cherenkov detector sitting a kilometer underground in a Japanese zinc mine. The 40-m-diameter containment vessel holds 50 kilotons of highly purified water monitored by 11 000 photomultiplier tubes. These 50-cm phototubes look for Čerenkov light generated by recoil electrons from neutrino collisions (or perhaps even proton decay) in the water. Super Kamiokande became operational in April.

FIGURE 1

predictions. The trouble is that both the p-p and ${}^7\text{Be}$ predictions are very solid. Given the observed parameters of the Sun, these predictions cannot be changed very much by tinkering with solar models. Furthermore, ${}^7\text{Be}$ is the only conceivable source of ${}^8\text{B}$ in the solar core. If one imagines shutting off the ${}^7\text{Be}$ production flux to satisfy the gallium results, one cannot explain why Kamiokande sees as many ${}^8\text{B}$ neutrinos as it does.

That's because each solar process has its own energy spectrum and each detector type has its own lowest-energy threshold. (See figure 2.) The gallium detectors, for example, are the only ones with a threshold (0.2 MeV) low enough to see neutrinos from the proton-proton fusion reaction that is presumed to be the Sun's principal power source. Kamiokande, by contrast, with the highest threshold (7.5 MeV), can see only the most energetic neutrinos from the decay of boron-8 nuclei in the solar core.

In all cases, the observed event rates are smaller than what was predicted. These deficits have given rise to three different "solar neutrino problems." First, the chlorine and Kamiokande experiments see fewer neutrino events than the standard model predicts for them. Second, the discrepancy between calculation and observation is larger for the chlorine experiment than for the Kamiokande experiment, even though both are primarily sensitive to the ${}^8\text{B}$ neutrinos. Because the chlorine detector can see ${}^8\text{B}$ neutrinos all the way down to 0.8 MeV, the significant difference between it and Kamiokande seems to suggest that the deficit depends in some way on neutrino energy. The third problem is that the gallium results imply that the flux of neutrinos from electron capture by beryllium-7 nuclei in the solar core is severely depleted, if one assumes that the p-p neutrino flux agrees with

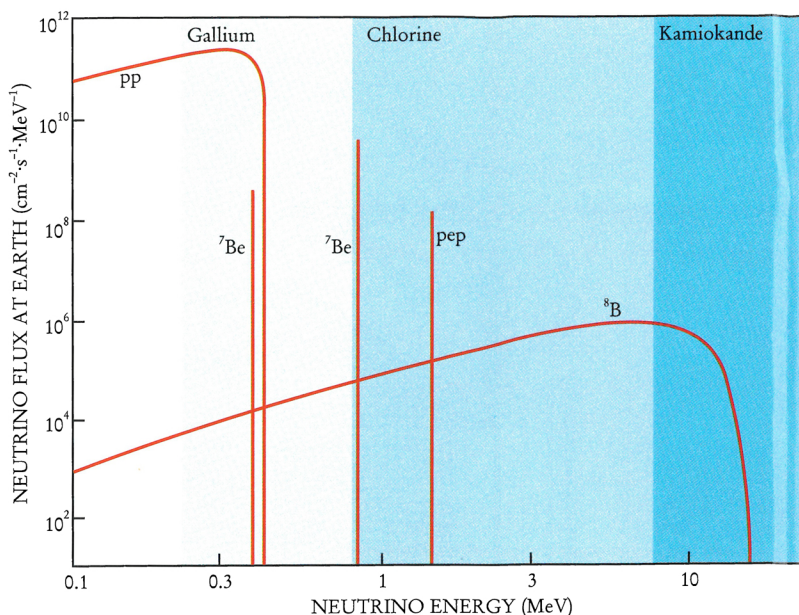
Many physicists and astronomers now believe that these observational paradoxes are due not to our faulty understanding of how the Sun works, but rather to our overly simplistic view of what neutrinos can do after they have been created. The solar neutrino deficits have given rise to a number of particle-physics solutions that involve plausible extensions of the standard model of the electroweak interactions. The most popular extensions involve neutrino mixing in the Sun or in space.

