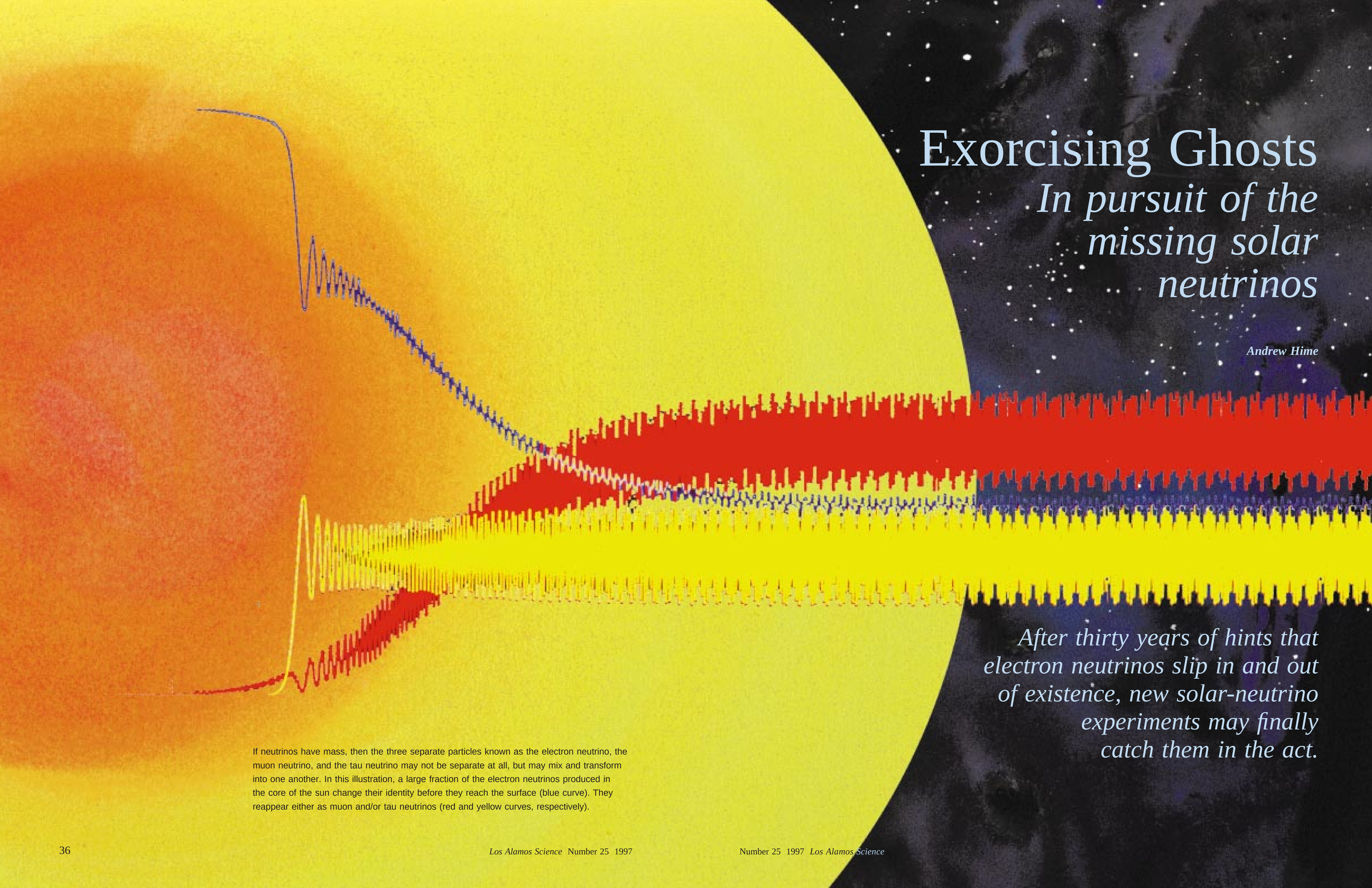


Exorcising Ghosts

In pursuit of the missing solar neutrinos

Andrew Hime

After thirty years of hints that electron neutrinos slip in and out of existence, new solar-neutrino experiments may finally catch them in the act.

If neutrinos have mass, then the three separate particles known as the electron neutrino, the muon neutrino, and the tau neutrino may not be separate at all, but may mix and transform into one another. In this illustration, a large fraction of the electron neutrinos produced in the core of the sun change their identity before they reach the surface (blue curve). They reappear either as muon and/or tau neutrinos (red and yellow curves, respectively).

In October 1920, Sir Arthur Eddington, one of the foremost astrophysicists of the century, delivered his residential address to the British Association at Cardiff. In his speech, entitled The Internal Constitution of the Stars," e referred to a proposal suggested the ear before by the former president of he association to bore a hole into the rust of the earth in order to discover the onditions deep below. Motivated by the apid progress in astronomy at the time, ir Eddington proposed something easier" to penetrate, namely, the Sun.

Eddington could scarcely have anticipated the ramifications of his suggeson. After more than seventy-five years f study, the scientific community's nvestigations of our closest star have ielded a remarkably detailed underanding of what makes the Sun shine. We now know that the Sun is powered y thermonuclear fusion and that its hot ore can be considered an immense furace producing not only heat and light, ut also vast numbers of neutrinos.

Because of the Sun's enormous size, he light produced deep in its interior akes tens of years to reach its surface. During that lengthy journey, the phoons that rain down upon us as sunlight nd make our existence on Earth ustainable lose all the information oncerning the detailed processes of he stellar core. Unlike photons, neutrios interact so feebly with matter that hey escape from the Sun in about seconds. They arrive on Earth a mere minutes later, and thus the solar eutrinos are a unique probe of a star's nnermost regions and of the nuclear eactions that fuel them.

During the past thirty years, detailed heoretical and experimental studies ave resulted in very precise predicons about the fluxes and energy speca of neutrinos produced deep within he Sun. But a problem has emerged. our different experiments have meaured the flux of solar neutrinos, and very one of them reports a flux that is gnificantly below theoretical predicons. The discrepancy is referred to s the *solar-neutrino problem*, and it is particularly puzzling because scientists have failed to find errors in the standard theoretical framework of the Sun or in the terrestrial experiments monitoring the neutrinos.

Where have the solar neutrinos gone? One intriguing answer may lie outside our conventional understanding of physics. Whereas a remedy based upon modifications in solar models appears difficult to construct, scientists are particularly excited about the possibility that something profound may happen to the neutrinos as they make their way out of the Sun en route to Earth.

We know of three different types, or flavors, of neutrinos—the electron, muon, and tau neutrinos. We also know that the nuclear reactions that power the Sun are energetic enough to produce only electron neutrinos. Moreover, existing experiments that detect solar neutrinos are only sensitive to the electron flavor. One can thus speculate that some of the electron neutrinos produced in the Sun have transformed, or oscillated, into muon and/or tau neutrinos as they make their way to Earth, thereby escaping our terrestrial detectors. The probability for oscillations to occur may even be enhanced in the Sun in an energy-dependent and resonant manner as neutrinos emerge from the dense core. This phenomenon, an example of the Mikheyev, Smirnov, and Wolfenstein (MSW) effect, is considered by many scientists to be the most favored solution to the solar-neutrino problem.

Neutrino oscillations, or the periodic changes in neutrino flavor, require that neutrinos possess mass and that neutrino flavor not be conserved in nature. No undebated evidence for neutrino mass exists despite years of painstaking research around the world. Indeed, the Standard Model of elementary particles requires that neutrinos be strictly massless. Nonetheless, quests for a Grand Unified Theory of the fundamental forces in nature suggest that neutrinos, like other elementary particles, should have mass. Consequently, should the solar-neutrino problem be resolved by invoking neutrino mass and oscillations, the result would be evidence for physics beyond the Standard Model. The models that emerge from elementary particle physics, astrophysics, and cosmology would be subject to a new set of constraints and would have to be modified with potentially profound implications.

The status of the solar-neutrino problem, along with how new experiments propose to solve it, forms the central theme of this article. Particular emphasis is reserved for the Sudbury Neutrino Observatory, an experiment under construction that promises to resolve the question of whether neutrino oscillations, and in particular the MSW effect, are responsible for the observed shortfall of solar neutrinos.

Neutrinos from the Sun

Given the enormous power produced by the Sun and its twenty-billion-year lifetime, it is a steadfast conclusion that the Sun produces energy via thermonuclear fusion. During the late 1920s and early 1930s, theoretical calculations, including the seminal work of a young Hans Bethe, elucidated our understanding of the details of these processes. As shown in Figure 1, the fusion of protons into helium proceeds via three branches. Neutrinos are created in four different reactions, referred to simply as the *pp*, *pep*, beryllium-7 (^{7}Be), and boron-8 (^{8}B) reactions. The neutrinos flee the Sun and begin their voyage to Earth. (In Figure 1, we have omitted neutrinos that emerge from the carbon-nitrogen-oxygen, or CNO, cycle. The cycle is another, though less important, set of neutrino-producing reactions in the Sun.)

Figure 2 shows the predictions of the standard solar model for the flux of electron neutrinos at the earth's surface. The flux is the number of neutrinos per square centimeter per second. (The figure assumes no electron neutrinos have oscillated into a different flavor.) The *pp* reaction is the primary mode of neutrino production, and the reaction completely dominates energy production in the Sun.

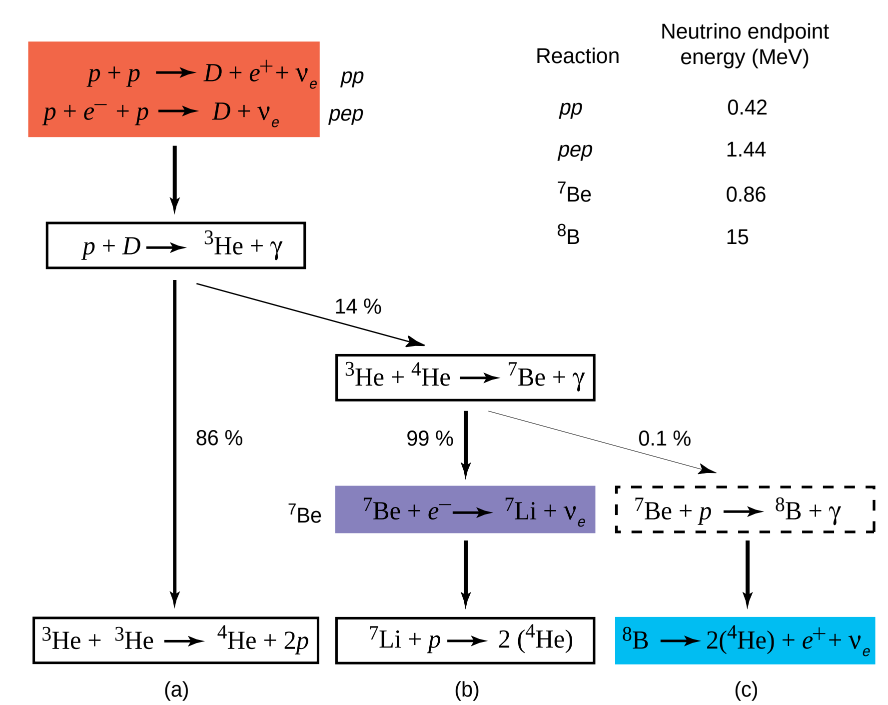


Figure 1. The Primary Neutrino-Producing Reactions in the Sun
Nearly all the Sun's energy comes from the fusion of protons into deuterium nuclei. The deuterium is converted into helium-4 by following one of three reaction pathways (labeled a, b, and c). Of the reactions shown, four proceed via charge-changing weak interactions (colored boxes) and therefore produce electron neutrinos. Over 95 percent of the neutrinos are created in the *pp* fusion reaction. One proton undergoes inverse beta decay, creating a neutron, positron, and an electron neutrino. The neutron then binds to the proton to form a deuteron (labeled D). Other neutrino-producing reactions are *pep* (electron capture), ^{7}Be (electron capture), and ^{8}B (beta decay). Notice that ^{7}Be is needed to produce ^{8}B (dashed box). Modern experiments, however, observe neutrinos from the *pp* reaction and ^{8}B decay, but hardly any from ^{7}Be decay.

