Direct Measurement of the Sun's Total Neutrino Output Confirms Flavor Metamorphosis

A kiloton of ultrapure heavy water lets a detector deep inside a Canadian mine record high-energy neutrinos from the Sun, regardless of flavor changes en route.

The 1 July issue of *Physical Review Letters* reports an important result from the Sudbury Neutrino Observatory (SNO), 2 km underground in an Ontario nickel mine.[1] This much-anticipated paper describes the first direct measurement of the total flux of neutrinos (above the detector's energy threshold) arriving from the core of the Sun, irrespective of any "flavor" metamorphoses along the way. And that total flux turns out to be in excellent agreement with the neutrino output predicted by the so-called standard solar model (SSM).

That reassuring accord does much more than simply bolster our confidence that astrophysicists understand how the Sun works. It also confirms the particle physicists' presumption that neutrinos are capable of more tricks than the minimal standard particle theory permits: They can change flavor as they travel. That presumption has grown gradually with three decades of observed shortfalls of solar neutrinos. The nuclear processes that power the Sun can produce only electron neutrinos (ν_e). And before SNO, with its innovative core of heavy water (D_2O), solar-neutrino detectors were sensitive only, or primarily, to ν_e (see PHYSICS TODAY, August 2001, page 13).

The new SNO measurement demonstrates convincingly that just about two-thirds of the highest-energy electron neutrinos emerging from the solar core have become either muon neutrinos (ν_μ) or tau neutrinos (ν_τ) by the time they signal their arrival by interacting with either a deuteron or an electron in the heavy water. There is good reason to believe that these are the only three neutrino varieties in nature—except perhaps for a speculative "sterile" variety that might be involved in flavor metamorphosis but would otherwise be impervious to the usual weak interactions.

Neutrino oscillation

The prevailing theoretical view is that the flavor metamorphosis is a manifestation of neutrino oscillation, a phenomenon accommodated by an extension of standard particle theory. Neutrino oscillation is characterized by a transition probability that, in vacuum, oscillates periodically with L/E, the neutrino's travel distance divided by its energy. One can make the excellent simplifying approximation that only two neutrino mass eigenstates are involved in solar-neutrino oscillation. Then, the period and amplitude of that oscillation are governed by two parameters: Δm^2, the difference between the squared masses of the two mass eigenstates whose superposition makes up the electron neutrino, and θ, the mixing angle of that superposition. If all neutrino varieties were truly massless, there could be no flavor oscillation.

A companion paper reports the SNO collaboration's finding of small differences—of at most two standard deviations—between day and night measurements of the solar-neutrino spectrum.[2] At night, neutrinos must traverse Earth to reach the detector. For certain regions of the θ, Δm^2 parameter space, the oscillation theory predicts significant enhancement of flavor metamorphosis as a neutrino makes its way through the high electron density of Earth's interior.

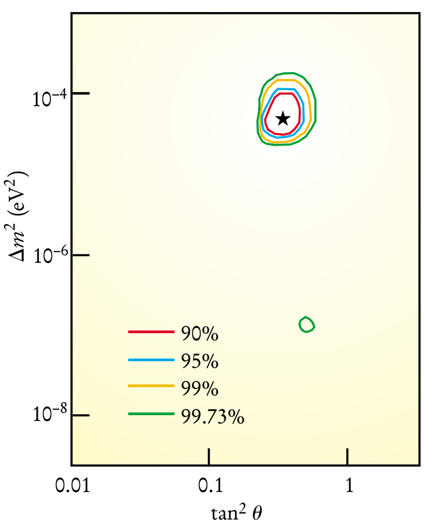

FIGURE 1. NEUTRINO OSCILLATION parameters from a fit to solar-neutrino data from the Sudbury Neutrino Observatory and other detectors. Δm^2 is the difference between the squared masses of the two mass eigenstates whose superposition makes up the electron neutrino, and θ is the mixing angle of that superposition. The star shows the best fit and the contours indicate confidence levels. (Adapted from ref. 2.)

The sign and modest magnitude of the observed day–night asymmetry help to localize the parameters of solar-neutrino oscillation (see figure 1). At a confidence level of 99%, the SNO data, taken together with earlier measurements from other solar neutrino detectors, point to a Δm^2 of order 10^{-4} eV^2 and a rather large mixing angle θ—something like 30°. That would make ν_e a roughly equal superposition of two mass eigenstates separated in mass by, at most, a few hundredths of an eV.