Neutrinos come in three "flavors," associated respectively with the three charged leptons: the electron, the muon and the much heavier tau. The solar energy cycle produces only *electron* neutrinos, and they, indeed, are the only ones to which the radiochemical detectors are sensitive. In standard particle theory, these flavors are rigorously conserved. But already in 1967, Bruno Pontecorvo suggested the possibility that neutrino flavors can become mixed *in vacuo*. The effect is called neutrino oscillation, because the probability of metamorphosis between two flavors has a sinusoidal dependence on path length. This can happen only if there is a mass difference between the two neutrino varieties.

In 1985 S. Mikheyev and A. Smirnov, building on earlier work by Lincoln Wolfenstein, proposed that such exotic mixing might be sufficiently amplified by interaction

SOLAR NEUTRINO SPECTRA predicted by a standard solar model.¹⁴ Shadings indicate lowest-energy thresholds of the various first-generation detectors.

Neutrinos from the dominant proton-proton fusion reaction in the solar core can be seen only by the gallium detectors. The chlorine detector can see monoenergetic neutrino lines from electron-assisted proton fusion (pep) and from electron capture by beryllium-7 nuclei. ⁷Be also produces boron-8 in the solar core. The subsequent ⁸B decay produces neutrinos so energetic that Kamiokande can see them. The monoenergetic line fluxes are shown in cm⁻²s⁻¹. The second-generation water-Čerenkov experiments hope to have neutrino-energy detection thresholds of about 5 MeV. FIGURE 2



with matter on the way out of the Sun to explain the observed solar neutrino deficit.¹² Although the Mikheyev-Smirnoff-Wolfenstein (MSW) effect is now believed by many to hold the key to the solar neutrino puzzle, a number of other speculative particle-physics solutions are still being considered—for example, resonant magnetic-moment transitions, sterile neutrino species, neutrino decay and violations of the equivalence principle.

The principal goal for the next generation of solar neutrino experiments is to establish whether any particle-physics effect beyond the simplest version of the standard electroweak model is required by solar neutrino observations. Additional experiments later on may be necessary to discriminate among the various particle-physics solutions, should the three second-generation experiments discussed in this article prove that new physics is required.

The new detectors

The most difficult task for all solar neutrino experiments is to reduce the external backgrounds caused by cosmic rays and by radioactivity in the surrounding material. In addition to a mile or so of earth above it, each of the new underground facilities has a large pure water shield to protect its fiducial volume from radioactivity in the ground or in detector components. Time-of-flight techniques divide each detector into an outer shield and an innermost, low-background fiducial zone separated from the container wall by that shield. All three new detectors will produce a prompt signal for each neutrino reaction, giving an event-by-event account of the neutrino detections. The old radiochemical detectors, by contrast, provide only an integrated signal after weeks of exposure, when the system is chemically combed for a handful of nuclei transmuted by neutrino collisions.

Because of the large event rates (several thousand per year per experiment) expected from all three of the new detectors, it should be possible to search with high statistical significance for time-dependent effects characteristic of some of the proposed particle-physics solutions. If, for example, matter-enhanced MSW neutrino mixing occurs, some electron neutrinos that have metamorphosed to other neutrino flavors on their way out of the Sun can be regenerated as they traverse the Earth. This would

produce a telltale day-night difference in the flux and energy spectrum of electron neutrinos. If the experiments find seasonal variation of observed neutrino fluxes (beyond the trivial effect of the Earth's orbital eccentricity), such variation might be indicative of the sensitive dependence of *vacuum* neutrino oscillation on the varying distance from the Sun to the Earth. If the neutrino has a magnetic moment, its interaction with solar magnetic fields could produce correlations between the neutrino deficit and the well known 11-year cycle of sunspot activity.

Potentially more important is the fact that each of the new experiments can provide crucial diagnostic tests of the combined standard predictions of electroweak theory and the solar models. For example, both Super Kamiokande and SNO will be able to measure the shape of the solar neutrino energy spectrum. Both are water-Čerenkov detectors that should see only ⁸B beta-decay neutrinos. The shape of the neutrino spectrum produced by ⁸B decays in the core of the Sun should be just like that of ⁸B decaying in a laboratory.¹³ If Super Kamiokande and SNO find something other than the laboratory spectral shape, irrespective of the integrated size of the flux, it will be evident that some kind of new, nonstandard physics is happening to the ⁸B neutrinos somewhere between the solar core and the underground detector. A simple failure of the solar model might affect the size of the ⁸B signal, but not its energy dependence.