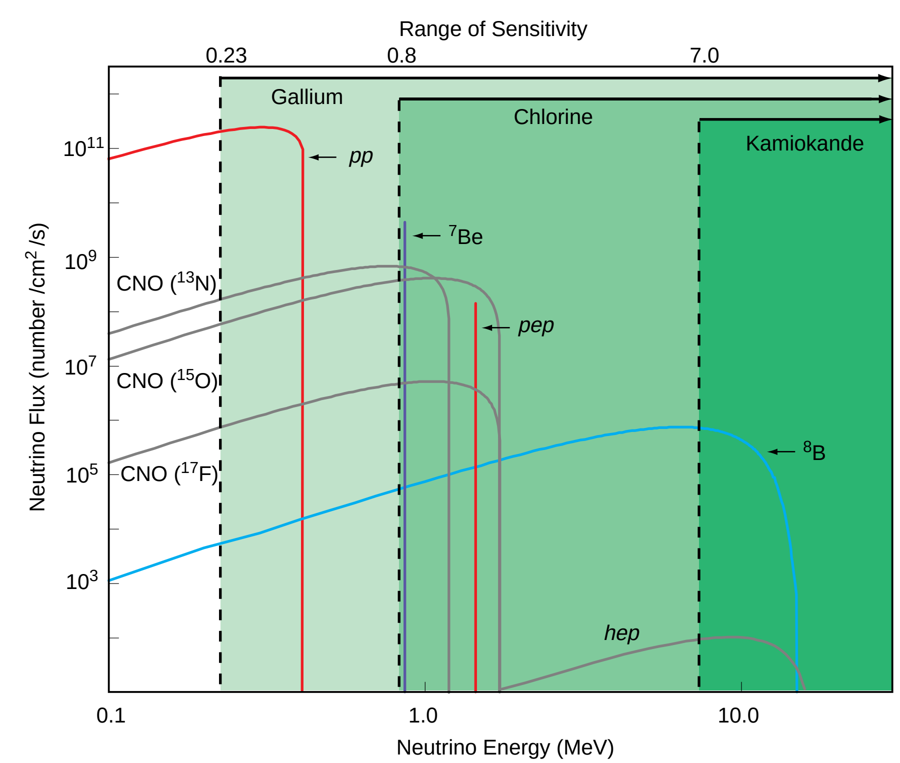


Figure 2. Solar-Neutrino Spectrum
The total integrated flux of all solar neutrinos reaching the earth is about 65 billion per square centimeter per second. In this figure, the neutrino flux and energy are plotted on log scales; so, for example, the *pp* flux is about 50 times greater than the ^{7}Be flux. Also shown are the spectra of neutrinos produced from the CNO cycle (gray curves). The *pp*, ^{8}B, and CNO neutrinos are created in beta decay reactions. A neutrino so produced shares energy with another light particle. Hence, all those neutrinos have a broad energy spectrum. The ^{7}Be and *pep* neutrinos result from electron capture: A proton in a nucleus captures an electron from an atomic orbital, turns into a neutron, and a monoenergetic neutrino is created. The sensitivity range of the various solar-neutrino experiments is also shown here. The gallium experiments have energy thresholds around 0.23 MeV and are sensitive to all solar neutrinos. The chlorine experiment detects neutrinos from the ^{7}Be and CNO reactions, but is primarily sensitive to those from the ^{8}B reaction. Kamiokande is a water Cerenkov detector that can detect only the high-energy portion of ^{8}B neutrinos.

onsequently, it is ultimately linked to many solar observables. Indeed, measurements of the light output of the un (its luminosity) place rather stringent constraints on the rate of the *pp* eaction. As such, a prediction of the associated *pp* neutrino flux hardly changes s the details of a solar model change.

But neutrino fluxes from the ^{7}Be and B reactions are many times smaller han the *pp* flux. The magnitude of hose fluxes depends critically on the etails of a solar model and in particuar on the physical inputs that can alter he central temperature of the Sun (typcally calculated to be about 15 million elvins). Specifically, the ^{8}B flux, which is manifested as a mere one hunredth of 1 percent of the total flux of olar neutrinos, varies as the 25th ower of the core temperature. Hence, variation in this temperature of only a ew percent can drastically alter the rediction of the ^{8}B neutrino flux.

Four pioneering experiments have measured the solar-neutrino flux. These xperiments were designed to detect eutrinos via their interactions with uclei or electrons in the target material making up the host detector. Because he target materials were different, the xperiments were sensitive to different eutrino energies, as indicated in igure 2. Taken together, the experiments that are discussed below have rovided a coarse mapping of the entire olar-neutrino spectrum.

The Pioneering Experiments

Given data on the Sun's luminosity, he standard solar model provides a ather straightforward prediction for the otal flux of solar neutrinos reaching the arth. Specifically, some 6.57×10^{10} re predicted to pass through every quare centimeter of our planet each econd. Despite this impressive number, he neutrinos interact so weakly with matter that the probability of detecting ny one of them is miniscule. Another way to state the problem is that an tom presents an extremely tiny target to the neutrino. Hence, to have any hope of catching a neutrino, one either waits a long time or builds a monstrous detector that contains a huge number of target atoms.

Solar-neutrino experiments exploit both strategies. The experiments run for years and make use of detectors that contain hundreds to thousands of tons of target material. Even so, neutrino interactions are still rare in these watchful behemoths. Typically, one expects to record only a few events *per day*! Consequently, the detectors are buried under mountains or burrowed into mine shafts in order to prevent cosmic rays from striking the target and inducing background signals. The locations underscore the ironic truth surrounding solar-neutrino experiments—one can move deep into the earth and still see the sun shine!

The Chlorine Experiment. This ground-breaking experiment has been in progress for nearly thirty years. Situated 4,500 feet underground in the Homestake Mine in South Dakota, the experiment uses a large tank of perchloroethylene (C_2Cl_4), a common dry-cleaning fluid, to snare the ghostly neutrinos.

Electron neutrinos ν_e from the Sun make themselves known through the inverse-beta-decay reaction on chlorine nuclei:

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^- \quad . \qquad (1)$$

A neutron in the chlorine-37 (^{37}Cl) nucleus is transformed into a proton to yield the daughter argon-37 (^{37}Ar) nucleus with the emission of an electron (e^-). The neutrino must have at least 0.814 million electron volts (MeV) of energy in order to drive this reaction. This means (see Figure 2) that the chlorine experiment is sensitive to neutrinos from the ^{7}Be, *pep*, and ^{8}B reactions. Although the number of ^{7}Be neutrinos is predicted to be far greater than that of ^{8}B neutrinos, the largest signal in the chlorine experiment is due to the ^{8}B neutrinos. This is because the daughter ^{37}Ar nucleus has an excited state that can be accessed only by the high-energy neutrinos present in the ^{8}B spectrum. Consequently, those neutrinos have a larger interaction-cross-section and are detected at a greater rate.

Once produced, the unstable ^{37}Ar atoms eventually decay by recapturing an orbital electron (half-life approximately 35 days) and become once again ^{37}Cl. Characteristic x-rays are emitted that signal the decay, but they can only be detected after the ^{37}Ar atoms have been extracted from the chlorine tank. Bubbling helium gas through the vat of cleaning fluid entrains and removes the unstable ^{37}Ar atoms, which are swept into an external detector that looks for the x-rays.

To say that the extraction procedure needs to be efficient is a severe understatement. Only a single atom of ^{37}Ar is produced every two days in a 615-ton detector housing some 2×10^{30} chlorine nuclei! Yet exhaustive tests of the ^{37}Ar extraction process have proved it is not only efficient, but also reliable. After twenty-seven years of operation in the Homestake Mine, the chlorine experiment has measured an average neutrino flux that falls a factor of 3 below the predictions of the standard solar model.

The Kamiokande Experiment. The discrepancy between the measured and predicted solar-neutrino flux gave rise to much speculation about its origin, including exotic solutions such as neutrino oscillations. It also motivated the development of new solar-neutrino experiments.

First to come online of the "second-generation" experiments was Kamiokande. That experiment, situated 1 kilometer underground in the Kamioka Mine in the Japanese Alps, used a detector that was originally constructed to search for proton decay. Although the proton is a stable particle in the Standard Model of elementary particles, Grand Unified Theories predict that the proton would decay, albeit with an extremely long half-life.

But Kamiokande revealed no proton decays, and given the persistence of the solar-neutrino deficit measured in the chlorine experiment, the detector was upgraded to increase its sensitivity to the solar-neutrino signal.

The Kamiokande detector—a huge, cylindrical tank filled with 3,000 tons of purified water (H_2O)—is a Cerenkov detector. Neutrinos are detected in real time after they undergo elastic scattering with electrons in the water target:

$$\nu_e + e^- \rightarrow \nu_e + e^- \quad . \qquad (2)$$

The neutrino imparts energy to the electron, which streaks through the water at relativistic speeds. The Cerenkov radiation emitted by that speedy electron was detected by an array of photomultiplier tubes surrounding the water target. Reconstructing the event allowed determining the energy and direction of the neutrino. Of all the first- and second-generation neutrino experiments, only Kamiokande could determine that the detected neutrinos indeed originated in the Sun.

The Kamiokande experiment could detect neutrinos with energies greater than 7 MeV. (The signals from lower-energy neutrinos were overwhelmed by detector background signals.) Kamiokande therefore provided a measurement of only the high-energy portion of the ^{8}B solar-neutrino flux (see Figure 2). After about 2,000 days of data acquisition, the Kamiokande collaboration reported results that were a factor of 2 below the predictions of the standard solar model. Hence, like the chlorine experiment, Kamiokande witnessed a significant deficit of solar neutrinos by comparison with solar-model predictions.

How does one reconcile this nagging discrepancy between theory and experiment? As mentioned earlier, the intensity of the ^{7}Be and ^{8}B neutrino fluxes depends delicately on the details of astrophysical models. Indeed, the core temperature of the Sun need only be a wee bit lower in order to reduce the ^{8}B flux prediction by a factor of 2. Furthermore, the ^{8}B branch of the solar-neutrino spectrum constitutes a meager 0.01 percent of the total integrated neutrino flux from the Sun. Hence, one is inclined to simply ignore the small departure from theory and to appreciate a remarkable achievement: The solar model has predicted correctly (albeit within a factor of about 2) the intensity of a 0.01 percent branch of a solar-neutrino signal that varies as the 25th power of the core temperature! This fact alone is a clear indication that the basic ingredients of the astrophysical models are sound and that the models of the Sun and other main-sequence stars are essentially correct.

Nonetheless, physicists are a tenacious breed. Confident of their models and their experimental results, they speculated that the explanation behind the "missing" neutrinos lay fundamentally in the properties of the neutrino, rather than in some misunderstanding about astrophysics. And while the strong dependence of the ^{8}B flux on temperature left significant room to question the solar models, the fundamental nature of the neutrino deficit became even more compelling with data from two experiments that measured the dominant *pp* neutrino flux.

