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).

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.
I n October 1920, Sir Arthur Eddington, one of the foremost astrophysicists of the century, delivered his residential address to the British Association at Cambridge. In his speech, entitled "The Internal Constitution of the Stars," he referred to a proposal suggested the ear before by the former president of the association to bore a hole into the rust of the earth in order to discover the conditions deep below. Motivated by the rapid progress in astronomy at the time, Eddington proposed something easier" to penetrate, namely, the Sun. Eddington could scarcely have anticipated the ramifications of his suggestion. After more than twenty-five years of study, the scientific community’s investigations of our closest star have yielded a remarkably detailed understanding of what makes the Sun shine. We now know that the Sun is powered by thermonuclear fusion and that its hot core can be considered an immense furnace producing not only heat and light, but also vast numbers of neutrinos. Because of the Sun’s enormous size, the light produced deep in its interior takes tens of years to reach its surface. During that lengthy journey, the photons that rain down upon us as sunlight interact with matter that they escape from the Sun in about seconds. They arrive on Earth a mere minutes later, and thus the solar neutrinos are a unique probe of a star’s innermost regions and of the nuclear reactions that fuel them. During the past thirty years, detailed theoretical and experimental studies have resulted in very precise predictions about the fluxes and energy spectra of neutrinos produced deep within the Sun. But a problem has emerged: our different experiments have measured the flux of solar neutrinos, and one of them reports a flux that is significantly below theoretical predictions. The discrepancy is referred to as 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 and near 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 be enhanced in the Sun as 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 undetected evidence for neutrino mass exists despite years of painstaking research around the world. Indeed, on 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, and thus of all other solar experiments, is also shown here. The gallium experiments have energy thresholds around 0.23 MeV and are sensitive to the B neutrinos that emerge from the carbon-nitrogen-oxygen, or CNO, cycle (gray curves). The B neutrinos are created in beta decay. Notice that the B neutrino is produced from the pp reaction and B decay, but hardly any from B decay. 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 B flux. Also shown are the spectra of neutrinos produced from the CNO cycle (gray curves). The pp, 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 B and B neutrinos result from electron capture: A proton in a nucleus captures an electron from an atomic orbital, turns into a neutron, and is converted into a neutrino. Meanwhile, the B neutrino is produced from the pp reaction and B decay, but hardly any from B decay. Given the enormous power produced by the Sun and its twenty-billion-year lifetime, it is a stadistic 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, pp, beryllium-8 (B), and boron-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. 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 B flux. Also shown are the spectra of neutrinos produced from the CNO cycle (gray curves). The pp, 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 B and B neutrinos result from electron capture: A proton in a nucleus captures an electron from an atomic orbital, turns into a neutron, and is converted into a neutrino. Meanwhile, the B neutrino is produced from the pp reaction and B decay, but hardly any from B decay. 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The Pioneering Experiments

Given data on the Sun’s luminosity, the standard solar model provides a rather definite prediction for the total flux of solar neutrinos reaching the Earth. Specifically, some 6.57 x 10^{10} re/second would cross through every square centimeter of our planet each second. Despite this impressive number, neutrinos interact so weakly with matter that the probability of detecting any individual neutrino is extremely small. It is this extremely small probability of detection that provides the unique way to state the problem is that an tons present 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 contains hundreds to thousands of tons of target material. Even so, neutrino interactions are still rare in these watchful beehives. 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 producing 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 perchloroethy- ylene (C_2Cl_4), a common dry-cleaning fluid, to snare the ghostly neutrinos. Electron neutrinos \( \nu_e \) from the Sun make themselves known through the inverse-beta-decay reaction on chlorine nuclei:

\[ \nu_e + ^{37}\text{Cl} \rightarrow ^{37}\text{Ar} + e^- . \]  

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

The Pioneering Experiments

The detection and measurement of the pp flux were a triumph of three puzzles 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 had to conclude that the basic ingredients describing how the sun shines were understood and correctly implemented in astrophysicists’ models.