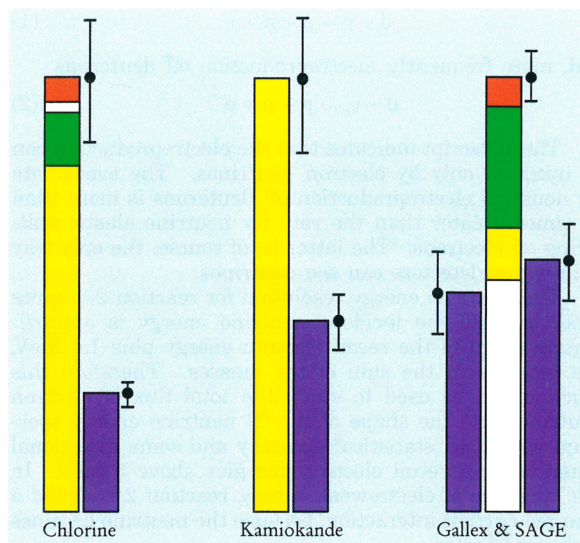
We will discuss other specific tests of the combined standard predictions of particle theory and solar models as we describe the individual detectors:

Super Kamiokande

Super Kamiokande detects a neutrino of any flavor on the rare occasion when one of them scatters elastically off an electron in the detector's huge volume of highly purified water and imparts to it enough recoil energy to generate a wake of Čerenkov radiation. The scattering cross section for a 10-MeV electron neutrino to produce a recoil electron with an energy of at least 5 MeV is very small—only 4×10^{-44} cm². For the other neutrino flavors it's even smaller. Kinematics dictates that the electrons are scattered mainly within 15° of the incoming neutrino direction.

Super Kamiokande's neutrino-energy detection threshold depends primarily on the intensity of low-energy

SOLAR NEUTRINO FLUXES observed (purple) by the four first-generation detectors show large deficits when compared with standard solar-model predictions. The different predicted total fluxes, normalized here to unity, comprise various individual solar processes, indicated by colors: white for p-p fusion (with and without electron assistance); green for electron capture by ${}^7\text{Be}$; yellow for ${}^8\text{B}$ decay; and red for the stellar carbon-nitrogen-oxygen cycle, which is calculated to play only a small role in the Sun. FIGURE 3



background events. A 10-MeV electron generates about a thousand Čerenkov photons at visible wavelengths as it traverses the detector. These photons are monitored by 11 000 photomultiplier tubes uniformly arrayed on the detector's inner walls. With this imposing coverage, Super Kamiokande has an effective neutrino energy threshold of 5 MeV.

Because of their ability to measure electron directions by means of the Čerenkov light pattern, water-Čerenkov detectors, unlike radiochemical detectors, have a handle on the incident direction of the scattering neutrino. Thus the prototype Kamiokande detector, in 1989, was the first to show directly that the observed neutrinos do indeed come from the direction of the Sun.

Early last year, after 9 years of fruitful service Kamiokande's solar-neutrino mission came to an end. Sitting a kilometer underground in the Kamioka zinc mine, about 200 km west of Tokyo, Kamiokande had a fiducial volume of only 700 tons of water, monitored by about a thousand 50-cm photomultiplier tubes. Because of a significant contamination of radon dissolved in the water, Kamiokande could not reliably detect electrons with a recoil energy of less than 7 MeV.

Kamiokande's total recorded flux of ${}^8\text{B}$ neutrinos was just about half of what the standard model predicted, as calculated by John Bahcall and Marc Pinsonneault.¹⁴ The shape of the recoil electron energy spectrum was consistent with the standard model predictions, but the statistical uncertainties were large. Within the statistical errors, Kamiokande found no interesting time variation of the neutrino flux.