Gallium Experiments. SAGE (for Soviet-American, later Russian-American, gallium experiment) and GALLEX (gallium experiment) were new radiochemical experiments similar in nature to the chlorine experiment. However, they employed gallium as the neutrino target, which extended the energy sensitivity of the detector down to the energy of the *pp* neutrinos. The experiments were based on the reaction

$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^- \quad . \qquad (3)$$

This reaction has an energy threshold of only 0.2332 MeV. As shown in Figure 2, SAGE and GALLEX were sensitive to all components of the solar-neutrino spectrum. SAGE, for which Los Alamos National Laboratory was the lead American institution, is described in detail in the box "The Russian-American Gallium Experiment" on page 152.

The detection and measurement of the *pp* flux were something of a triumph for physicists. They represented the first experimental verification that the sun is indeed powered by thermonuclear fusion and that the power generated by the sun derives mostly from the *pp* fusion reaction. Again, theorists were led to conclude that the basic ingredients describing how the sun shines were understood and correctly implemented in astrophysical models.

However, the data from both SAGE and GALLEX confirmed the solar-neutrino deficit. Approximately half of the expected flux was observed. Those results significantly reshaped our understanding of the solar-neutrino problem.

The Modern Solar-Neutrino Puzzle

Data from the four pioneering experiments—chlorine, Kamiokande, SAGE, and GALLEX—provided information essentially across the entire solar-neutrino spectrum, from the low-energy and dominant *pp* flux up to and including the high-energy, but much less intense, ^{8}B flux. The experimental results and theoretical predictions are summarized in Table I. In all cases, the experimental results fall significantly below the predictions of the standard solar model. However, as indicated by the analysis outlined in Table II, the problem is even more perplexing.

Because each experiment is sensitive to different but overlapping regions of the solar-neutrino spectrum, the individual contributions to the total neutrino flux of the *pp*, ^{7}Be, and ^{8}B neutrinos can be estimated. All that is required is an analytical procedure that simultaneously takes into account all the experimental results and the solar-luminosity constraint. The intriguing result is

able I. Summary of Pioneering Solar-Neutrino Experiments

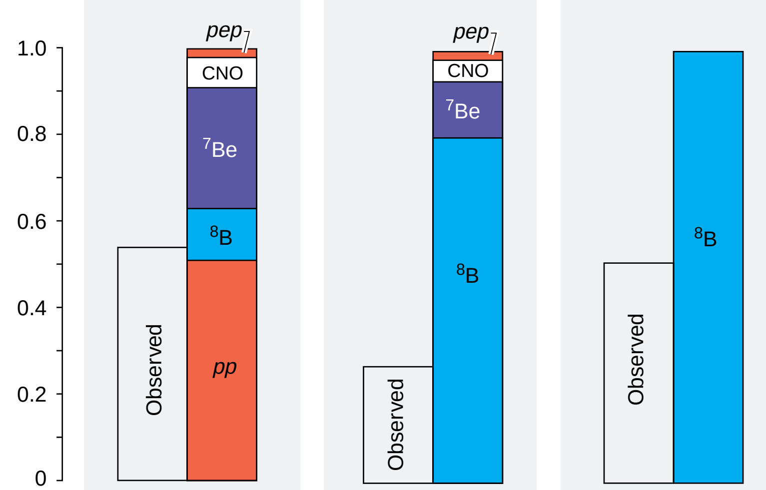
	SAGE + GALLEX	Chlorine	Kamiokande
Target Material	^{71}Ga	^{37}Cl	H_2O
Reaction	$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$	$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$	$\nu + e^- \rightarrow \nu + e^-$
Detection Method	Radiochemical	Radiochemical	Cerenkov
Detection Threshold	0.234 MeV	0.814 MeV	7.0 MeV
Neutrinos Detected	All	^7Be and ^8B	^8B
Predicted Rate	132 ± 7 SNU*	9 ± 1 SNU	5.7 ± 0.8 flux units**
Observed Rate	74 ± 8 SNU	2.5 ± 0.2 SNU	2.9 ± 0.4 flux units

*1 SNU = 10^{-36} captures per target atom per second.
**In units of 10^6 neutrinos per square centimeter per second.

ach column summarizes an experiment and compares the predicted rate of neutrino interactions (based on the Bahcall-insonneault standard solar model) to the observed rate. The radiochemical experiments report their results in SNU, a convenient nit that facilitates comparison between experiments. Kamiokande reports results in flux units. Every experiment shows a significant eficit in the observed versus the predicted rate.

able II. Breakdown of the Predicted Rate by Neutrino-Producing Reaction

Neutrino Reaction	SAGE + GALLEX	Chlorine	Kamiokande
pp	70 SNU	0 SNU	0
pep	3 SNU	0.2 SNU	0
^7Be	38 SNU	1.2 SNU	0
^8B	16 SNU	7.4 SNU	5.7
CNO	10 SNU	0.5 SNU	0
otal Predicted Rate	132 ± 7 SNU	9 ± 1 SNU	5.7 ± 0.8
Observed Rate	74 ± 8 SNU	2.5 ± 0.2 SNU	2.9 ± 0.4



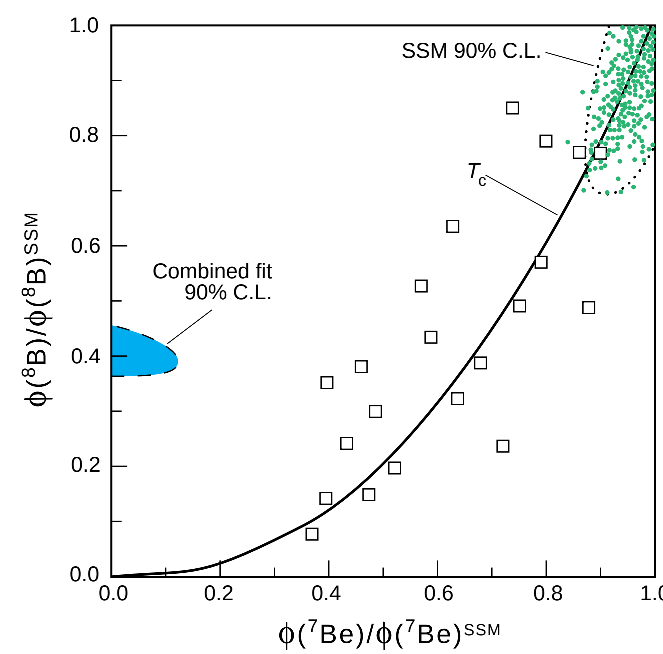
Based on the standard solar model, the total predicted rate of neutrino events can be broken down into contributions from each of the neutrino-producing reactions in the Sun. This information is listed in each column (rounded to the nearest SNU) and is displayed as a bar graph. (The bars corresponding to the total predicted rate have been normalized to 1.) Each colored segment within a bar corresponds to a specific reaction. Kamiokande observed approximately half of the expected flux of ^8B neutrinos. All the neutrinos detected by the chlorine experiment can likewise come from the ^8B reaction. The solar luminosity essentially fixes the rate of *pp* neutrinos that SAGE and GALLEX must see. Those experiments are consistent with an observation of the full *pp* flux plus some of the ^8B flux. Taken together, the experiments indicate that the solar-neutrino deficit results from a lack of intermediate-energy (CNO, ^7Be, and *pep*) neutrinos.

Figure 3. The Modern Solar-Neutrino Problem

One can deduce how the theoretical neutrino flux needs to be distorted in order to match the experimental results. In their analysis, Hata and Langacker (1994) constructed an arbitrary solar model in which the neutrino fluxes are allowed to vary freely instead of being tied to nuclear physics or to astrophysics. The only constraint is the one imposed by the solar luminosity, namely, that the sum of the *pp*, ^7Be, and CNO fluxes roughly equals 6.57×10^{10} neutrinos per square centimeter per second (the total neutrino flux). The model is then "fit" to the combined data from all experiments.

Source of Neutrinos	Φ/Φ^{SSM}
pp	1
^7Be	0
^8B	0.4

The model that best fits the data is one in which the *pp* flux is identical with the standard-solar-model (SSM) prediction, the ^7Be flux is nearly absent, and the ^8B flux is only 40 percent of the SSM prediction. These results are presented in the table (left) as the ratio of Φ, the flux derived from the combined fit, to Φ^{SSM}, which is the neutrino flux predicted by the SSM.



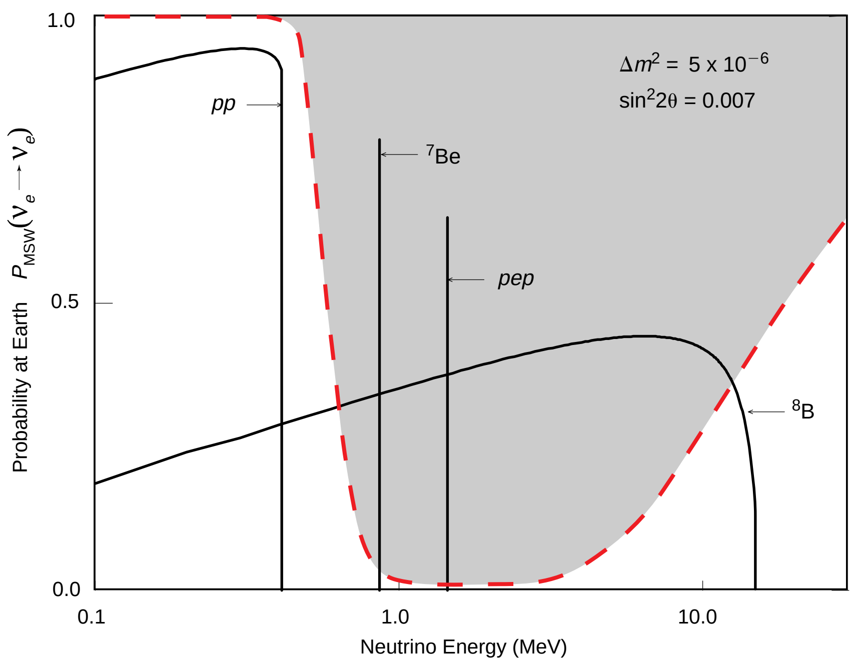
The 90 percent confidence level for the combined fit is shown in blue on this graph of ^8B flux versus ^7Be flux (each normalized to the SSM predictions). The 90 percent confidence level for the Bahcall-Pinsonneault SSM is shown at the upper right-hand corner. Filling that contour are the results of 1,000 Monte Carlo simulations (green dots) that vary the parameters of the SSM. The square markers indicate the results of numerous nonstandard solar models, which include, for example, variations in reaction cross sections, reduced heavy-element abundances, reduced opacity models, and even weakly interacting massive particles. Most of the models call for a power law relation between the ^8B and ^7Be fluxes (the curve labeled T_c). As the figure shows, the SSM and all nonstandard models are completely at odds with the best fit to the combined experimental results.

shown in Figure 3. Compared with the solar-model predictions, the *pp* neutrino flux, with a maximum neutrino energy of 0.42 MeV, seems to be present in full strength. The intermediate-energy ^7Be neutrinos, however, seem to be missing entirely, while only 40 percent of the high-energy ^8B neutrinos are observed.

This energy-dependent suppression of the solar-neutrino spectrum establishes what we now refer to as the *modern solar-neutrino problem*. It is particularly puzzling given the apparent lack of ^7Be neutrinos. At a glance, this might imply that ^7Be is not being produced in the sun. But those nuclei are needed to produce ^8B (refer to Figure 1). Hence, if there are no ^7Be neutrinos, why are *any* ^8B neutrinos observed? While modifications to the solar models have been attempted by many authors, it appears extremely difficult to render an astrophysical explanation that would solve this puzzle. As seen in Figure 3, no model has successfully reduced the ^7Be flux without reducing the ^8B flux even more!

