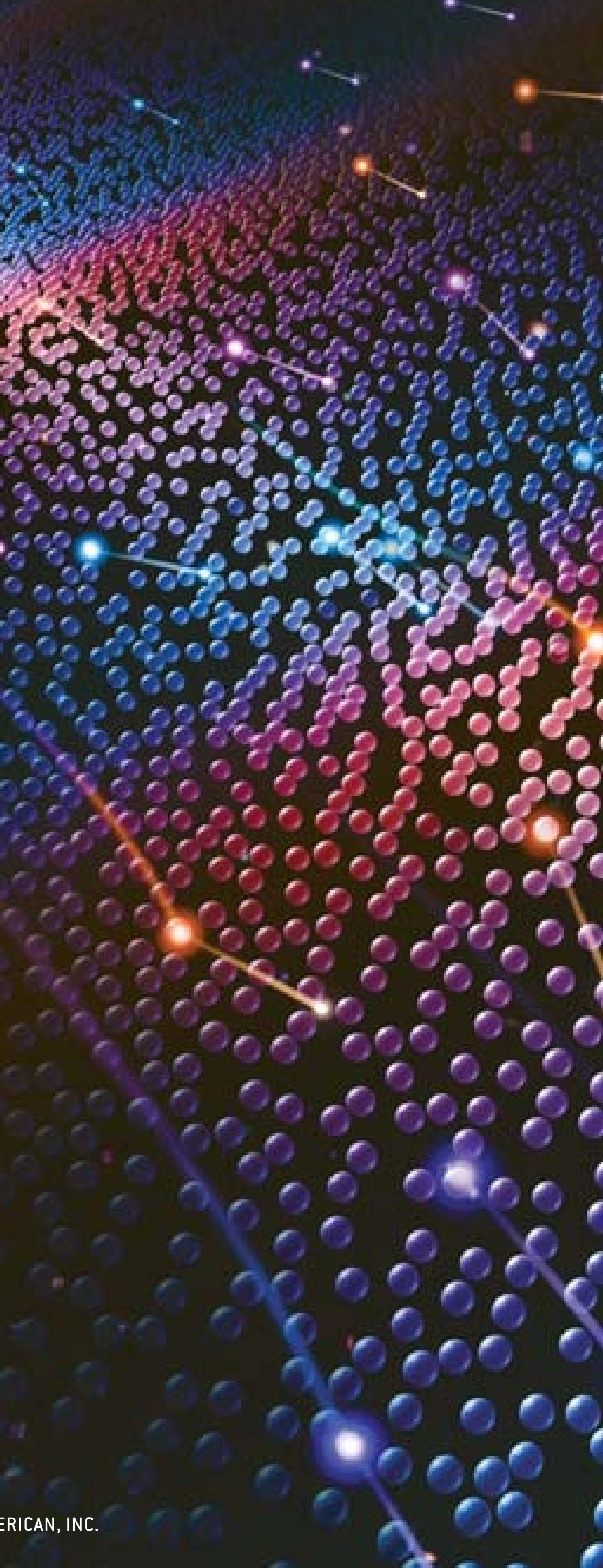
Solving the

The Sudbury Neutrino Observatory has solved a 30-year-old mystery by showing that neutrinos from the sun change species en route to the earth

By Arthur B. McDonald, Joshua R. Klein and David L. Wark



Building a detector the size of a 10-story building two kilometers underground is a strange way to study solar phenomena. Yet that has turned out to be the key to unlocking a decades-old puzzle about the physical processes occurring inside the sun. English physicist Arthur Eddington suggested as early as 1920 that nuclear fusion powered the sun, but efforts to confirm critical details of this idea in the 1960s ran into a stumbling block: experiments designed to detect a distinctive by-product of solar nuclear fusion reactions—ghostly particles called neutrinos—observed only a fraction of the expected number of them. It was not until last year, with the results from the underground Sudbury Neutrino Observatory (SNO) in

Solar Neutrino Problem

Ontario, that physicists resolved this conundrum and thereby fully confirmed Eddington's proposal.

Like all underground experiments designed to study the sun, SNO's primary goal is to detect neutrinos, which are produced in great numbers in the solar core. But unlike most of the other experiments built over the previous three decades, SNO detects solar neutrinos using heavy water, in which a neutron has been added to each of the water molecules' hydrogen atoms (making deuterium). The additional neutrons allow SNO to observe solar neutrinos in a way never done before, by counting all three types, or "flavors," of neutrino equally. Using this ability, SNO has demonstrated that the deficit of solar neutrinos seen by earlier experiments resulted not from poor measurements or a misunderstanding of the sun but from a newly discovered property of the neutrinos themselves.

Ironically, the confirmation of our best theory of the sun exposes the first flaw in the Standard Model of particle physics—our best theory of how the most fundamental constituents of matter behave. We now understand the workings of the sun better than we do the workings of the microscopic universe.