To make further progress toward solving the solar neutrino problems with a water-Čerenkov detector, one needs a larger target volume and a lower energy threshold. To that end the ambitious Super Kamiokande proposal was put forward. It was approved in 1991 and construction began in December of that year. In addition to advancing the study of solar neutrinos, the new facility will also be exploited to expand a number of other investigations to which its predecessor has made important contributions: the apparent deficit of muon neutrinos in cosmic ray showers (PHYSICS TODAY, October 1994, page 22), the search for proton decay and, with luck, the observation of supernova neutrinos.

The collaboration currently consists of about 100 scientists from 11 Japanese and 12 US institutions. The US contingent has produced an anticoincidence counting system for the outer detector.

Super Kamiokande sits in a large cylindrical excavation in the Kamioka zinc mine. The bottom and side walls of the cavity are lined with stainless steel plates to form a 50 000-m³ water tank. The eleven thousand 50-cm photomultiplier tubes have been installed on an enclosing frame 3 m inside the tank walls, so that the inner volume

monitored by the tubes is 32 000 m³. The 3-m-thick water layer between the frame and the tank walls is watched over by 1800 smaller photomultipliers, whose function is to veto cosmic ray muons and radioactivity from the surroundings.

With all the water and all the photomultiplier tubes in place, Super Kamiokande began looking for neutrinos and proton decays on 1 April. It is expected to record about 10 000 solar neutrino collisions a year—that's 80 times the rate of its predecessor.

The photomultiplier array provides a photosensitive coverage of 40%, twice as good as Kamiokande's coverage. The greater coverage lowers the neutrino detection threshold by 2 MeV and improves the electron energy resolution by 40%. This better resolution helps discriminate against a significant background of electrons from bismuth-214 beta decay, which has an endpoint energy of 3.3 MeV.

For Kamiokande, the limiting factor in determining the absolute solar neutrino flux was the systematic errors resulting from the energy calibration. Super Kamiokande employs an electron linear accelerator to calibrate the various regions of the detector with electrons from 5 to 15 MeV.

Sudbury Neutrino Observatory

SNO is also a water-Čerenkov detector. But, unlike Super Kamiokande, it contains heavy water. Although SNO will have a broad range of physics and astrophysics capabilities, its primary activity will be the detection of neutrinos from ${}^8\text{B}$ decays in the Sun. With its deuterium nuclei, SNO will be able to distinguish electron neutrinos from the other neutrino varieties. Furthermore, because detectable neutrino interaction rates are much higher in heavy water than in ordinary water, SNO will have about the same event rate as Super Kamiokande, with much less water. Of course heavy water is very expensive, but Canada has a large reserve, in connection with its heavy-water reactor industry.

The collaboration includes members from 12 institutions in Canada, the US and Britain. One of the originators of the experiment was Herbert Chen of the University of California at Irvine, who died in 1987.

Neutrino interactions with ordinary hydrogen or oxygen nuclei are not useful for detection. But deuterons are different. In addition to elastic neutrino scattering off electrons, SNO will avail itself of quasi-elastic deuteron breakup

$$d + \nu \rightarrow p + n + \nu \quad (1)$$

and, more frequently, electroproduction off deuterons

$$d + \nu_e \rightarrow p + p + e \quad (2)$$

The subscript indicates that the electroproduction can be initiated only by electron neutrinos. The event rate for neutrino electroproduction off deuterons is more than 10 times greater than the rate for neutrino elastic scattering off electrons. The latter is, of course, the only way light-water detectors can see neutrinos.

The neutrino energy resolution for reaction 2 is quite good, because the incident neutrino energy is approximately equal to the recoil electron energy plus 1.4 MeV, the increase in the sum of the masses. Therefore this reaction can be used to study the total flux of electron neutrinos and the shape of the ^8B neutrino energy spectrum with good statistical accuracy and some directional sensitivity, for recoil electron energies above 5 MeV. In the language of electroweak theory, reaction 2 is called a charged-current interaction, because the neutrino becomes a charged lepton.