Distinguishing flavors

SNO, run by a collaboration of Canadian, British, and US groups led by Arthur McDonald, began taking data in 1998. The heart of the detector is a kiloton of ultrapure heavy water in a transparent acrylic vessel surrounded by 9500 photomultiplier tubes that monitor the Čerenkov light that signals neutrino interactions in the water.

The sensitivity threshold of large water-Čerenkov detectors restricts them to seeing neutrinos with energies above about 5 MeV. For neutrino interactions in a heavy-water detector that liberate neutrons, the threshold can be lowered to 2.2 MeV, the binding energy of the deuteron. But, in any case, the only significant source of neutrinos at this high-energy end of the solar-neutrino spectrum is the decay of boron-8 nuclei produced in a minor byway of the chain of fusion reactions that power the Sun. The observation of ^{8}B neutrinos provides a particularly stringent test of solar models.

In its first major paper, a year ago,[3] the SNO collaboration reported on about 1000 events in which a solar ν_e hitting a deuteron produced the reaction

$$\nu_e + d \rightarrow e + p + p. \qquad (1)$$

The instigating neutrino has to be a ν_e

because the reaction turns it into the telltale electron. Reaction 1 is called a charged-current (CC) interaction because it involves the virtual exchange of the charged intermediate vector boson ($W^{\pm}$). (The analogous CC reactions that would create the heavier μ and τ charged leptons from ν_μ and ν_τ require energies that are far beyond the solar-neutrino spectrum.)

Last year's SNO result from the CC events was a ν_e flux roughly a third of the ^{8}B neutrino output predicted by the SSM. To see what becomes of the missing two-thirds of the predicted solar flux, the SNO detector could exploit another possible result of a ν–d collision:

$$\nu + \mathrm{d} \rightarrow \nu + \mathrm{p} + \mathrm{n}. \qquad (2)$$

This quasi-elastic breakup of the deuteron is called a neutral-current (NC) interaction because it is mediated by the neutral intermediate vector boson (Z^0). Because reaction 2 can be produced with equal probability by a neutrino of any of the three flavors, it serves as a direct measure of the total flux of solar neutrinos, regardless of any flavor oscillation—assuming that none have been rendered sterile.

A year later

Detecting reaction 2 is, however, particularly tricky. So that's why we've had to wait an extra year for the NC events. The neutron freed in the deuteron breakup can signal its presence through Čerenkov light generated by a 6.25-MeV γ emitted when the neutron is subsequently captured by another deuteron. But, more often than not, the neutron is captured by some other nuclear species that yields no telltale γ, or it escapes the heavy-water vessel entirely. Of even more concern is the low-level contamination of uranium and thorium in the heavy water and its surroundings. Their decay chains produce gammas that can photodisintegrate deuterons, thus creating a background of spurious neutrons.

Taking unprecedented precautions to build and maintain the detector as free as possible of radioactive contaminants, the collaboration has managed to beat down the background of nuclear decays far enough to harvest 577 NC events with an estimated background of only 44 neutrons from photodisintegrations—in 306 days of active running.

The NC yield corresponds to a flavor-blind total flux of $(5.09 \pm 0.62) \times 10^6/(\mathrm{cm}^2\ \mathrm{s})$ ^{8}B neutrinos from the Sun. The SSM flux prediction[4] for ν_e produced by ^{8}B decays in the solar core is $(5.05 \pm 0.91) \times 10^6/(\mathrm{cm}^2\ \mathrm{s})$. But the SNO measurement of the flux of ^{8}B *electron* neutrinos, now based on some 2000 CC events, is only $(1.76 \pm 0.11) \times 10^6/(\mathrm{cm}^2\ \mathrm{s})$. So here we have strong evidence that solar neutrinos change flavor en route.

The case for neutrino oscillation becomes even stronger when one includes the data for the elastic scattering of solar neutrinos off electrons:

$$\nu + \mathrm{e} \rightarrow \nu + \mathrm{e}. \qquad (3)$$

If the incident neutrino is a ν_e, both Z and W exchange contribute to this reaction. For the other neutrino flavors, however, only the smaller Z-exchange term can contribute to scattering off electrons. Doing the calculation, one finds that the total rate for reaction 3 is proportional to the incident ν_e flux plus only about 15% of the combined incident flux of ν_μ and ν_τ.