The Problem

THE FIRST SOLAR NEUTRINO EXPERIMENT, conducted in the mid-1960s by Raymond Davis, Jr., of the University of Pennsylvania and his co-workers, was intended to be a triumphant confirmation of the fusion theory of solar power generation and the start of a new field in which neutrinos could be used to learn more about the sun. Davis's experiment, located in the Homestake gold mine near Lead, S.D., detected neutrinos by a radiochemical technique. The detector contained 615 metric tons of liquid tetrachloroethylene, or dry-cleaning fluid, and neutrinos transformed atoms of chlorine in this fluid into atoms of argon. But rather than seeing one atom of argon created each day, as theory predicted, Davis observed just one every 2.5 days. (In 2002 Davis shared the Nobel Prize with Masatoshi Koshiba of the University of Tokyo for pioneering work in neutrino physics.) Thirty years of experiments following Davis's all found similar results despite using a variety of different techniques. The number of neutrinos arriving from the sun was always significantly less than the predicted total, in some cases as low as one third, in others as high as three fifths, depending on the energies of the neutrinos studied. With no understanding of why the predictions and the measurements were so different, physicists had to put on hold the original goal of studying the solar core by observing neutrinos.

While experimenters continued to run their neutrino experiments, theorists improved the models used to predict the rate of solar neutrino production. Those theoretical models are complex, but they make only a few assumptions—that the sun is powered by nuclear reactions that change the element abundances, that this power creates an outward pressure that is balanced by the inward pull of gravity, and that energy is transported by photons and convection. The solar models continued to predict neutrino fluxes that exceeded the measurements, but other projections they made, such as the spectrum of helioseismologic vibrations seen on the solar surface, agreed very well with observations.

The mysterious difference between the predictions and the measurements became known as the solar neutrino problem. Although many physicists still believed that inherent difficulties in detecting neutrinos and calculating their production rate in the sun were somehow the cause of the discrepancy, a third alternative became widely favored despite its somewhat revolutionary implications. The Standard Model of particle physics holds that there are three completely distinct, massless flavors of neutrinos: the electron-neutrino, muon-neutrino and tau-neutrino. The fusion reactions in the center of the sun can produce only electron-neutrinos, and experiments like Davis's were designed to look exclusively for this one flavor—at solar neutrino energies, only electron-neutrinos can convert chlorine atoms to argon. But if the Standard Model were incomplete, and the neutrino flavors were not distinct but instead mixed in some way, then an electron-neutrino from the sun might transform into one of the other flavors and thus escape detection.

The most favored mechanism for a change in neutrino flavor is neutrino oscillation [*see illustration on page 44*], which requires that the neutrino flavors (electron-, muon- and tau-neutrinos) are made up of mixtures of neutrino states (denoted as 1, 2 and 3) that have different masses. An electron-neutrino could then be a mixture of states 1 and 2, and a muon-neutrino could be a different mixture of the same two states. Theory predicts that as they travel from the sun to the earth, such mixed neutrinos will oscillate between one flavor and another.

Particularly strong evidence of neutrino oscillation was provided by the Super-Kamiokande collaboration in 1998, which found that muon-neutrinos produced in the upper atmosphere by cosmic rays were disappearing with a probability that depended on the distance they traveled. This disappearance is explained extremely well by neutrino oscillations, in this case muon-neutrinos that are probably turning into tau-neutrinos. The former are easily detected by Super-Kamiokande at cosmic-ray energies, but the latter mostly evade detection [see "De-