Reaction 1, which is called a neutral-current interaction, occurs with equal probability for all three neutrino varieties. Therefore it provides a normalizing measure of the total flux of ^8B neutrinos above a threshold of 2.2 MeV (the deuteron's binding energy), even if many of the original electron neutrinos from the solar core have changed flavor. If the observed rate for reaction 2, relative to reaction 1, turns out to be significantly less than the standard model prediction, SNO will have demonstrated the mixing of neutrino flavors.

Reaction 1, with no recoil electron, is detected through the neutron it produces. Two different techniques will be used: In one, the heavy water will be spiked with magnesium chloride, and neutron capture on the chlorine will produce 8.6-MeV gammas. These high-energy gammas produce electrons that generate Čerenkov light. In the second technique, neutrons will be detected by proportional counters filled with helium-3.

The main background at SNO will come from gammas from uranium and thorium decay chains. A gamma more energetic than 2.2 MeV can photodisintegrate a deuteron, a process that is hard to distinguish from reaction 1. The detector water will be continually purified to minimize the appearance of these decay gammas.

The SNO detector is sited 2 km underground near Sudbury, in an active nickel mine owned by INCO. It sits in a cavity 22 m wide and 34 m high, lined with concrete and an 8-mm-thick polyurethane layer that keeps the water in and radon gas out. The detector's inner heavy-water container is a transparent acrylic sphere 12 m in diameter. (See figure 4.) The heavy water is monitored from outside this vessel by ten thousand 20-cm-diameter photomultipliers supported on a geodesic structure 18 m in diameter. The region outside the kiloton of heavy water is filled with ordinary water serving as a shield against radioactivity. As a further precaution against radioactivity, the detector is being constructed from very pure materials and the air will be stringently filtered during construction and operation. As one participant describes it, "It's like building a 10-story building a mile underground in a working mine with less than a quarter of an ounce of dust."

The acrylic heavy-water vessel and the surrounding geodesic photomultiplier structure are about half completed. Water filling will begin early next year. The initial phase of operations, with pure heavy water, will continue for at least eight months. Examination of radioactive backgrounds during this period will determine which of the two

different neutron detection techniques will be used first.

If the standard-model predictions are correct, the SNO experimenters will see about 9000 charged-current interactions of solar neutrinos with deuterons per year and about one-third that many neutral-current events. If the observed fraction of neutral current events is substantially higher than that, it will indicate that some of the electron neutrinos produced in the solar core have become mu or tau neutrinos. Various contaminating backgrounds are expected to contribute less than 10% to the observed neutron signal.

Like Super Kamiokande, the Sudbury facility will also be able to investigate many nonsolar phenomena. In addition to studying cosmic-ray shower neutrinos and looking for supernova neutrinos, SNO will also be able to look for neutron-antineutron transitions in deuterium. And, because the heavy-water detector can, to some extent, distinguish among neutrino flavors, it will be able to extract mu- and tau-neutrino masses as small as 30 eV from the arrival-time profiles of supernova neutrinos.

Borexino

The results from the four first-generation solar neutrino detectors suggest that the flux of electron neutrinos from electron capture by ^7Be in the solar core is very much less than the standard model prediction. This is a crucial issue, because one sees far too much ^8B neutrino flux to simply argue that the shortage of ^7Be neutrinos implies a corresponding shortage of ^8B nuclei in the Sun.

None of these detectors, however, measure the ^7Be neutrino flux directly. The radiochemical chlorine and gallium experiments accumulate all events above the energy threshold for the relevant nuclear transmutation, without any event-by-event energy record. Therefore they cannot determine what fraction of the total recorded flux is due to the two monoenergetic ^7Be lines in the solar neutrino spectrum (figure 2). They can only set upper limits on the ^7Be contributions. All the water-Čerenkov detectors, including SNO, have energy thresholds too high to see any ^7Be neutrinos. If the missing ^7Be neutrinos have in fact been rendered invisible to the radiochemical detectors by neutrino oscillation, they might be made to reveal themselves as mu or tau neutrinos, detectable by their elastic scattering off electrons in a detector whose threshold is low enough.