Thus, although reaction 2 provides the most direct and precise measure of the total incident neutrino flux, regardless of flavor, one can also measure that total flux by combining data from only reactions 1 and 3. That was, in fact, how the SNO collaboration was able to estimate the total solar-neutrino flux last year,[3] before the analysis of the reaction-2 data was ready. That result relied heavily on the accumulated e–ν elastic-scattering data from the much larger Super Kamiokande light-water Čerenkov detector in Japan.[5]

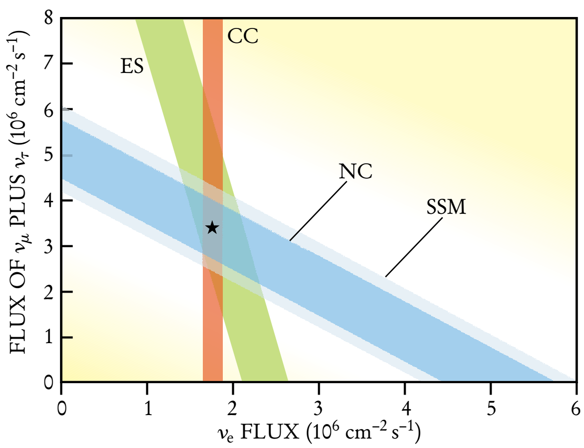

FIGURE 2. FLUX OF NEUTRINOS from boron-8 decay in the Sun, detected in various flavors by the Sudbury Neutrino Observatory. The flux of electron neutrinos is plotted against the combined flux of μ and τ neutrinos. The 1-standard-deviation bands indicate data for the charged-current reaction (CC), the neutral-current reaction (NC), and elastic scattering (ES) off electrons. The best overall fit (star) indicates that two-thirds of the Sun's ^{8}B neutrinos have changed flavor. The light blue band behind the NC data is the standard solar-model (SSM) prediction for the total ^{8}B neutrino flux, irrespective of flavor changes. (Adapted from ref. 1.)

The 50-kiloton Super Kamiokande detector has to be much larger than SNO because the cross section for reaction 3, which is the only useful neutrino interaction in a light-water Čerenkov detector, is so much smaller than the deuteron interaction cross sections. Of course, a kiloton of heavy water is enormously expensive. But SNO was able to borrow the precious liquid from Canada's heavy-water reactor program.

Figure 2 translates the event rates observed in SNO for the three reactions into three linear bands on a plot of the incident ν_e flux against the combined flux for the other two neutrino flavors. The point where they cross yields the flavor decomposition of the arriving flux of solar neutrinos. Confidence in this decomposition is bolstered by the observation that the three experimental bands do indeed cross essentially at one point. And a fourth band, impressively shadowing the newly measured experimental band for the neutral-current reaction 2, is the SSM theoretical prediction for the total flux of ^{8}B neutrinos from the Sun. The message is that the Sun's output of electron neutrinos is just about what astrophysical theory expects, but that about two-thirds of the highest-energy solar neutrinos arrive here in altered guises.

To improve the detection efficiency for neutrons liberated in the neutral-current reaction, the SNO collaboration has recently added salt to the heavy water. Chlorine captures neutrons more readily than does deuterium, and the capture releases a more energetic γ. Eventually, neutron counters filled with helium-3 will be deployed throughout the detector. Near Super Kamiokande, a new facility called KamLAND is just now getting into the solar-neutrino business.[6] The KamLAND detector, housing a kiloton of liquid scintillator, will not only be peering at the Sun. It also looks at surrogate "solar" neutrinos from more than a dozen power reactors 80–800 km away. Those distances and the energy spectrum of the reactor neutrinos turn out to be particularly felicitous for examining neutrino oscillation in the region of θ, Δm^2 parameter space favored by the SNO solar-neutrino results.

When experimenter Raymond Davis, theorist John Bahcall, and coworkers, in back-to-back *Physical Review Letters* in May 1968, reported the first evidence of a shortfall of solar neutrinos, the reaction—aside from skepticism—was that the prevailing theory of the solar core must be inadequate. Now it's quite clear that the inadequacy lay elsewhere—in our understanding of the neutrino. The complexities of neutrino physics, as they are gradually revealed in the various observational domains that appear to exhibit flavor oscillation, may turn out to be the guideposts that point the way to a more encompassing theory beyond today's standard model of the fundamental particles.