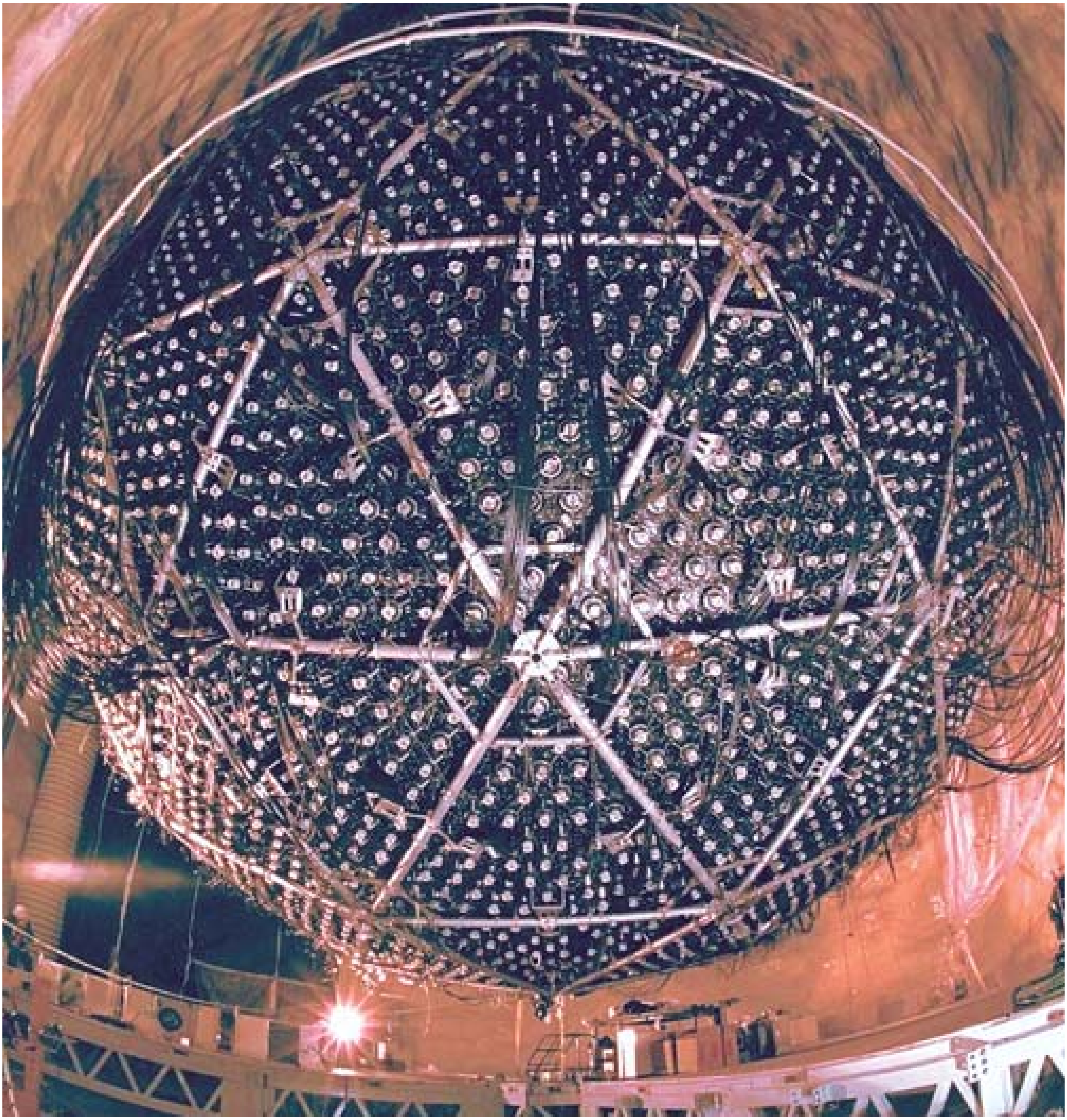
Overview/*Oscillating Neutrinos*

- Since the 1960s, underground experiments have been detecting far fewer electron-neutrinos from the sun than theory predicts. The mystery came to be known as the solar neutrino problem.
- In 2002 the Sudbury Neutrino Observatory (SNO) resolved the solar neutrino problem by determining that many of the electron-neutrinos produced inside the sun change to other flavors of neutrinos before reaching the earth, causing them to go undetected by past experiments.
- SNO's result confirms that we understand how the sun is powered and implies that neutrinos, long thought to be massless, have masses. The Standard Model of particle physics, which is otherwise extraordinarily successful, must be modified to accommodate this change.

SLIM FILMS (*preceding pages*)

tecting Massive Neutrinos," by Edward Kearns, Takaaki Kajita and Yoji Totsuka; SCIENTIFIC AMERICAN, August 1999].

A similar process could explain the solar neutrino deficit. In one scenario, the neutrinos would oscillate during their eight-minute journey through the vacuum of space from the sun to the earth. In another model, the oscillation is enhanced during the first two seconds of travel through the sun itself, an effect caused by the different ways in which each neutrino flavor interacts with matter. Each scenario requires its own specific range of neutrino parameters—mass differences and the amount of intrinsic mixing of the flavors. Despite the evidence from Super-Kamiokande and other experiments, however, it remained possible



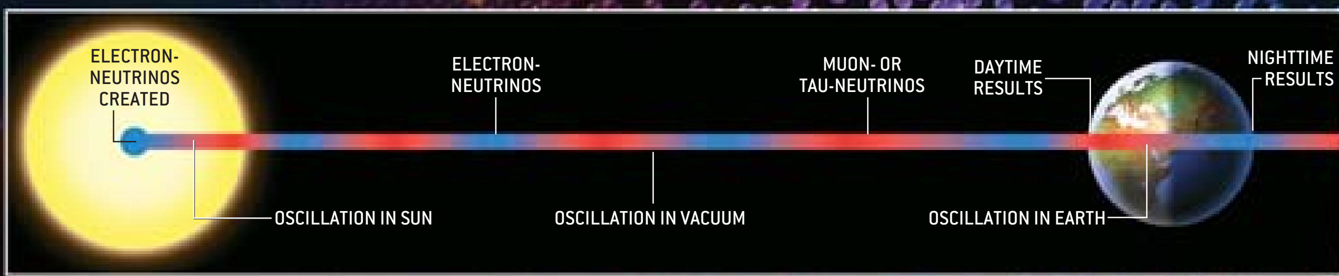
PHOTOMULTIPLIER TUBES—more than 9,500 of them—on a geodesic sphere 18 meters in diameter act as the eyes of the Sudbury Neutrino Observatory. The tubes surround and monitor a 12-meter-diameter acrylic sphere that contains 1,000 tons of heavy water. Each tube can detect a single photon of light. The entire assembly is suspended in ordinary water. All the materials that make up the detector must be extraordinarily free of natural traces of radioactive elements to avoid overwhelming the tubes with false solar neutrino counts.