Because standard solar models associate about 15% of the Sun's luminosity with the ^7Be electron capture reaction, one can calculate the Sun's production of ^7Be neutrinos with relatively high precision and considerable confidence. About 90% of the ^7Be neutrinos appear in the 0.86-MeV spectral line, which is above the threshold of the Borexino detector.

The Borexino design is the result of a collaborative effort by scientists from Germany, Italy, Russia and the US to develop an electronic solar neutrino detector with a threshold low enough to see the ^7Be neutrinos. The 100-ton facility will be housed near Gallex, in the underground laboratory adjacent to the highway tunnel that burrows under the Gran Sasso d'Italia, about 100 km east of Rome. Borexino is expected to be in full-scale operation by about 1999.

The detector is based on liquid scintillation spectroscopy, a standard method for detecting particles in nuclear and high-energy physics. But the size of the detector and its requirement for exceptionally low backgrounds are not at all standard. They require the development of new high-purity, low-background materials and techniques.

The 0.86-MeV ^7Be neutrinos will be detected through their elastic scattering off electrons in an organic liquid scintillator. The recoil electrons from these monoenergetic



NO DETECTOR'S heavy-water containment vessel in March, as one of its 130 transparent acrylic panels was being led into place. Through the vessel's still open top one can see part of the geodesic array of 9500 photomultiplier tubes that will look for Čerenkov light coming out through the walls of the 12-meter-diameter spherical vessel. When the vessel is completed next year, the dust covers will have come off the phototubes, and everything outside the acrylic vessel, including the phototubes, will be immersed in light water. SNO is 2 kilometers underground in a northern Ontario nickel mine. (Courtesy of Sudbury Neutrino Observatory.) **FIGURE 4**

neutrinos will have a continuous Compton-like spectrum up to a maximum energy of 665 keV. In the recoil electron, the scintillation liquid produces about 10 000 photons per MeV of energy loss, producing about 100 times more light than one gets from the same energy loss in water.

Scintillation photons are to be detected with an array of 9500 photomultiplier tubes. The total emitted light is proportional to the recoil electron's energy loss in the liquid. But, unfortunately, the direction of the recoil electron is not determined. The signature for the monoenergetic 6-MeV ${}^7\text{Be}$ solar neutrinos will be the unique peak in the recoil electron spectrum, with an energy of 665 keV.

Currently planned, the experiment will employ a volume of about 100 m³ of liquid scintillator. For a detector of this size, the standard solar model without oscillation predicts about 18 000 events per year from solar electrons in the energy range 250–665 keV. One can see scintillation light from any electron with an energy above 50 keV, but the recoil below 250 keV may not be useful because of a background from carbon-14. Solar neutrino energies above the 0.86-MeV ${}^7\text{Be}$ line can, of course, be seen from the recoil electron energies above 665 keV.

Even though all three neutrino flavors can scatter elastically off electrons in the scintillation liquid, the scattering cross section is highest for electron neutrinos, because they can be scattered elastically via both neutral-current and charged-current interactions.