However, this pattern for the solar-neutrino spectrum is perfectly explained by the mechanism of matter-enhanced neutrino oscillations, or the MSW effect. (See the article "MSW" on page 156.) MSW suggests that the probability for neutrino oscillations to occur *in vacuo* can be augmented in an energy-dependent, resonant fashion when neutrinos travel through dense matter. The muon or tau neutrinos would not be detected in the existing experiments on Earth, and hence a deficit would be seen in the solar-neutrino flux. For suitable choices of neutrino masses and mixing angles, experiments would measure the full, predicted flux of *pp* neutrinos, the ^7Be flux would be highly suppressed, and the measured flux of ^8B neutrinos would be reduced to 40 percent! (See Figure 4.)

Have three decades of solar-neutrino research culminated in the discovery of neutrino mass? Our interpretation of the modern solar-neutrino problem relies upon our confidence that the standard



igure 4. Energy-Dependent Survival Probability for Solar Neutrinos

he MSW effect predicts that the energy spectrum of the Sun's electron neutrinos ould be distorted from standard-solar-model predictions. Because of their charged-urrent interactions with electrons, electron neutrinos can acquire an effective mass hen they pass through dense matter. If that effective mass becomes as large as the trinsic mass of a muon or tau neutrino, the electron neutrino can resonantly trans-orm into another flavor. The spectrum becomes distorted. The MSW survival robability $P_{MSW}(\nu_e \rightarrow \nu_e)$ that an electron neutrino remains an electron neutrino epends on the neutrino mass difference (Δm^2), the mixing angle θ between the fferent neutrino flavors, the neutrino energy, the electron density in the material, nd the strength of the interaction between electron neutrinos and electrons. Given he Sun's density profile, the chosen values for Δm^2 and $\sin^2 2\theta$ will yield a survival robability that distorts the predicted solar-neutrino energy spectrum for best greement with the measured flux. The result is the red curve, which has been uperimposed over a simplified picture of the solar-neutrino spectrum. The *pp* flux unaffected, but the ^{7}Be and *pep* fluxes have almost no probability of surviving. oughly 40 percent of the ^{8}B neutrino flux survives.

olar model correctly predicts the solar-eutrino spectrum and that the existing xperimental results are accurate. Given he implications of massive neutrinos or elementary particle physics, strophysics, and cosmology, it is f paramount importance to confirm he solar-neutrino problem and to test he hypothesis of neutrino oscillations. hus, while theorists continue to nalyze and refine the solar models, xperimentalists are moving forward with the next generation of experiments.

The super-Kamiokande experiment, a 50,000-ton water-filled Cerenkov detector, is currently up and running. Because of its immense size, this detector accumulates in one day more data than its predecessor Kamiokande was capable of providing in one month! It has collected a significant amount of data on the high-energy region of the ^{8}B neutrino flux and has confirmed the results of Kamiokande.

Complementing that experiment is BOREXINO, an experiment that is still in its planning stages. The proposal calls for a detector to be situated in the Gran Sasso tunnel in Italy. Like super-Kamiokande, BOREXINO exploits the scattering of neutrinos from electrons in the target material, but unlike super-Kamiokande, it will use a liquid scintillator instead of water as the neutrino target. This allows for a much lower energy threshold so that the experiment will be highly sensitive to the ^{7}Be neutrinos. Because of the inherent energy resolution of its detector, BOREXINO should be able to focus on and isolate the ^{7}Be neutrino flux and thus allow scientists to deduce, independently, whether that branch is indeed missing from the solar-neutrino spectrum.

But it is fitting at this point to reemphasize that the Sun is energetic enough to produce only electron neutrinos and that the pioneering experiments were sensitive *only* to electron neutrinos. Deductions about neutrino oscillations came about only because the measured electron neutrino flux was found lacking when compared with the predictions of the standard solar model.

The ideal experiment would not have to rely on a model to allow data interpretation. Such an experiment would independently measure the electron neutrino flux and the *total* neutrino flux (electron, muon, and tau neutrinos). Independent measurement of the latter is perhaps the "Holy Grail" of solar-neutrino experiments. If electron neutrinos are experiencing flavor transitions into other states, then the electron neutrino flux would be observed to be lower than the total flux, and the neutrino oscillation hypothesis would be tested in a *model-independent* fashion. Such an experiment forms the motivation for establishing the Sudbury Neutrino Observatory.[1]

[1]In principle, super-Kamiokande is also sensitive to all neutrino flavors via the neutral-current channel of elastic scattering. The neutral- and charged-current signals, however, are identical and cannot be distinguished from each other. Experimenters cannot analyze the data and deduce that they have seen muon or tau neutrinos from the Sun, unless they compare their measured flux with one predicted by the solar model.

The Sudbury Neutrino Observatory (SNO)

SNO is a next-generation, real-time experiment that is designed to make independent measurements of (1) the flux and energy spectrum of ^{8}B electron neutrinos reaching the earth and (2) the *total* integrated flux of all ^{8}B neutrinos that reach the earth. These goals can be met because the water Cerenkov detector that is at the heart of SNO will be filled with a unique neutrino target consisting entirely of "heavy" water.

A heavy-water molecule has two deuterium atoms bonded to an oxygen atom (D_2O rather than H_2O). The deuterium nucleus—the deuteron—is a heavy isotope of hydrogen that consists of a bound proton and neutron. Thus, heavy water is chemically identical to ordinary "light" water (H_2O), and the SNO detector functions very much like the light-water Cerenkov detector used by Kamiokande and, later, super-Kamiokande. But the signal from a light-water Cerenkov detector derives solely from the elastic scattering of neutrinos with electrons. The heavy water in the SNO detector also allows for neutrino interactions with the nucleons making up the deuterium nucleus. And crucial to the SNO experiment, deuterium responds in different ways to charged- and neutral-current interactions (see Figure 5).

When the deuteron (D) interacts with electron neutrinos through the charged-current exchange of a W^+ boson, the neutron transforms into a proton, and a relativistic electron is emitted. The newly created nucleus contains two protons. These repel each other and break the nucleus apart:

$$\nu_e + D \rightarrow p + p + e^- \quad . \tag{4}$$

The protons do not recoil with sufficient energy to create a signal in the detector, but the electron produces Cerenkov radiation as it zips through the heavy water. The energy and direction of the electron neutrino can be extracted from that Cerenkov signal.

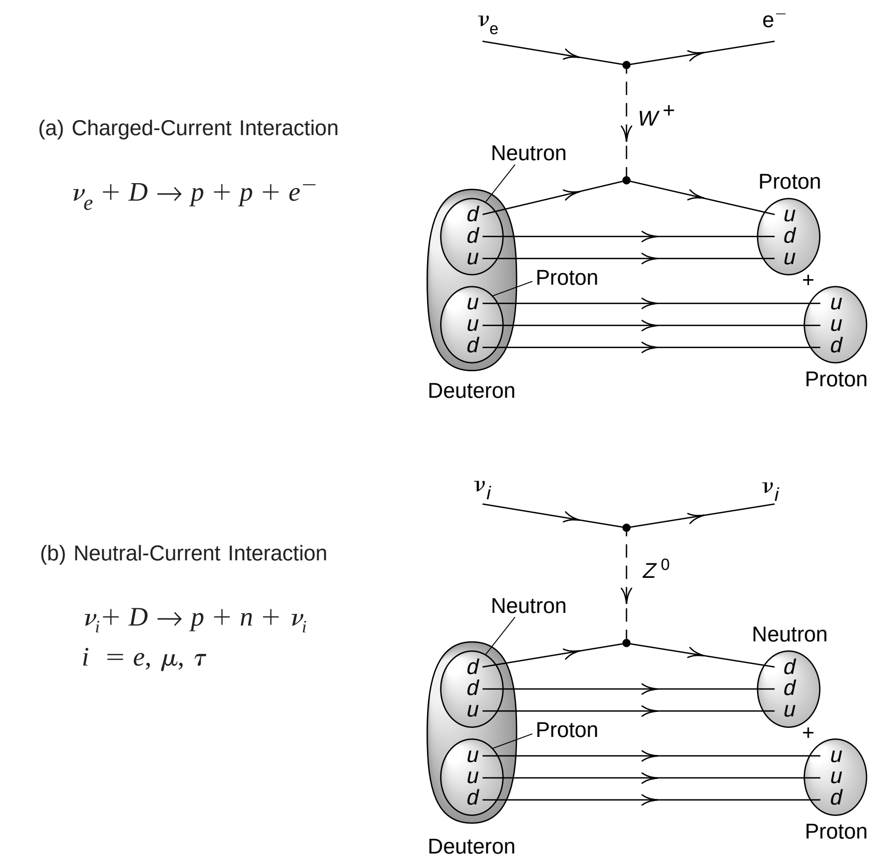


Figure 5. Neutrino Interactions in SNO

(a) The charged-current weak interaction in SNO proceeds only with electron neutrinos ν_e. The neutrino is transformed into an electron e^- as it exchanges a W^+ boson with one of the two down quarks *d* making up the neutron (*udd* quark combination). The quark is transformed into an up quark *u*, thus creating a proton (*uud*). The proton originally present in the deuteron does not participate in the interaction; it is merely a spectator. The unstable diproton system instantly breaks apart, so that the deuteron appears to disintegrate into two free protons and a relativistic electron. That electron is the signature of the reaction. (b) The neutral-current interaction can proceed with a neutrino of any flavor. The neutrino scatters from one of the quarks in either nucleon (proton or neutron) through the exchange of a Z^0 boson. Energy is transferred to the entire nucleon. If the energy transfer is greater than the 2.22 MeV nuclear binding energy, the deuteron breaks apart. The unbound neutron is the signature of the neutral-current interaction.

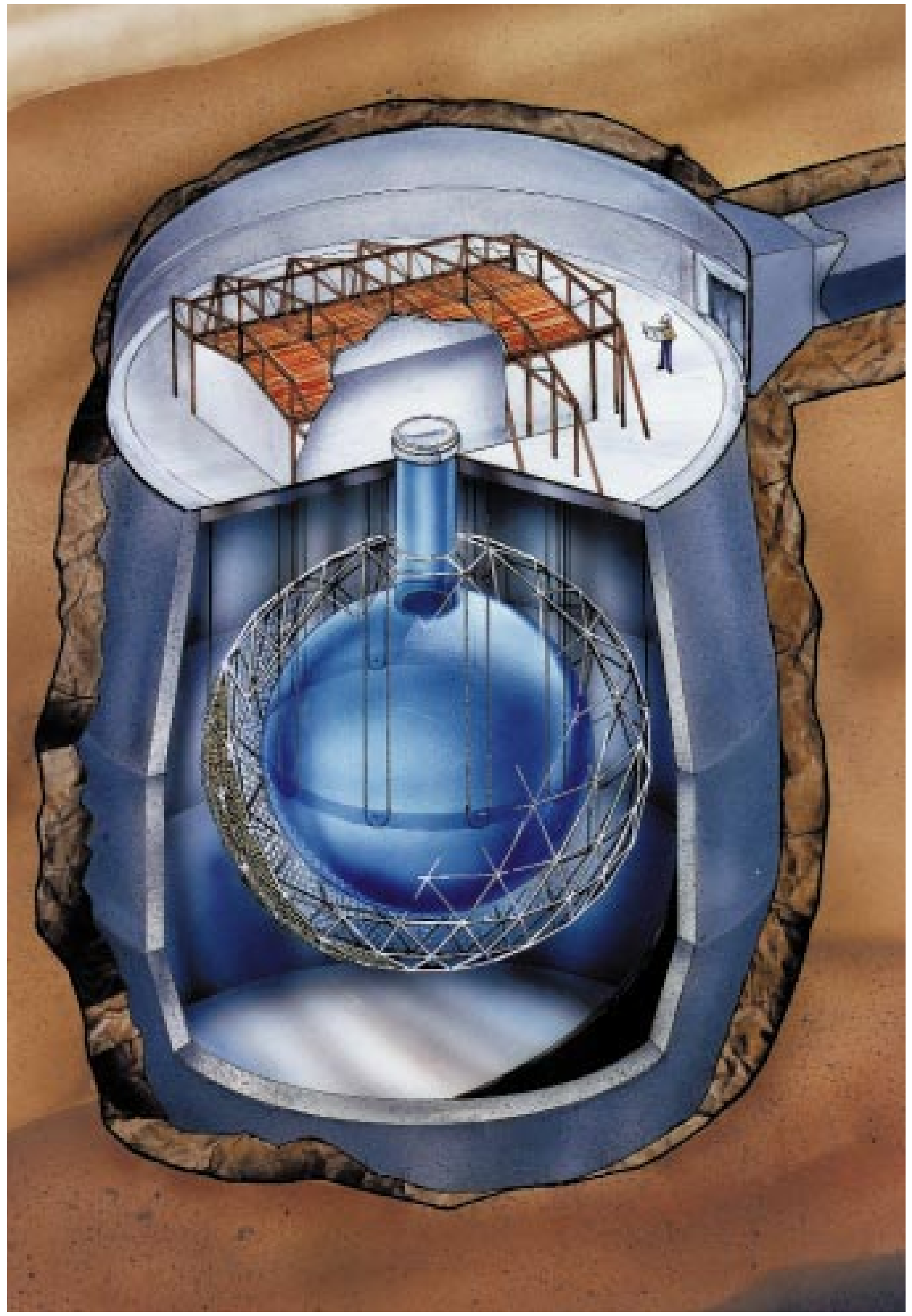
The neutral-current interaction, however, causes the deuteron to disintegrate without any change in particle identity. An exchange of a Z^0 boson transfers energy into the deuteron, which breaks into a proton and a neutron:

$$\nu + D \rightarrow \nu + p + n \quad . \tag{5}$$

Reaction (5) occurs with equal probability for any flavor of neutrino whose energy is above the 2.22-MeV binding energy of the deuteron. Detecting the free neutron is the key to observing this reaction, and techniques for extracting that signal will be discussed later. The main point to appreciate is that SNO can detect all neutrinos (regardless of flavor) and the electron neutrinos in two independent measurements. A comparison of the two fluxes will provide a definitive test of the

igure 6. The Sudbury Neutrino Observatory

he SNO detector sits in a large cavity at is over 2 kilometers underground in e Creighton Mine in Sudbury, Canada. he barrel-shaped cavity is 22 meters in ameter and 30 meters high. In its center es an acrylic bottle that will contain bout 1,000 tons of 99.92 percent isotopi- ally enriched D_2O. The 12-meter-diameter crylic sphere at the bottom of the bottle, e largest sphere of its kind in the world, constructed of 122 panels, each centimeters thick, that are machined and ermoformed before being assembled nderground. Surrounding the sphere will e a geodesic frame anchoring an array 9,800 photomultiplier tubes (PMTs). he 20-centimeter-diameter PMTs will be quidistantly spaced, 2.5 meters apart, utside the acrylic vessel. Filling the mainder of the cavity will be about 500 tons of ultrapure H_2O, which shields e D_2O volume from radioactive back- rounds while simultaneously providing echanical support for the acrylic vessel. ectron neutrinos interact in the detector produce relativistic electrons. The ectrons create Cerenkov radiation that detected by the PMTs. Based on the erenkov photons' time of arrival at the MTs and the number of PMTs that are iggered, the location, energy, and direc- on of the electron can be determined. All eutrino flavors can create free neutrons the D_2O by neutral-current interactions. he neutrons can be detected through e Cerenkov light produced by neutron apture on chlorine dissolved in the D_2O r, otherwise, by a secondary detector hat would sit inside the acrylic bottle.



eutrino oscillation hypothesis.

The idea of using heavy water as a eutrino target was first proposed in 984 by H. H. Chen. Upon visiting the reighton Mine in Sudbury, Canada, to iscuss a proton decay experiment, hen became aware that the Atomic nergy Commission of Canada had arge stockpiles of heavy water. He ubsequently pursued the possibility of orrowing about 1,000 tons. The SNO ollaboration was formed shortly there- after, and a feasibility study started in 1985 to evaluate the capabilities and practicality of building a heavy-water Cerenkov detector.

In 1986, an exploratory site was located wherein a cavity 20 meters in diameter could be constructed 6,800 feet underground in the Creighton Mine. A detailed proposal for SNO was reviewed in June 1988 by an international scien- tific and technical review committee that recommended that SNO be approved and funded as proposed. The SNO project is currently under construction by collaborators from twelve institutions in Canada, the United States, and the United Kingdom.

As shown in Figure 6, the 1,000 tons of 99.92 percent isotopically enriched heavy water will fill a huge acrylic bottle that is the centerpiece of the SNO detector. Surrounding the bottle will be 9,800 photomultiplier tubes that will detect the feeble Cerenkov light.

Approximately 7,500 tons of purified light water will encase the bottle and phototubes. That light-water jacket is needed to shield the detector from radioactive emissions emanating from the rock surrounding SNO.

The Charged-Current Spectrum in SNO. Measuring the Cerenkov spectrum due to the charged-current interaction of ^8B electron neutrinos shown in Reaction (4) is one of the primary goals of SNO. Should the neutral- to charged-current ratio indicate neutrino oscilla- tions, the shape of the charged-current spectrum could be used to probe differ- ent solutions to the solar-neutrino problem. For example, the MSW effect predicts a depletion in the flux of lower- energy ^8B neutrinos, and this reduced flux would be mostly evident as a change in the shape of the spectrum between about 5 and 8 MeV, as shown in Figure 7. SNO's detection ability and sensitivity to the charged-current signal have been assessed with computer simu- lations that predict the response of the detector to that signal and various anticipated background signals.

An example of such a simulation is shown in Figure 8. Below about 4 MeV, the detector is recording Cerenkov light that is due mostly to background processes (the "Cerenkov background wall"). Uranium and thorium atoms, which will unavoidably contaminate the heavy water and the detector materials, decay and produce energetic beta particles and gamma rays. These emissions create Cerenkov light when they streak through the heavy water. Signals due to neutrino events cannot be discerned beneath this wall of background light, and thus SNO is only expected to be sensitive to neutrinos with energies greater than about 5 MeV.

It is also evident from Figure 8 that between about 5 and 8 MeV, the summed Cerenkov spectrum derives from a complex overlap of different signals. The charged-current spectrum, which extends all the way to about 14 MeV, peaks in that region. But the

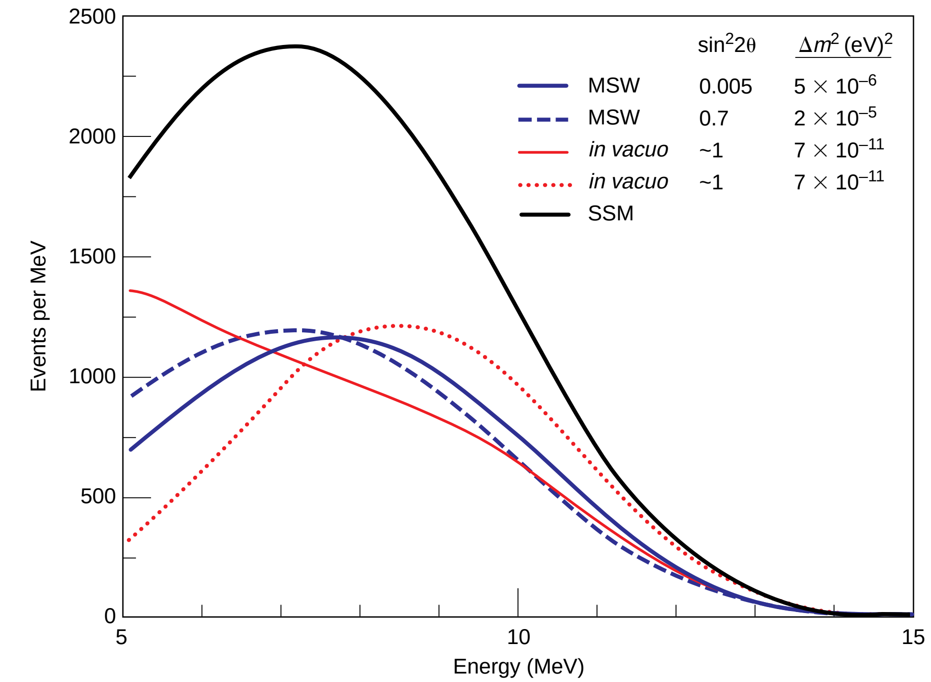


Figure 7. Theoretical Distortions in the Charged-Current Spectrum

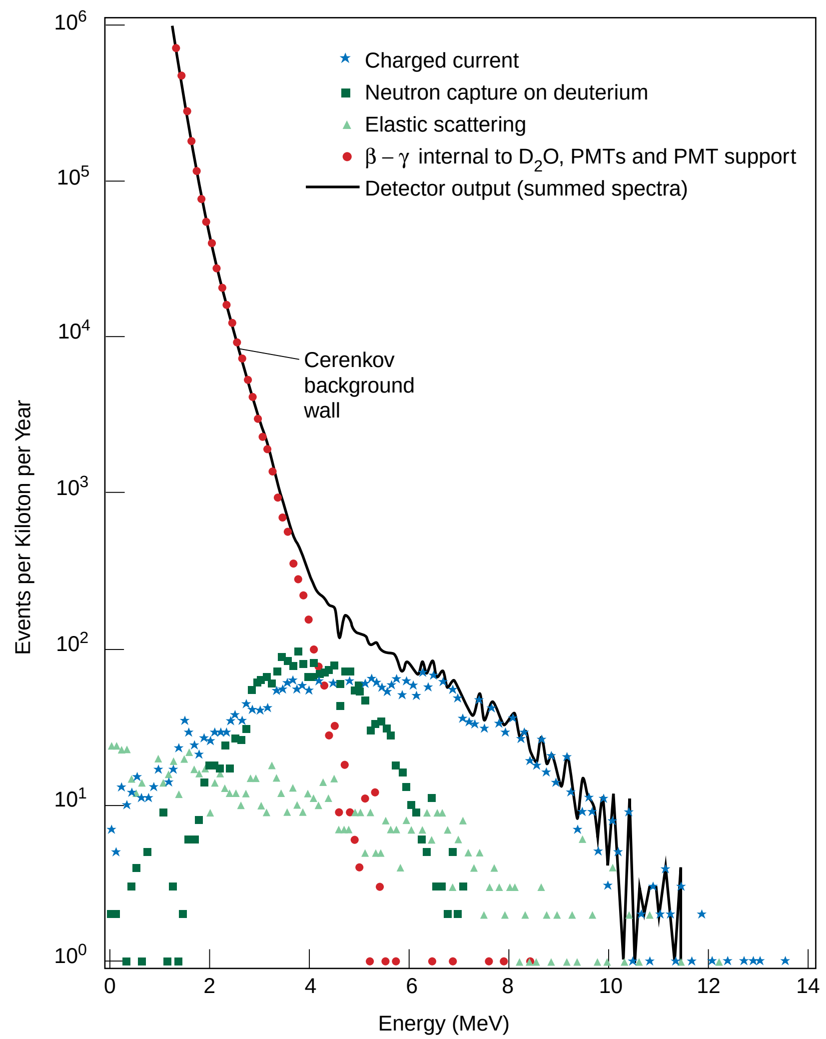
By assuming a ^8B neutrino spectrum, one can simulate what SNO would record for the charged-current (electron neutrino) Cerenkov spectrum. The black curve results from the standard-solar-model (SSM) spectrum, whereas the other curves are the result of distorting the ^8B spectrum either through *in vacuo* neutrino oscillations (red curves) or the MSW effect (blue curves). The amount of distortion depends on the amplitude and wavelength of the oscillations, which are characterized by the amount of mixing between neutrino flavors (the parameter $\sin^2 2\theta$) and the mass difference between neutrino mass states (the parameter Δm^2), respectively. The red curves reflect two of the five "just so" solutions for *in vacuo* neutrino oscillations, labeled as such because the large mixing angles and tiny mass differences are just right to make the oscillation length match the earth's orbit. The two blue curves derive from two different MSW solutions that are consistent with the existing data. The solid curve results when one assumes that electron neutrinos become muon neutrinos over a density range that is short compared with the neutrino oscillation length (nonadiabatic MSW solution), whereas the dashed curve results from a theory that assumes essentially the opposite (adiabatic, or large-angle, solution). The most favored solution to the solar-neutrino problem is the nonadiabatic MSW solution.

neutral-current spectrum and neutrino elastic-scattering spectrum are also present. Whereas detecting these latter signals is one of the design goals for SNO, in the context of isolating and measuring the charged-current spectrum, the signals represent complicating backgrounds.