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6. See http://www.awa.tohoku.ac.jp/html/KamLAND.

Bell Labs Convenes Committee to Investigate Questions of Scientific Misconduct

For the past two years, the sun has been shining brightly on researchers from Bell Labs, Lucent Technologies, who have come up with a method to endow many organic materials with unexpected and exciting properties. A dark cloud now looms over these researchers because of apparent similarities among figures that they published in different papers, reporting on different experiments. As soon as outside scientists called these similarities to the attention of Bell Labs management, Cherry Murray, senior vice president of physical-sciences research, appointed a special committee to explore whether the figures are evidence of scientific misconduct. The committee, headed by Malcolm Beasley of Stanford University, hopes to complete its inquiry by summer's end.

The concern arose when some researchers within Bell Labs told Lydia Sohn of Princeton University that they had noticed a strong resemblance between two papers by three of their Bell Labs colleagues, one appearing in *Nature* and the other in *Science*.[1,2] Both papers described field-effect transistors (FETs) made from self-assembled monolayers of organic materials, but the two papers dealt with slightly different materials. One can lay one curve on top of the other and see that the patterns of noise at the low and high voltage ends is the same, down to each supposedly random wiggle, as seen in parts *a* and *b* of the figure on page 16. The lead author on both papers, Jan Hendrik Schön, has since claimed he got the figures mixed up and has published a corrected figure.[3]

Paul McEuen of Cornell University then found a third figure, from an earlier paper[4] reporting on an FET made with pentacene crystals, whose high voltage tail looks the same as that in the other two papers, as seen in part *c* of the figure. McEuen and Sohn went on to find two other sets of similar curves from different papers. In all, the suspicions extended to figures from six papers, appearing in *Science, Nature*, and *Applied Physics Letters*. Schön is the lead author on all six papers and the only one with his name on each. Since then, questions have been raised about some related Bell Labs papers.

> Is there an innocent explanation for the appearance of similar figures in different publications?

Members of the condensed matter community interviewed for this story were all saddened by these events. They recognize that the evidence, taken at face value, is quite disturbing. However, they are hoping for the most benign possible explanation, which neither invalidates the exciting phenomena that have been reported nor besmirches the reputations of the scientists involved, all of whom have been highly regarded. Some, like Schön have been seen as very promising young researchers, and the most senior-ranking coauthor on many of the papers, Bertram Batlogg (now at ETH Zürich), has a distinguished research record.

Promising devices

Much of the research that is being brought into question uses an FET. Such a device typically consists of a thin crystal that has been coated on top with a thin layer of insulator, usually aluminum oxide. A gate electrode is placed on top of the insulating layer, so that applying a voltage of a given sign to the gate repels charges of the same sign in the crystal, leaving an excess of the opposite charge on the crystal's surface. A voltage difference applied across the crystal by way of source and drain electrodes then causes current to flow through the charged region.

The FET arrangement essentially allows Schön and colleagues to dope organic materials electronically. They began by studying the semiconducting behavior of organic crystals, measuring mobilities of holes and electrons, and so forth.[5] More dramatically, they reported making superconductors out of such unexpected candidates as pentacene and tetracene (see Physics Today, September 2000, page 16). They also reported doping carbon-60 molecules with holes, a feat that hadn't been possible by chemical means; they made such hole-doped buckyballs superconduct at higher temperatures than their electron-doped counterparts—and at even higher temperatures when they intercalated additional atoms between the multicarbon spheres (see Physics Today, January 2001, page 15, and October 2001, page 19).

Such results as superconducting properties of pentacene use the FETs as a tool for doping; other Bell Labs work deals with organic-based FETs as devices in their own right. The three sets of figures originally called into question concern the device characteristics of the FETs.

Even before the recent concern about similar-looking figures, condensed matter researchers had been growing increasingly frustrated and uneasy about the Bell Labs work on organic crystals and thin films because no team had been able to reproduce the results. Arthur Ramirez and his group at Los Alamos National Laboratory now seem to be on the right track: They have used the FET arrangement to dope a C_{60} crystal grown at Bell Labs and to reduce its resistance to a value consistent with metallicity. They are hoping to be able to make it superconduct.

Of course, the lack of confirming evidence is an entirely different matter from evidence of data tampering. As Beasley commented, members of his committee will have to divide the information they are gathering into strong criticism that is a normal part of the scientific process and claims of