COURTESY OF SUDBURY NEUTRINO OBSERVATORY (*photograph*); SLIM FILMS (*next two pages*)

DETECTING FICKLE NEUTRINOS

HOW NEUTRINOS OSCILLATE

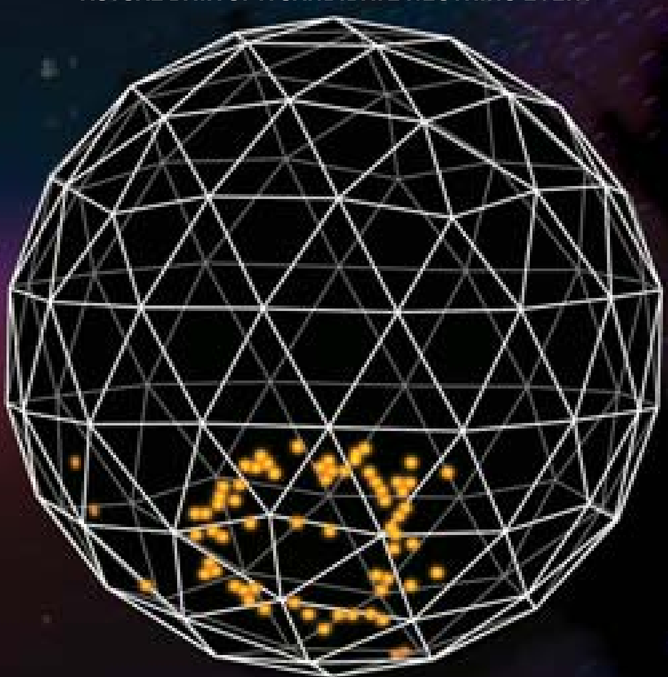
An electron-neutrino (*left*) is actually a superposition of a type 1 and a type 2 neutrino with their quantum waves in phase. Because the type 1 and type 2 waves have different wavelengths, after traveling a distance they go out of phase, making a muon- or a tau-neutrino (*middle*). With further travel the neutrino oscillates back to being an electron-neutrino (*right*).



WHERE NEUTRINOS OSCILLATE

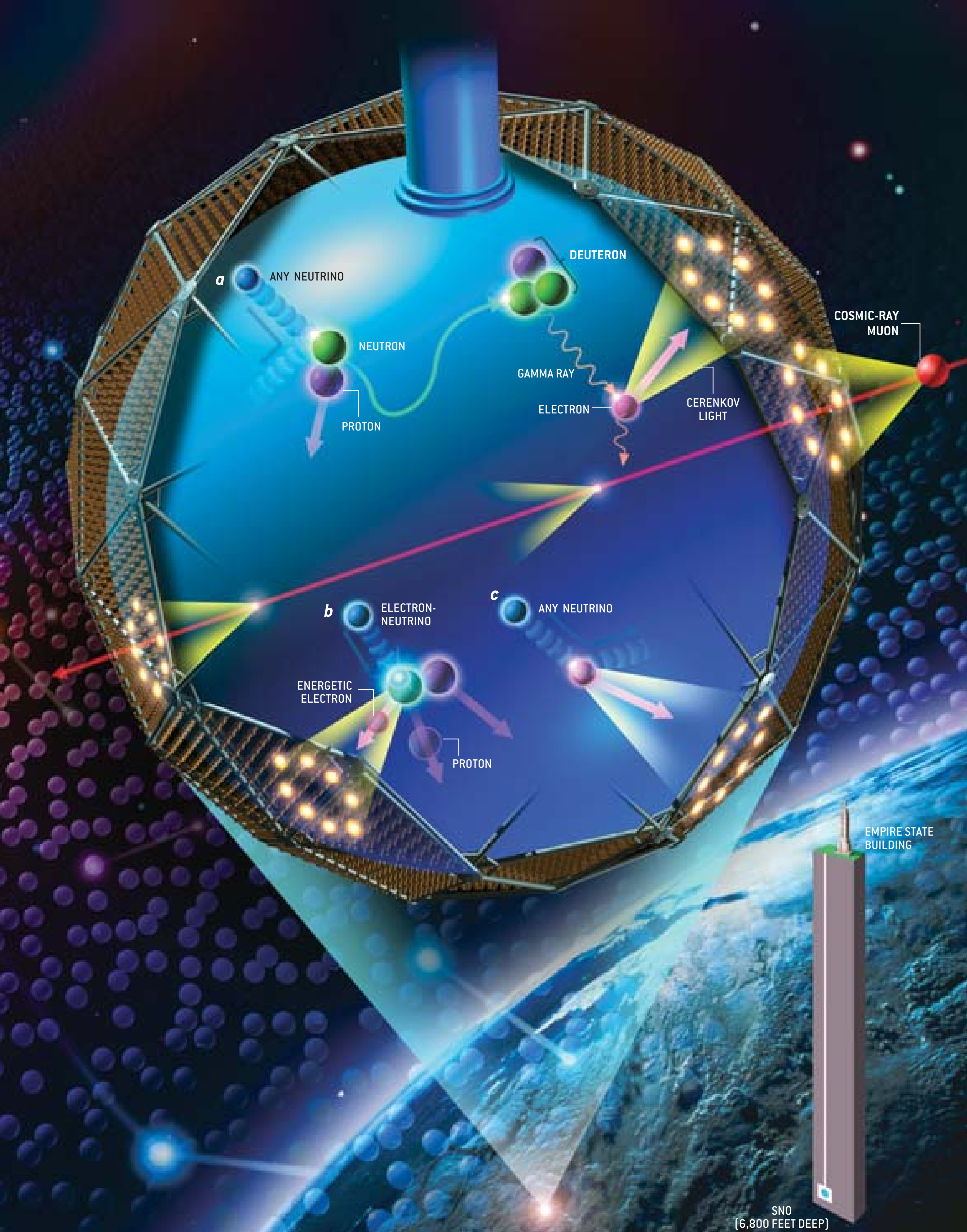
The electron-neutrinos produced at the center of the sun may oscillate while they are still inside the sun or after they emerge on their eight-minute journey to the earth. Which oscillation occurs depends on details such as the mass differences and the intrinsic degree of mixing of type 1 and 2 neutrinos. Extra oscillation may also occur inside the earth, which manifests as a difference between daytime and nighttime results.