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 neutrino flux to the high-energy \( ^{37}\text{Cl} \) and \( ^{37}\text{Ar} \) neutrinos. It became apparent that the detected neutrinos were not a mere 1/3 below the predictions of the standard solar model. 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 structure of the Sun is dominated by reactions that generate about half of the expected flux. It was evident that the solar neutrino flux is smaller than predicted. Physicists turned to models that included a new source of solar neutrinos, the pp flux, which was a factor of 2 below the predictions of the standard solar model.

Exorcising Ghosts

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Table I. Summary of Pioneering Solar-Neutrino Experiments

<table>
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<tr>
<th>Neutrino Reaction</th>
<th>SAGE + GALLEX</th>
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<td>pp</td>
<td>70 SNU</td>
<td>0 SNU</td>
<td>0</td>
</tr>
<tr>
<td>pep</td>
<td>3 SNU</td>
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</tr>
<tr>
<td>7Be</td>
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<td>0</td>
</tr>
<tr>
<td>CNO</td>
<td>10 SNU</td>
<td>0.5 SNU</td>
<td>0</td>
</tr>
<tr>
<td>Observed Predicted Rate</td>
<td>132 ± 7 SNU</td>
<td>9 ± 1 SNU</td>
<td>5.7 ± 0.8</td>
</tr>
<tr>
<td>Observed Rate</td>
<td>74 ± 8 SNU</td>
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<td>2.9 ± 0.4</td>
</tr>
</tbody>
</table>

*1 SNU = 10^6 neutrinos per square centimeter per second.
**In units of 10^6 neutrinos per square centimeter per second.

Each 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 unit that facilitates comparison between experiments. Kamioke reports results in flux units. Every experiment shows a significant effect in the observed versus the predicted rate.

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

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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. Kamioke observed approximately half of the expected flux of 7Be neutrinos. All the neutrino detectors detected by the chlorine experiment can likewise come from the 7Be 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 7Be flux. Taken together, those 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 x 10^10 neutrinos per square centimeter per second (the total neutrino flux). The model is then fit to the combined data from all experiments.

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 ψ, the flux derived from the combined fit, to ψSSM, 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 ψB flux versus ψBe flux (each normalized to the SSM predictions). The 90 percent confidence level for the Bahcall-Insonneault 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 T7). As the figure shows, the SSM and all nonstandard models are completely at odds with the best fit to the combined experimental results.

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 with out 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 is 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 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, 7Be, and 8B 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
The super-Kamiokande experiment, 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.

A heavy-water molecule has two deuterium atoms bonded to an oxygen atom (D$_2$O rather than H$_2$O). 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$_2$O), 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:

$$v_e + D \rightarrow p + p + e^-.$$  

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. Therefore, they compare their measured flux with one predicted by the solar model.

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Collaboration was formed shortly thereafter, borrowing about 1,000 tons. The SNO large stockpiles of heavy water. He recommended that SNO be discussed a proton decay experiment, in June 1988 by an international scientific and technical review committee. The idea of using heavy water as a neutrino target was first proposed in 1985 to evaluate the capabilities and practicality of building a heavy-water Cerenkov detector. The electron neutrinos interact in the detector proton to produce electrons. The electrons create Cerenkov radiation that is detected by the PMTs. Based on the electron photons' time of arrival at the PMTs and the number of PMTs that are triggered, the location, energy, and direction of the electron can be determined. All neutrino flavors can create free neutrons the D\(_2\)O volume from radioactive backgrounds while simultaneously providing e\(_{\text{c}}\) neutrinos 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 simulations 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 neutrons 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 deviates from a complex overlap of different signals. This charged-current spectrum, which extends all the way to about 14 MeV, peaks in that region. But the neutral-current spectrum and neutrino elastic-scattering spectrum are also present. When 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 importance of maintaining an ultraclean detector environment in order to minimize 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 unirradiated purity 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, several 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
Neutrons easily penetrate the thin-3He. which means that the neutral-current interaction is frequently used in nuclear and particle-physics experiments. Each counter is made up of a cylindrical tube filled with a gas mixture containing neutrons. However, the signal produced by neutrons undergoes elastic scattering with electrons, a process shown in Reaction (2) in the main text. Energy is transferred to the electron, which then travels through the heavy water. The components of the summed spectra are particularly difficult to sort out between about 5 and 8 MeV, precisely the region that is of most interest.