The simulation shows the impor- tance of maintaining an ultraclean detector environment in order to mini- mize the Cerenkov wall, especially in the critical region between 5 and 8 MeV. (See the box "Nothing to Dust: The Meaning of Clean" on page 149.) Although ensuring the radiopurity of construction materials has been a major focus in this project, the background levels in the light-water jacket and in the heavy water will be monitored by a variety of techniques. In addition, sev- eral calibration sources will establish the optical properties of the SNO detector and its response to electrons, gamma rays, and neutrons. These sources will be inserted in the

igure 8. Monte Carlo Simulation of he Charged-Current Spectrum and Backgrounds in SNO

any processes produce Cerenkov light the SNO detector, and the detector out- ut (black line) is really the sum of many pectra. The charged-current spectrum is hown in blue, and all other spectra can e considered as backgrounds. The red pectrum results when radioactive mpurities in the D_2O and the detector omponents decay. The beta and gamma missions create the Cerenkov light. This pectrum completely dominates the etector response below about 4 MeV he "Cerenkov background wall"). The ark green spectrum results when a free eutron, produced through either the eutral-current interaction or the gamma- ay-induced photodisintegration of euterium, is captured by a deuterium ucleus. The neutron capture results in Cerenkov-producing gamma ray. The ght green spectrum results when neutri- os undergo elastic scattering with elec- ons, a process shown in Reaction (2) in he main text. Energy is transferred to the ectron, which zips through the heavy ater. The components of the summed pectra are particularly difficult to sort ut between about 5 and 8 MeV, precisely he region that is of most interest.



eavy-water vessel and will mimic a wide range of natural sources.

Neutral-Current Detection. The eutron liberated by the disintegration f the deuteron—Reaction (5)—leads to he all-important neutral-current signal rom which one infers the total solar- eutrino flux). The free neutron can be aptured by a deuterium nucleus, which hen emits a 6.25-MeV gamma ray that reates a shower of Cerenkov radiation n the detector. The spectrum is shown n Figure 8 (dark green squares).

However, the signal produced by eutron capture on deuterium would be ery difficult to observe. As shown in he figure, the spectrum lies substantially eneath the Cerenkov background wall, which means that the neutral-current signal would be overwhelmed by back- ground signals. One way around this problem is to "boost" the neutral- current signal toward higher energies. Neutron capture on ^{35}Cl yields an 8.6-MeV gamma ray, which produces Cerenkov light that can be safely discriminated against background. Dis- solving about 2.5 tons of magnesium salt ($MgCl_2$) into the heavy water should allow this detection method.

But there is still a complication. Because both the neutral- and charged- current interactions produce Cerenkov light, the two signals become part of the total Cerenkov signal that is recorded by SNO. In effect, the two signals become backgrounds to each other. To disentangle the signals, the detector would have to operate first with and then without salt. A subtrac- tion of one data set from the other would allow separation of the charged- current and neutral-current signals. As an alternative, the data could be analyzed with sophisticated pattern- recognition techniques. These could help discriminate a neutron event from other Cerenkov signals and would obvi- ate the need for data subtractions.

It is clearly desirable to have a direct way of distinguishing between neutral- and charged-current events in real time. But a direct detection method can only be achieved if the neutrons pro- duced by the neutral-current interaction are observed by means other than Cerenkov light. To this end, a research and development program started at Los Alamos several years ago. Its goal

Nothing to Dust: The Meaning of Clean

The standard solar model predicts that electron neutrinos will produce about 30 charged-current events per day in the SNO detector. According to the interpretation of the existing solar-neutrino results, this number will be reduced by about a factor of 2 to 3. Similarly, one expects about 14 neutrons to be produced per day through the neutral-current interaction. Relatively speaking, those estimated rates make SNO a "high-rate" solar-neutrino detector, but obviously, neutrino events are sufficiently rare that great strides must be taken to ensure an extraordinarily low background environment.

Any Cerenkov radiation that does not originate from a neutrino event is a background signal. The background sources could be cosmic rays or the energetic beta and gamma rays coming from the decay of radioactive elements. The cosmic-ray background is eliminated simply because SNO is buried underground with an overburden of 6,800 feet of rock. Also, emissions from radioactive elements in the norite rock surrounding the detector are eliminated by the 7,500 tons of light water engulfing the acrylic heavy-water (D_2O) bottle. All this leaves the dominant source of background to be one from within, that is, from the radiation emitted by radionuclide impurities present in the materials used to construct the detector.

All materials naturally contain small quantities of radionuclides. Unfortunately, those quantities are in general many orders of magnitude larger than what can be tolerated in a solar-neutrino experiment. For example, if the long-lived isotopes thorium-232 (^{232}Th) and uranium-238 (^{238}U) were present in even minute quantities, their beta and gamma activity would produce enough Cerenkov radiation to completely mask the electron neutrino signal. Also, the decay of thallium-208 and bismuth-214, which lie at the bottom of the ^{232}Th and ^{238}U decay chains, respectively, yields gamma rays above the binding energy of the deuteron. The gamma rays can cause the deuteron to photodisintegrate and liberate a neutron that is indistinguishable from neutrons produced via the all-important neutral-current interac- tion. Consequently, any material considered for use in constructing the SNO detector must be chosen with extreme care. An extensive research program was initiated to identify appropriate construction materials and to measure the intrinsic radioactive-impurity levels.

The most stringent requirement for purity falls upon the heavy water because there is so much of it. Specifically, thorium and uranium levels must be reduced to parts in 10^{14} by weight for the ensuing backgrounds not to exceed about 10 percent of the expected solar- neutrino signal. In other words, the 1,000 tons of heavy water cannot contain more than about 10 *micrograms* of heavy radioactive isotopes! Impurity levels in the acrylic bottle are less restrictive because of the bottle's smaller mass and must be reduced to parts in 10^{12} by weight. Fortunately, because acrylic turns out to be an intrinsically pure material with respect to the nasty thorium and uranium, it can meet the strict requirements of the SNO detector. The photomultipliers for detecting Cerenkov light, the photomultiplier support structure, and the cables—all poised roughly 2.5 meters from the acrylic vessel—must also meet strict requirements for radiopurity. The light-water shield effectively attenuates most of the radioemissions before they enter the D_2O target. Nonetheless, the photomultipliers are constructed from a low-radioactivity glass containing thorium and uranium at levels 10 times lower than those of standard glass.

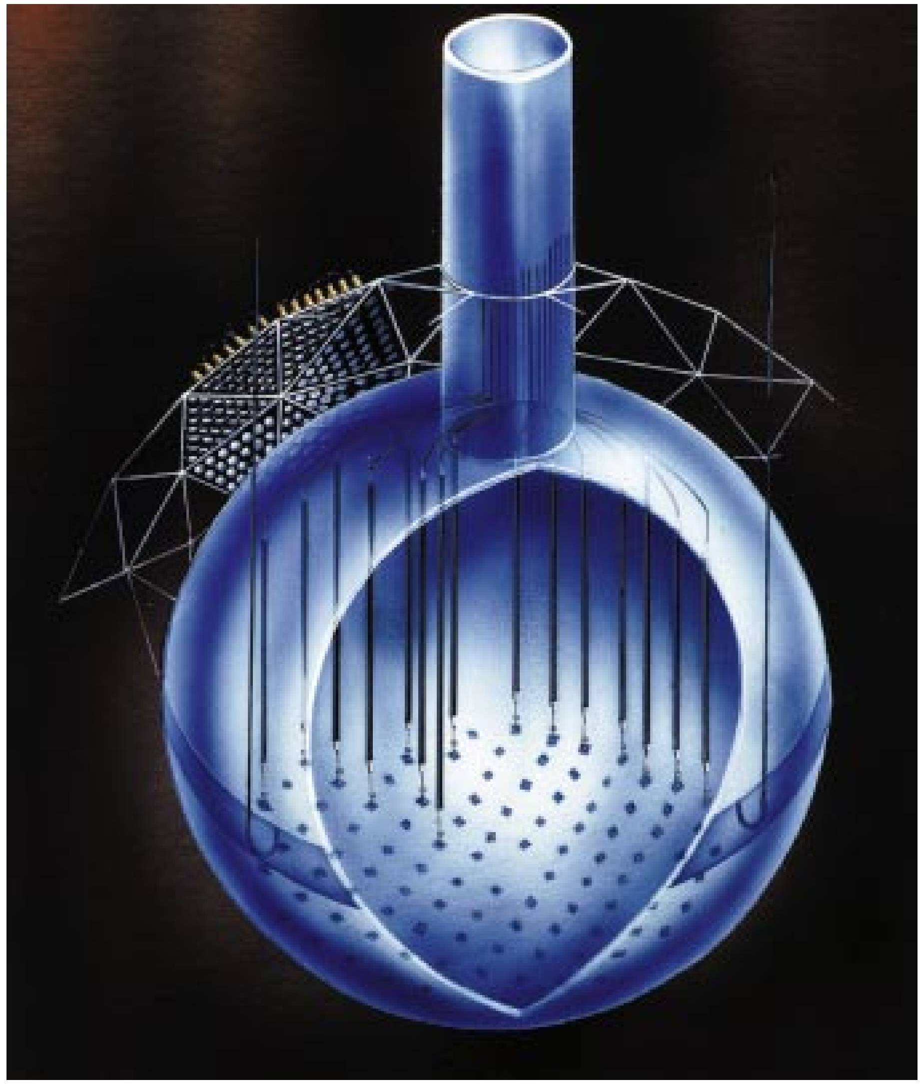
All these purity constraints would be moot if, during the construction phase, dust and impurities from the outside world were reintroduced into the materials. For this reason, the site where SNO is under construction—an enormous cavity more than 1 mile underground—has been turned into a giant clean room with surface-deposition rates of dust particles kept to about 1 microgram per square centimeter per month. Paradoxically, a normally filthy environment now houses one of the world's cleanest rooms.

was to design a discrete, ultralow- background neutron detector that could be deployed inside the heavy-water vessel. This secondary detector would have the capability of independently detecting neutrons while working simultaneously with the main SNO detector. After several years of development, such a detector is entering the stage of full-scale construction by SNO collaborators at Los Alamos, the University of Washington, and Lawrence Berkeley National Laboratory.