ACTUAL DATA OF A CANDIDATE NEUTRINO EVENT



HOW SNO DETECTS NEUTRINOS

The Sudbury Neutrino Observatory, or SNO (*opposite page*), detects a neutrino by seeing a characteristic ring of Cerenkov light emitted by a high-speed electron. The neutrino produces the energetic electron in SNO's heavy water (*large blue sphere*) in one of three ways. In deuteron breakup (*a*), the neutrino (*blue*) splits a deuterium nucleus into its component proton (*purple*) and neutron (*green*). The neutron eventually combines with another deuteron, releasing a gamma ray (*wavy line*), which in turn knocks free an electron (*pink*) whose Cerenkov light (*yellow*) is detected. In neutrino absorption (*b*) a neutron absorbs the neutrino and is thereby turned into a proton and an energetic electron. Only electron-neutrinos can be absorbed in this way. Less often the neutrino may collide directly with an electron (*c*). Cosmic-ray muons (*red*) are distinguished from neutrinos by the amount of Cerenkov light they produce and where they produce it—outside the detector as well as inside. The number of muons is reduced to manageable levels by positioning the detector two kilometers underground.


a
ANY NEUTRINO
NEUTRON
PROTON
DEUTERON
GAMMA RAY
ELECTRON
CERENKOV LIGHT
COSMIC-RAY MUON
b
ELECTRON-NEUTRINO
ENERGETIC ELECTRON
PROTON
c
ANY NEUTRINO
EMPIRE STATE BUILDING
SNO (6,800 FEET DEEP)

that neutrinos were disappearing by some process other than oscillation. Until 2001 scientists had no *direct* evidence of solar neutrino oscillation, in which the transformed solar neutrinos themselves were detected.

The Observatory

THE SUDBURY NEUTRINO OBSERVATORY was designed to search for this direct evidence, by detecting neutrinos using several different interactions with its 1,000 tons of heavy water. One of these reactions exclusively counts electron-neutrinos; the others count all flavors without distinguishing among them. If the solar neutrinos arriving at the earth consisted only of electron-neutrinos—and therefore no flavor transformation was occurring—then the count of neutrinos of all flavors would be the same as the count of electron-neutrinos alone. On the other hand, if the count of all flavors was far in excess of the count of the electron-neutrinos, that would prove that neutrinos from the sun were changing flavor.

The key to SNO's ability to count both electron-neutrinos alone and all flavors is the heavy water's deuterium nuclei, also called deuterons. The neutron in a deuteron produces two separate neutrino reactions: neutrino absorption, in which an electron-neutrino is absorbed by a neutron and an electron is created, and deuteron breakup, in which a deuterium nucleus is broken apart and the neutron liberated. Only electron-neutrinos can undergo neutrino absorption, but neutrinos of any flavor can break up deuterons. A third reaction detected by SNO, the scattering of electrons by neutrinos, can also be used to count neutrinos other than electron-neutrinos but is much less sensitive to muon- and tau-neutrinos than the deuteron breakup reaction [*see illustration on preceding page*].

SNO was not the first experiment to use heavy water. In the 1960s T. J. Jenkins and F. W. Dix of Case Western Reserve University used heavy water in a very early attempt to observe neutrinos from the sun. They used about 2,000 liters (two tons) of heavy water aboveground, but the signs of solar neutrinos were swamped by the effects of cosmic rays. In 1984 Herb Chen of the University of California at Irvine proposed bringing 1,000 tons of heavy water from Canada's CANDU nuclear reactor to the bottom of INCO Ltd.'s Creighton nickel mine in Sudbury—a location that was deep enough to enable a clear measurement of both neutrino absorption and deuteron breakup for solar neutrinos.

Chen's proposal led to the establishment of the SNO scientific collaboration and ultimately to the creation of the SNO detector. The 1,000 tons of heavy water are held in a 12-meter-diameter transparent acrylic vessel. The heavy water is viewed by more than 9,500 photomultiplier tubes held on an 18-meter-diameter geodesic sphere [*see illustration on page 43*]. Each tube is capable of detecting a single photon of light. The entire structure is submerged in ultrapure ordinary water filling a cavity carved out of the rock two kilometers below the surface of the earth.

SNO's Measurement

SOLAR NEUTRINOS CAN BE OBSERVED deep underground because of the extreme weakness of their interaction with matter. During the day, neutrinos easily travel down to SNO through two kilometers of rock, and at night they are almost equally unaffected by the thousands of kilometers that they travel up through the earth. Such feeble coupling makes them interesting from the perspective of solar astrophysics. Most of the energy created in the center of the sun takes millions of years to reach the solar surface and leave as sunlight. Neutrinos, in contrast, emerge after two seconds, coming to us directly from the point where solar power is created.