The Discrete Neutral-Current Detector. Lawrence Berkeley National Laboratory.

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, only about 14 neutrons are produced per day through the neutral-current interaction. Relatively speaking, these 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 heavy rock surrounding the detector are eliminated by the 7,500 tons of light water engulfing the acrylic heavy-water (D₂O) bottle. This leaves the dominant source of background to be one from within, that is, from the radiation emitted by radon and radon isotopes present in the materials used to construct the detector.

All materials contain small quantities of radionuclides. Unfortunately, those quantities are in general orders of magnitude larger than what can be tolerated in a solarsolar neutrino experiment. For example, if the long-lived isotopes thorium-232 (232Th) and uranium-238 (238U) 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 214Pb and 235U 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 interaction. 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 isotopes must be reduced to parts in 10¹⁴ by weight for the detector 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 milligrams 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 10¹⁴ 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 radioactivity. The light-water shield effectively attenuates most of the radio emissions before they enter the D₂O 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.
Figure 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 current pulse that is picked up by the signal lines snaking through the neck of the acrylic bottle. The array of counters enables independent measurement of the neutrino charged-current interaction, even as the main detector measures the electron neutrino charged-current interaction. The full array will use about 800 meters worth of proportional counters and will include individual gas tubes up to 11 meters in length (very long relative to conventional counters). While being immersed in water, the counters must operate in a reliable and stable fashion for a period of up to 10 years.

characteristic current pulses allows ejection and counting of the neutrons. An artist’s drawing of the array niched inside the acrylic bottle is shown in Figure 9. Designing the proportional counters or neutron detection is a long-standing problem 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.

A SNO Spinoff
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Further Reading

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.S. and M.S. 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 alphas for precision measurements of fundamental symmetries and, in particular, to pursue the particle-nuclear nature of the weak interaction. Hime is currently the associate director of the Neutral-Current Detector Program for the Sudbury Neutrino Observatory.

Exorcising Ghosts
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The Russian-American Gallium Experiment

Tom Bowles

Exorcising Ghosts

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 Caucasus 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 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.

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:

\[ \nu_e + ^{71}\text{Ga} \rightarrow ^{71}\text{Ge} + e^- \]

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.

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 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.

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 (\(^{71}\text{Ge}\)) 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 (\(\text{GeH}_2\)), 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 duff, liquid gallium metal.
Half a million curies of anything is not to be treated lightly. The neutrinos anticipate to extract and observe about 147 atoms. Chromium-51 (51Cr) decays with a 27.7-day half-life by experiment used an extremely intense, artificial neutrino source to produce 71Ge. The definitive test of the extraction, however, was performed in 1995. The experiment began operation in May 1988 with the purification of 30 tons of gallium. Large quantities of long-lived 64Ge (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 71Ga to be 71Ga capture rate = 71 ± 12 over 10 (statistical) ± 7 (systematic) SNU.

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 GALEX measurement of 79 ± 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 unstable atoms and producing an unstable germanium atom. These unstable atoms are extracted from the niks once a month. The red motors are driven by motors and the red motors are driven by a system. The counter is then sealed and placed in the well of a sodium iodide (NaI) detector.

The definitive test of the extraction, however, was performed in 1995. The experiment used an extremely intense, artificial neutrino source to produce 71Ge inside the detector. Chromium-51 (41Cr) decays with a 27.7-day half-life by electron capture, thereby producing monoenergetic neutrinos. By placing a source containing 0.52 megacurie of 41Cr inside 13 tons of gallium, one could expect to produce 50 times more 71Ge 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, 51Cr decays by emitting a 320-kilo-electron-volt gamma ray. Left unshielded, these 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 and converted to 71Ga, 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 71Ga 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.

Taking into account all efficiencies, the team expects SAGE to detect only about eight of the 71Ge 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 zirconium-tritide 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 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 arsine, 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 was demonstrated by 71Ge 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 71Ge.

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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.