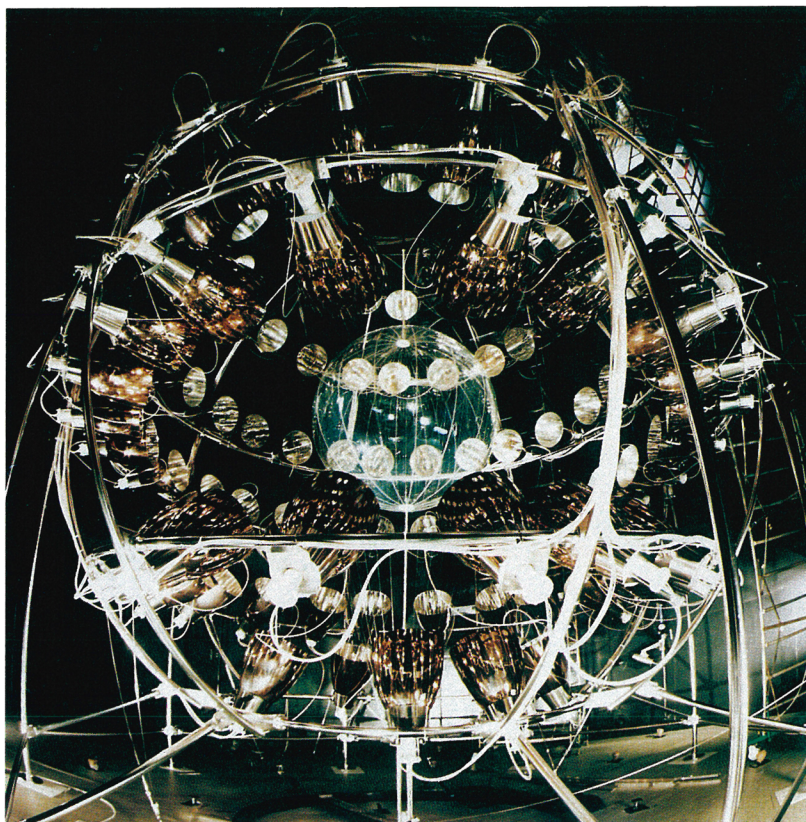
The key experimental requirement is an extremely low level of internal radioactivity in the scintillator—less than one count per week per ton. The reason for this demanding requirement, more stringent than the requirements for Super Kamiokande and SNO, is that the ${}^7\text{Be}$ neutrino energy is very close to what one gets from naturally occurring contaminants such as uranium, thorium and radioisotopes of potassium and carbon.

One important advantage of the organic liquid scintillator over the water in a Čerenkov detector is that the solubility of common contaminant salts is ten million times less in the scintillator. The ubiquitous radon-222 gas, a daughter of uranium-238, is a serious problem. Not only does it occur in the atmosphere, but it can also diffuse into the scintillator from materials in the containment vessel. An additional background problem comes from man-made radionuclei such as krypton-85, now present in the atmosphere because of the widespread use of nuclear power reactors.

The Counting Test Facility in the Gran Sasso Labo-

THE COUNTING TEST FACILITY, a small prototype of the Borexino solar neutrino detector planned for the Gran Sasso underground laboratory in an Italian mountain tunnel, is shown here before it was filled with liquid scintillator and water. The central 2-m-diameter nylon sphere now holds 4.5 tons of scintillator and is surrounded by a kiloton of very pure water. The scintillation light is detected with a hundred 20-cm-diameter photomultiplier tubes fitted with large light concentrators. Because the scintillator is much less dense than water, the floating inner vessel has to be held down by nylon fishing line.

FIGURE 5



BOREXINO COLLABORATION

ratory is a 4.5-ton prototype detector designed to develop and test low-background detector materials that will be needed for the full-scale Borexino experiment. Its main purpose is to measure the intrinsic radioactivity of the scintillator liquid and to develop on-line purification techniques. The facility has now been operating for more than a year. It comprises a water-filled tank in which are submerged a 2-meter-diameter nylon vessel filled with liquid scintillator and an array of 100 photomultiplier tubes made with low-radioactivity glass. (See figure 5.) The water tank, filled with low-radioactivity deionized water, serves as a shield against external radiation such as room-background neutrons and gammas and additional gammas from the photomultipliers.

Measurements with the test facility have yielded encouraging results. Even before the facility's novel on-line purification plant began operating, the levels of radioactive carbon, uranium and thorium were found to be acceptably low. In particular, the beta decay of ^{14}C , with its endpoint energy of 155 keV, should have no adverse effect on Borexino's 250-keV threshold at these contaminant concentrations. Other sources of background radioactivity, such as ^{85}Kr and the long-lived daughters of ^{222}Rn , were identified in the scintillator, but the purification plant has reduced them to levels below the detection limit.

The first 30 years of solar neutrino experiments have confirmed the hypothesis that the Sun shines because of nuclear fusion reactions in its core. In the next decade, research will focus on the question: Are the solar neutrino deficits observed by the first-generation detectors caused by exotic neutrino behavior that goes beyond the standard electroweak theory of particle physics? We expect that the three new detectors described here will answer this question definitively, pointing us toward a better understanding of particle physics and of stellar evolution.

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