With neither the whole sun nor the entire earth able to impede the passage of neutrinos, capturing them with a detector weighing just 1,000 tons poses something of a challenge. But although the vast majority of neutrinos that enter SNO pass through it, on very rare occasions, one will—by chance alone—collide with an electron or an atomic nucleus and deposit enough energy to be observed. With enough neutrinos, even the rarity of these interactions can be overcome. Luckily, the sun's neutrino output is enormous—five million high-energy solar neutrinos pass through every square centimeter of the earth every second—which leads to about 10 neutrino events, or interactions, in SNO's 1,000 tons of heavy water every day. The three types of neutrino reaction that occur in SNO all generate energetic electrons, which are detectable through their production of Cerenkov light—a cone of light emitted like a shock wave by the fast-moving particle.

This small number of neutrino events, however, has to be

EIGHT DECADES OF THE SUN AND NEUTRINOS

IT HAS TAKEN MOST OF A CENTURY to verify fully that we understand how the sun generates its power. Along the way, neutrinos have gone from speculative hypothesis to key experimental tool. Their oscillations point to fundamental new physics to be discovered in the decades to come.

1920 — 1940

1920 Arthur Eddington proposes that the sun is powered by nuclear fusion converting hydrogen atoms into helium

1930 Wolfgang Pauli rescues conservation of energy by hypothesizing an unseen particle, the neutrino, that carries away energy from some radioactive decays

1938 Hans Bethe analyzes the basic nuclear processes that could power the sun and accurately estimates the sun's central temperature

1956 Frederick Reines and **Clyde Cowan** first detect the neutrino using the Savannah River nuclear reactor distinguished from flashes of Cerenkov light caused by other particles. In particular, cosmic-ray muons are created continually in the upper atmosphere, and when they enter the detector they can produce enough Cerenkov light to illuminate every photomultiplier tube. The intervening kilometers of rock between the earth's surface and SNO reduce the deluge of cosmic-ray muons to a mere trickle of just three an hour. And although three muons an hour is a far greater rate than the 10 neutrino interactions a day, these muons are easy to distinguish from neutrino events by the Cerenkov light they produce in the ordinary water outside the detector.

A far more sinister source of false neutrino counts is the intrinsic radioactivity in the detector materials themselves. Everything inside the detector—from the heavy water itself to the acrylic vessel that holds it to the glass and steel of the photomultiplier tubes and support structure—has trace amounts of naturally occurring radioactive elements. Similarly, the air in the mine contains radioactive radon gas. Every time a nucleus in these radioactive elements decays inside the SNO detector, it can release an energetic electron or gamma ray and ultimately produce Cerenkov light that mimics the signal of a neutrino. The water and the other materials used in SNO are purified to remove the bulk of the radioactive contaminants (or were chosen to be naturally pure), but even parts per billion are enough to overwhelm the true neutrino signal with false counts.

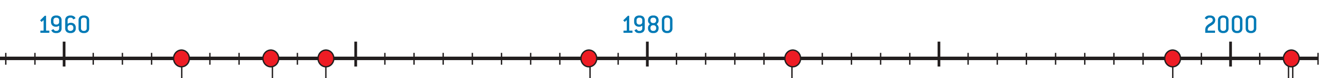
The task before SNO is therefore very complex—it must count neutrino events, determine how many are caused by each of the three reactions, and estimate how many of the apparent neutrinos are caused by something else, such as radioactive contamination. Errors as small as a few percent in any of the steps of analysis would render meaningless SNO's comparison of the electron-neutrino flux to the total neutrino flux. Over the 306 days of running, from November 1999 to May 2001, SNO recorded nearly half a billion events. By the time the data reduction was complete, only 2,928 of these remained as candidate neutrino events.

SNO cannot uniquely determine whether a given candidate neutrino event was the result of a particular reaction. Typically an event like the one shown on page 44 could equally well be the result of deuteron breakup as neutrino absorption. Fortunately, differences between the reactions show up when we examine many events. For example, deuteron breakup, the splitting of a deuterium nucleus in the heavy water, always leads to a gamma ray of the same energy, whereas the electrons produced by neutrino absorption and electron scattering have a broad spectrum of energies. Similarly, electron scattering produces electrons that travel away from the sun, whereas the Cerenkov light from deuteron breakup can point in any direction. Finally, the locations where the reactions occur differ as well—electron scattering, for instance, occurs as easily in the outer layer of light water as in the heavy water; the other reactions do not. With an understanding of those details, SNO researchers can statistically determine how many of the observed events to assign to each reaction.

Five million high-energy solar neutrinos pass through every square centimeter of your body every second.

Such an understanding is the result of measurements that were complete nuclear physics experiments in their own right: to determine how to measure energy using Cerenkov light, sources of radioactivity with known energies were inserted inside the detector. To measure how the Cerenkov light travels through and reflects off the various media in the detector (the water, the acrylic, the photomultiplier tubes), a variable wavelength laser light source was used. The effects of radioactive contamination were assessed by similar experiments, including radioassays of the water using new techniques designed specifically for SNO.