The Discrete Neutral-Current Detector. The discrete detector is an array of ^{3}He proportional counters. These are standard devices for detecting neutrons with high efficiency, and they are frequently used in nuclear and particle physics experiments. Each counter is made up of a cylindrical tube filled with a gas mixture containing ^{3}He. Neutrons easily penetrate the thin- walled tube and are captured on ^{3}He:

$$^3\mathrm{He} + n \rightarrow {}^3\mathrm{H} + p \ . \qquad (6)$$

The reaction produces an energetic proton and triton, both of which lose energy by ionizing the gas molecules. The resulting cloud of charged ions is attracted to a thin wire strung down the center of the tube that is kept at an electrical potential of about 1,800 volts. Monitoring the high-voltage line for



igure 9. The Neutral-Current Detector for SNO

he long, vertical tubes strung throughout the vessel containing heavy water are He proportional counters. A neutron passing through the tube wall will trigger a urrent pulse that is picked up by the signal lines snaking through the neck of the crylic bottle. The array of counters enables independent measurement of the neutrino eutral-current interaction, even as the main detector measures the electron neutrino harged-current interaction. The full array will use about 800 meters worth of propor- onal counters and will include individual gas tubes up to 11 meters in length (very rge relative to conventional counters). While being immersed in water, the counters ust operate in a reliable and stable fashion for a period of up to 10 years.

haracteristic current pulses allows etection and counting of the neutrons. An artist's drawing of the array nchored inside the acrylic bottle is hown in Figure 9.

Designing ^{3}He proportional counters or neutron detection is a long-standing nd well-practiced art, but several hallenging constraints had to be met before the counters could realize their potential as a secondary detector in SNO. The most stringent constraint was purity. Because the neutron signal is predicted to be so low and because the array is inside the main detector, the bulk materials used to construct the counters could not contain thorium and uranium in concentrations greater than parts per trillion by weight. Such levels are about 1,000 times lower than those typically found in commercially available construction materials. Consequently, most of the detector tubes have been fabricated from ultrapure nickel by a special chemical-vapor deposition process. The inherent radioactive content of these tubes is so low that the sensitivity for extracting the neutron signal is some 250 times greater than that of any previously constructed, low-background proportional counter.

Prototype detectors have been constructed and placed in an underground test facility at the Waste Isolation Pilot Plant near Carlsbad, New Mexico. The underground tests have demonstrated that the detectors can meet the cleanliness requirements for the SNO experiment. In addition, all the components that enter into the construction of the detector are assayed for their radiopurity with sophisticated radiochemical techniques unique to Los Alamos. An interesting application of those techniques is described in the box "A SNO Spinoff" on the facing page.

Summary and Outlook

Currently under construction in the Creighton Mine in Sudbury, Canada, by some 150 physicists, engineers, and technicians, SNO has met many triumphant milestones. The immense cavity needed to house the detector has been excavated, and the water-purification systems are in place. Construction of the heart of SNO is well underway: the assembly of the upper hemisphere of the heavy-water acrylic vessel is finished, and the upper portion of the photomultiplier array is fully installed. Construction of the lower half of the SNO detector is proceeding. It is anticipated that the detector will be ready for operation and "first fill" toward the end of 1997.

Full-scale construction of the discrete neutral-current detector is now also underway and will continue in parallel with the construction of the main SNO detector over a period of about ten months. As independent proportional counters of the array are fabricated, they will be shipped to Sudbury and then stored underground for a period of six months. This "cool-down" period will allow any cosmogenically produced radioactivity to die out before the counters are deployed. After the SNO detector is filled with heavy water, a "shake-down" period will follow in order to assess the detector backgrounds, monitor the performance of the photomultiplier tubes, and fine-tune the many channels of electronics and data acquisition. When it is time to install the neutral-current detector, another delicate program will begin. Each counter must be installed through the top of the acrylic vessel with a remotely controlled submarine—so much effort to capture the elusive neutrino in its disappearing act!

But the neutrino has tempted and intrigued physicists for more than sixty years, ever since its existence was first postulated by Wolfgang Pauli. The present conundrum surrounding the missing solar neutrinos points to the possibility of very exciting physics. It may well be that, by the end of this century, the properties of the neutrino that at one time seemed undetectable may be revealed and may offer a long-awaited clue to some of the fundamental mysteries of the universe. ■

A SNO Spinoff

Research into ultralow-background fabrication techniques has created a potentially interesting spinoff relevant to the microelectronics industry. Because computer chips are becoming extremely small, the decay of natural radioactive elements in the construction materials is sufficient to create "single-bit upsets" from one binary number to another. In an effort to solve this problem, the Weak Interactions Group at Los Alamos is currently working with industry to provide ultralow-background particle detectors for screening microelectronic components. In an interesting and unexpected development, something as esoteric as hunting neutrinos may lead to creating a useful tool in the "practical" world.

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Andrew Hime is a technical staff member in the Weak Interactions Group of the Physics Division at the Los Alamos National Laboratory. He received his B.Sc. and M.Sc. in physics from the University of Guelph, Canada, in 1986 and 1988, respectively. Subsequently, Hime was awarded the distinguished overseas fellowship from the Royal Commission for the Exhibition of 1851 to pursue graduate studies at Oxford University. In 1991, based on his thesis involving precision searches for heavy neutrinos in nuclear-beta-decay spectra, Hime earned his D.Phil. degree in subatomic physics from Merton College, Oxford. Shortly thereafter, Hime joined the weak-interactions team at the Laboratory and was later nominated as an Oppenheimer Fellow. His research efforts center on fundamental investigations of the weak interaction, with emphasis upon the search for neutrino mass and the elucidation of the solar-neutrino problem. In addition, Hime has recently created a new program at the Laboratory to exploit magnetically trapped atoms for precision measurements of fundamental symmetries and, in particular, to pursue the parity-violating nature of the weak interaction. Hime is currently the associate director of the Neutral-Current Detector Program for the Sudbury Neutrino Observatory.

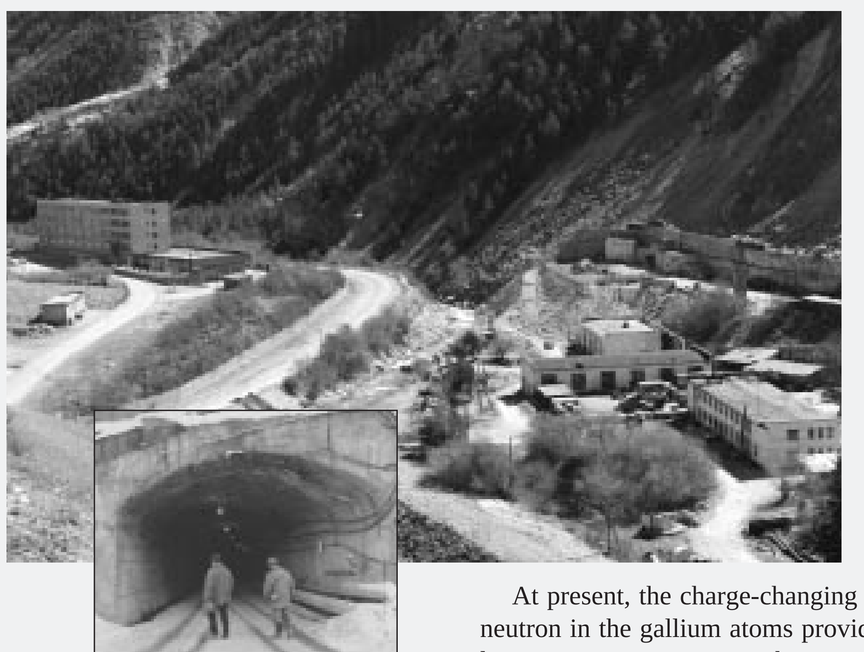
The Russian-American Gallium Experiment

Tom Bowles

he Soviet-American gallium experiment AGE) was renamed the Russian-American allium experiment after the breakup of the oviet Union. Los Alamos has served as the ad U.S. laboratory for the experiment, with e University of Washington, the University Pennsylvania, Princeton University, and ouisiana State University rounding out the .S. side of the collaboration.

Beginning life as seepage from the snow-covered slopes of Mount Elbrus, the Baksan River gradually gains momentum as it ambles slowly northwest through the rugged Caucacus Mountains. Eventually, the river rumbles past the august face of Mount Andyrchi and the incongruous cluster of buildings, homes, and shops at its base known as Neutrino Village. The Baksan Neutrino Observatory is tucked into the mountainside under about 1.6 kilometers of hard rock. About 1,000 scientists, engineers, and families are tucked into the village.

The neutrino observatory is the result of some ambitious planning on the part of Soviet scientists. In 1964, the scientists dreamed of building several large detectors dedicated to observing the evasive neutrinos that streamed unfettered through the planet. Soon, they realized that burying the experiments under tons of rock would reduce the effects of cosmic rays. The rock itself would have to be geologically stable and relatively immune to earthquakes and other natural disasters. With an eye toward saving money, the scientists thought of digging a horizontal tunnel into a steep mountain. Equipment could then be hauled around by rail rather than up and down in mineshaft elevators. The Baksan River Valley in southern Russia presented itself as the ideal site. Years later, the Institute for Nuclear Research of the Russian Academy of Sciences would build Neutrino Village for the sole purpose of accommodating the needs of the Baksan Neutrino Observatory.



eutrino Village lies at the base of ount Andyrchi in the northern aucacus Mountains. The Russians ored about 3.5 kilometers straight to the mountain in order to bury AGE under tons of rock, and thus a esearcher's access to the experiment egins with a journey through darkness.

The SAGE experiment is the largest research effort at Baksan. Initiated in 1985 as a collaborative effort between the United States and the former Soviet Union, the experiment was designed to measure the flux of *pp* neutrinos that are produced in the dominant energy-producing mechanism of the sun. That particular flux is directly tied to the measured solar luminosity and is essentially independent of solar models. Hence, observation of a significant deficit of *pp* neutrinos would strongly suggest that a resolution to the solar-neutrino problem lies in the properties of the neutrino, rather than in solar physics.

At present, the charge-changing interaction between electron neutrinos and a neutron in the gallium atoms provides the only feasible means to measure the low-energy *pp* neutrinos. The reaction transforms a stable gallium atom into a radioactive isotope of germanium:

$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^- \ .$$

Because the unstable germanium atoms decay with a characteristic spectrum, they can be detected and their numbers counted. In this way, the solar-neutrino flux can be measured, and with a threshold of only 0.233 MeV, the reaction is sensitive to nearly the entire energy spectrum of solar neutrinos. In particular, 54 percent of the detected signal should be due to neutrinos from the *pp* reaction, based on the predictions of the standard solar model for the total solar-neutrino flux.