For the final SNO data set, after statistical analysis, 576 events were assigned to deuteron breakup, 1,967 events to neutrino absorption and 263 to electron scattering. Radioactivity and other backgrounds caused the remaining 122. From these numbers of events, we must calculate how many actual neutrinos must be passing through SNO, based on the tiny probabilities that any particular neutrino will break up a deuteron, be absorbed or scatter an electron. The upshot of all the calcu-



1964 John Bahcall predicts the neutrino flux expected to be observed from the sun

1967 Raymond Davis, Jr., first measures neutrinos from the sun, using 600 tons of dry-cleaning fluid in a mine in Lead, S.D.

1969 Vladimir Gribov and **Bruno Pontecorvo** propose that neutrino oscillations explain the anomalously small number of neutrinos detected

1978 and 1985 Stanislav Mikheyev, Alexei Smirnov and **Lincoln Wolfenstein** posit that matter can enhance neutrino oscillations

1998 Super-Kamiokande assembles evidence of neutrino oscillation in cosmic-ray neutrinos

2002 SNO confirms that electron-neutrinos from the sun are oscillating to another flavor, fully resolving the solar neutrino problem

2002 KamLAND experiment detects oscillation of antineutrinos emitted from nuclear reactors

BRYAN CHRISTIE DESIGN

Some Other Neutrino Experiments

HOMESTAKE: Solar neutrino detector located in the Homestake gold mine in Lead, S.D. The original chlorine experiment, started in 1966, used 600 tons of dry-cleaning fluid. Supplemented in 1996 by a radiochemical sodium iodide experiment using 100 tons of iodine.

KAMIOKA: Houses Super-Kamiokande, a 50,000-ton light-water detector studying cosmic-ray and solar neutrinos, as well as muon-neutrinos beamed from the KEK facility 250 kilometers away ("K2K" experiment). Also houses KamLAND, a smaller detector (1,000 tons of liquid scintillator, which emits light when a charged particle passes through) that counts anti-electron-neutrinos emitted by all the nuclear reactors nearby in South Korea and Japan.

SAGE (Russian-American Gallium Solar Neutrino Experiment): Located at Baksan in the Caucasus Mountains in Russia. Uses 50 tons of gallium, which is capable of detecting the low-energy neutrinos produced by proton-proton fusion in the sun.

GRAN SASSO: The world's largest underground laboratory, accessed via a highway tunnel, located under the Gran Sasso Mountains about 150 kilometers east of Rome. Solar neutrino experiments include Gallex/GNO, which began in 1991 and uses 30 tons of gallium (as aqueous gallium trichloride), and Borexino, a sphere of 300 tons of scintillator viewed by 2,200 photomultipliers, scheduled for completion this year.

MINIBOONE (Booster Neutrino Experiment): Located at Fermilab in Illinois. Beams of muon-neutrinos and anti-muon-neutrinos travel through 500 meters of earth to be detected in an 800-ton tank of mineral oil. Endeavoring to test a controversial result reported by the LSND experiment at Los Alamos National Lab in 1995. Began collecting data in September 2002.

MINOS: Will beam neutrinos from Fermilab to the Soudan detector, 735 kilometers away in Minnesota. Detector is 5,400 tons of iron laced with plastic particle detectors. Projected to begin taking data in 2005.

lations is that the observed 1,967 neutrino absorption events represent 1.75 million electron-neutrinos passing through each square centimeter of the SNO detector every second. That is only 35 percent of the neutrino flux predicted by solar models. SNO thus first confirms what other solar neutrino experiments have seen—that the number of electron-neutrinos arriving from the sun is far smaller than solar models predict.

The critical question, however, is whether the number of electron-neutrinos arriving from the sun is significantly smaller than the number of neutrinos of all flavors. Indeed, the 576 events assigned to deuteron breakup represent a total neutrino flux of 5.09 million per square centimeter per second—far larger than the 1.75 million electron-neutrinos measured by neutrino absorption. These numbers are determined with high accuracy. The difference between them is more than five times the experimental uncertainty.

The excess of neutrinos measured by deuteron breakup means that nearly two thirds of the total 5.09 million neutrinos arriving from the sun are either muon- or tau-neutrinos. The sun's fusion reactions can produce only electron-neutrinos, so some of them must be transformed on their way to the earth. SNO has therefore demonstrated directly that neutrinos do not behave according to the simple scheme of three distinct massless flavors described by the Standard Model. In 20 years of trying, only experiments such as Super-Kamiokande and SNO have shown that the fundamental particles have properties not contained in the Standard Model. The observations of neutrino flavor transformation provide direct experimental evidence that there is yet more to be discovered about the microscopic universe.

But what of the solar neutrino problem itself—does the discovery that electron-neutrinos transform into another flavor completely explain the deficit observed for the past 30 years? It does: the deduced 5.09 million neutrinos agrees remarkably well with the predictions of solar models. We can now claim that we really do understand the way the sun generates its power. Having taken a detour lasting three decades, in which we found that the sun could tell us something new about neutrinos, we can finally return to Davis's original goal and begin to use neutrinos to understand the sun. For example, neutrino studies could determine how much of the sun's energy is produced by direct nuclear fusion of hydrogen atoms and how much is catalyzed by carbon atoms.

The Future

THE IMPLICATIONS OF SNO'S DISCOVERY go even further. If neutrinos change flavor through oscillation, then they cannot be massless. After photons, neutrinos are the second most numerous known particles in the universe, so even a tiny mass could have a significant cosmological significance. Neutrino oscillation experiments such as SNO and Super-Kami-

THE AUTHORS

ARTHUR B. McDONALD, JOSHUA R. KLEIN and *DAVID L. WARK* are members of the 130-strong Sudbury Neutrino Observatory (SNO) collaboration. McDonald, a native of Sydney, Nova Scotia, has been the director of the SNO Institute since its inception in 1989. He is also professor of physics at Queen's University in Kingston, Ontario. Klein received his Ph.D. from Princeton University in 1994 and began his work on SNO at the University of Pennsylvania. He is now assistant professor of physics at the University of Texas at Austin. Wark has spent the past 13 years in the U.K., at the University of Oxford, the University of Sussex and the Rutherford Appleton Laboratory, trying to explain the infield fly rule to cricket fans. He has worked on a number of neutrino experiments in addition to SNO.

okande measure only mass differences, not masses themselves. Showing that mass differences are not zero, however, proves that at least some of the masses are not zero. Combining the oscillation results for mass differences with upper limits for the electron-neutrino mass from other experiments shows that neutrinos make up something between 0.3 and 21 percent of the critical density for a flat universe. (Other cosmological data strongly indicate that the universe is flat.) This amount is not negligible (it is roughly comparable to the 4 percent density that arises from gas, dust and stars), but it is not quite enough to explain all the matter that seems to be present in the universe. Because neutrinos were the last known particles that could have made up the missing dark matter, some particle or particles not currently known to physics must exist—and with a density far in excess of everything we *do* know.

SNO has also been searching for direct evidence of the effects of matter on neutrino oscillations. As mentioned earlier, travel through the sun can enhance the probability of oscillations. If this occurs, the passage of neutrinos through thousands of kilometers of the earth could lead to a small reversal in the process—the sun might shine more brightly in electron-neutrinos at night than during the day. SNO's data show a small excess of electron-neutrinos arriving at night compared with during the day, but as of now the measurement is not significant enough to decide whether the effect is real.

The results reported by SNO so far are just the beginning. For the observations cited here, we detected the neutrons from the critical deuteron breakup events by observing their capture by other deuterium atoms—an inefficient process that produces little light. In May 2001 two tons of highly purified sodium chloride (table salt) were added to the heavy water. Chlorine nuclei capture neutrons with much higher efficiency than deuterium nuclei do, producing events that have more light and are easier to distinguish from background. Thus, SNO will make a separate and more sensitive measurement of the deuteron breakup rate to check the first results. The SNO collaboration has also built an array of ultraclean detectors called proportional counters, which will be deployed throughout the heavy water in mid-2003 to look for the neutrons directly. Making these detectors was a technical challenge of the first order because they must have a spectacularly low level of intrinsic radioactive background—corresponding to about one count per meter of detector per year. Those devices will essentially check SNO's earlier results by an independent experiment.

SNO has unique capabilities, but it is not the only game in town. In December 2002 the first results from a new Japanese-American experiment called KamLAND were reported. The KamLAND detector is at the Super-Kamiokande site and studies electron-antineutrinos produced by all the nuclear reactors nearby in Japan and Korea. If matter-enhanced neutrino oscillations explain the flavor change seen by SNO, theory predicts that these antineutrinos should also change flavor over distances of tens or hundreds of kilometers. Indeed, KamLAND has seen too few electron-antineutrinos, implying that they are oscillating en route from the nuclear reactors to the detector.

Future neutrino experiments might help explain why the universe is made of matter rather than antimatter.

The KamLAND results imply neutrino mass differences and mixing parameters similar to those seen by SNO.

Future neutrino experiments might probe one of the biggest mysteries in the cosmos: Why is the universe made of matter rather than antimatter? Russian physicist Andrei Sakharov first pointed out that to get from a big bang of pure energy to the current matter-dominated universe requires the laws of physics to be different for particles and antiparticles. This is called CP (charge-parity) violation, and sensitive measurements of particle decays have verified that the laws of physics violate CP. The problem is that the CP violation seen so far is not enough to explain the amount of matter around us, so phenomena we have not yet observed must be hiding more CP violation. One possible hiding place is neutrino oscillations.

To observe CP-violating neutrino oscillations will be a multistage process. First physicists must see electron-neutrinos appear in intense beams of muon-neutrinos. Second, higher-intensity accelerators must be built to produce beams of neutrinos so intense and pure that their oscillations can be observed in detectors located across continents or on the other side of the earth. Studies of a rare radioactive process called neutrinoless double beta decay will provide further information about neutrino masses and CP violation.

It will probably be more than a decade before these experiments become a reality. A decade may seem a long way off, but the past 30 years, and the sagas of experiments such as SNO, have shown that neutrino physicists are patient and very persistent—one has to be to pry out the secrets of these elusive particles. These secrets are intimately tied up with our next level of understanding of particle physics, astrophysics and cosmology, and thus persist we must. SA

MORE TO EXPLORE

The Origin of Neutrino Mass. Hitoshi Murayama in *Physics World*, Vol. 15, No. 5, pages 35–39; May 2002.

The Asymmetry between Matter and Antimatter. Helen R. Quinn in *Physics Today*, Vol. 56, No. 2, pages 30–35; February 2003.

The SNO Web site is at **www.sno.phy.queensu.ca**

The Neutrino Oscillation Industry Web site, maintained by Argonne National Laboratory, is at **www.neutrinooscillation.org**