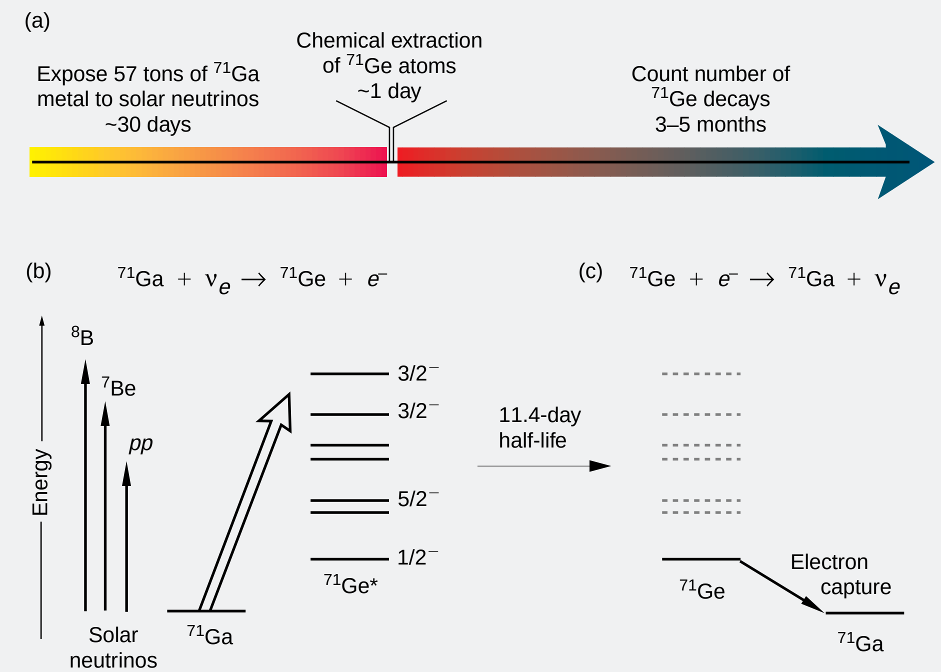
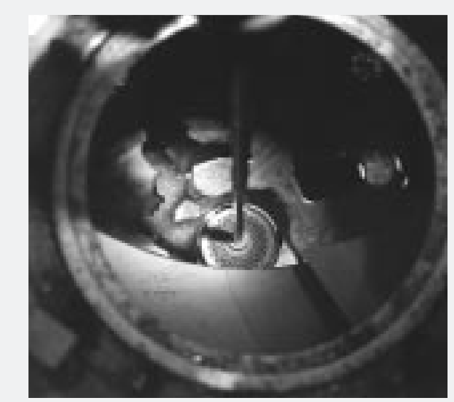


Figure 1. SAGE Overview
(a) SAGE has three distinct stages of operation: the transmutation of ^{71}Ga into unstable ^{71}Ge caused by solar neutrinos, the chemical extraction of the ^{71}Ge atoms, and the detection of the ^{71}Ge decays. The number of decays is proportional to the solar-neutrino flux.
(b) Because of low-lying excited states in the ^{71}Ge nucleus, the inverse-beta-decay reaction of gallium into germanium has a threshold of only 0.233 MeV. The reaction is therefore sensitive to *pp* and all other solar neutrinos. The energetic neutrinos leave the ^{71}Ge in an excited state, which quickly decays to the ground state.
(c) After an 11.4-day half-life, ^{71}Ge decays by capturing an orbital electron. The remaining electrons quickly reconfigure themselves around the new nucleus and dissipate excess energy by emitting x-rays and/or Auger electrons. These emissions are the signature of the decay.

In addition to SAGE, GALLEX (another international collaboration headed by MPIK Heidelberg) exploits the above reaction. The composition of the gallium target differs between the two experiments. SAGE uses metallic gallium (which becomes a liquid at just above room temperature), while GALLEX uses gallium in a liquid-chloride form. The different forms of the gallium are susceptible to very different types of backgrounds, and thus the two experiments provide a check for each other. This feature helps ensure that the observed events are due to reactions of solar neutrinos on gallium, rather than some background process.

Unlike other solar-neutrino detectors, the SAGE detector has a size that is of a conceptually manageable scale. The experiment initially employed about 30 tons of liquid gallium metal distributed among 4 tanks, each the size of a small hot tub. Today, the detector contains 57 tons of liquid metal distributed among 8 tanks. The Russians provided the gallium, valued at $40 million, in addition to the chemical extraction equipment, underground laboratory, and counting and analysis facilities. The Americans provided numerous pieces of equipment, including the primary counting system. The Americans also brought to the collaboration their substantial expertise in techniques for low-level counting. The Russians were responsible for operations, but both sides participated in data collection and analysis, as well as in publication of results.

SAGE indirectly measures the solar-neutrino flux by extracting and counting the germanium atoms produced in the gallium tanks. (See Figure 1.) About once a month, a chemical extraction is performed in which individual germanium-71 (^{71}Ge) atoms are plucked from among some 5×10^{29} gallium atoms. (Only 1.2 ^{71}Ge atoms are predicted to be produced per day in 30 tons of gallium, assuming the neutrino flux predicted by the standard solar model. The efficiency of the chemical extraction is simply incredible.) Just before the extraction, about 700 micrograms of stable germanium is added to the tanks. Monitoring the recovery of this natural germanium allows a measurement of the extraction efficiency for each run. The total germanium extract is purified and synthesized into germane (GeH_4), a measured quantity of xenon is added, and the mixture is inserted into a small-volume proportional counter.



The last bit of extract containing the unstable germanium is drawn out from the gallium tank. The extract appears as a silvery pool floating on top of the duller, liquid gallium metal.

The counter is then sealed and placed in the well of a sodium iodide (NaI) detector (used as a veto), which sits inside a large, passive shield.

Germanium-71 decays with an 11.4-day half-life to gallium-71 (^{71}Ga) by electron capture, in which an orbital electron in the ^{71}Ge atom is captured by a proton in the ^{71}Ge nucleus. The nucleus is converted to ^{71}Ga, but the decay also leaves the gallium atom in an excited state. The excess energy is carried off by low-energy electrons (Auger electrons) and by x-rays produced during the electron-shell relaxation of the ^{71}Ga atom. Taken together, the electron spectrum and the x-rays make for a characteristic decay signature. Pulse-shape discrimination and a maximum-likelihood analysis identify and distinguish that signature from all the other background signals detected by the proportional counter. The number of decays occurring over 4 to 6 months is recorded.

he tops of eight greenish tanks poke hrough the elevated floor of the Bakan Neutrino Observatory. The squat nks contain a total of 57 tons of trapure gallium. Heating the tanks o about 30 degrees centigrade keeps he gallium in liquid form. Once or wice a day, one of the hundred trilon or so solar neutrinos that pass hrough the tanks each second intercts with the gallium and produces n unstable germanium atom. These nstable atoms are extracted from the nks once a month. The red motors een perched above each tank are sed to rapidly stir the liquid gallium uring the extraction runs. The equipent seen in the foreground handles he chemicals used for the extraction. he red room to the left of the picture ouses all the electronics and control ystems used in the experiment.

Taking into account all efficiencies, the team expects SAGE to detect only about eight of the ^{71}Ge atoms produced in the 57 tons of gallium per run. Clearly, the backgrounds must be kept to a small fraction of a count per day. To yield such low backgrounds, the counters are made of specially selected quartz and zone-refined iron. All the components used in the NaI detector were specially selected; even the individual nuts and screws were measured for possible trace radioactivity.

The experiment began operation in May 1988 with the purification of 30 tons of gallium. Large quantities of long-lived ^{68}Ge (half-life = 271 days) had to be removed. They had been produced by cosmic rays while the gallium was on the earth's surface. By January 1990, the backgrounds had been reduced to sufficiently low levels that solar-neutrino measurements could begin. Since that time, extraction runs have been carried out monthly except for periods dedicated to calibration runs. SAGE reports the measured value of the solar-neutrino capture rate on ^{71}Ga to be

$$^{71}\text{Ga capture rate} = 72\ {}^{+12}_{-10}\ \text{(statistical)}\ {}^{+5}_{-7}\ \text{(systematic) SNU} \quad .$$

An SNU (solar-neutrino unit) is equal to 10^{-36} captures per atom per second. This unit facilitates the comparison of results between different radiochemical experiments. The SAGE result is in excellent agreement with the GALLEX measurement of 70 ± 8 SNU. The capture rate predicted by the solar model was 132 ± 7 SNU, or nearly a factor of 2 higher.

Because SAGE observed a low signal compared with the solar-model prediction, the experiment underwent thorough checking to ensure it was working correctly. Much of the attention focused on the germanium-extraction procedure. The first test consisted of extracting stable germanium doped with a known number of radioactive ^{71}Ge atoms from 7 tons of gallium. The results indicated an extraction efficiency of 101 ± 5 percent for the natural germanium and 99 +6/ −8 percent for ^{71}Ge.

The definitive test of the extraction, however, was performed in 1995. The experiment used an extremely intense, artificial neutrino source to produce ^{71}Ge inside the detector. Chromium-51 (^{51}Cr) decays with a 27.7-day half-life by electron capture, thereby producing monoenergetic neutrinos. By placing a source containing 0.52 megacurie of ^{51}Cr inside 13 tons of gallium, one could expect to produce 50 times more ^{71}Ge atoms than the solar neutrinos would produce and anticipate to extract and observe about 147 atoms.

Half a million curies of anything is not to be treated lightly. The neutrinos

themselves are harmless, but about 10 percent of the time, ^{51}Cr decays by emitting a 320-kilo-electron-volt gamma ray. Left unshielded, those gammas would make the source a deadly menace. (Anyone holding the source, which is as small as a Coke can, would be fatally irradiated in about 1 minute.) The source was made in a fast breeder reactor in Kazakhstan. That reactor had been formerly used for plutonium production. A special assembly inserted into the reactor core was used for producing ^{51}Cr from highly enriched ^{50}Cr rods. The source was shielded by being placed inside a tungsten container with walls that were about 1 inch thick. All but about 0.001 percent of the gamma rays were absorbed in the shielding. The container radiated heat like a 100-watt light bulb.

Shielded in this manner, the source was perfectly safe to transport. But getting it into Russia turned out to be a problem. All arrangements for bringing the source in had been worked out when Kazakhstan was part of the Soviet Union, but by the time the source was to be delivered, Kazakhstan had become a separate country! The American team stood around, extremely unhappy, as 15 percent of the activity decayed away while the source sat in Russian customs for six days. A remarkable navigation of diplomatic channels finally led to a meeting, on Christmas day, between the SAGE members and the President of the Kabardino-Balkarya Academy of Sciences. Approval to transport the source to Baksan was finally granted. The result of the calibration experiment showed that the extraction and counting efficiencies were 95 ± 12 percent of those expected. The experiment was indeed working correctly. Thus, the observed deficit of solar neutrinos in SAGE is not due to some experimental error. Instead, it reflects a real deficit in neutrinos coming from the Sun.

Five members of the SAGE research team (the five people on the left) pose in front of the tunnel entrance. From left to right: Tanya Knodel, Ray Davis, Jr., Ken Kande, Vladimir Gavrin, and George Zatsepin. Also shown (continuing from left to right) are George Cowan, Igor Barabanov, and Keith Rowley.

The problem is now one of understanding the reason for the deficit. Unfortunately, SAGE cannot answer that question directly. The detection method can only infer the number of neutrino events that occurred in the gallium tanks. There is no way to extract information about the neutrino energy and, hence, about the shape of the solar-neutrino spectrum. The SAGE result, however, taken together with the results of other solar-neutrino experiments and the predictions of the standard solar model for the flux, suggests that the low-energy *pp* neutrinos are present in full strength while the flux of other, higher-energy solar neutrinos is significantly reduced. Many authors argue that these results cannot be reconciled with an astrophysical explanation. New experiments such as SNO are required for determining the origin of the solar-neutrino problem in a model-independent manner.

We hope that SAGE can continue measurements for a few more years. We are also investigating the possibility of converting gallium metal into gallium arsinide, which would enable construction of a real-time electronic detector for the entire solar-neutrino spectrum with very good energy resolution (a few kilo-electron-volts). The feasibility of such a detector still needs to be researched. However, the fate of the gallium, which remains the property of the Russian government, is now in doubt. Recently, an edict was issued requiring that the Institute for Nuclear Research of the Russian Academy of Sciences, which oversees the Baksan Observatory, return the gallium so that it could be sold and thus help pay salaries for unpaid government workers. While being sympathetic to the plight of the Russian workers, we also feel that, given its extremely high purity and low levels of trace radioactivity, the gallium should be considered a world resource to be invested in future research. We hope the Russian government will reach the same conclusion and explore other means to ease its fiscal crisis. ■