Solar Neutrinos: Experimental Approaches

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This article discusses the new experiments, under way or proposed, that will measure the flux of solar neutrinos and so probe the "solar neutrino puzzle." Both radiochemical and electronic detector experiments are analyzed in terms of possible findings relevant to astrophysics and neutrino properties. Important elements are sensitivity to the principal components of the solar neutrino spectrum, directionality of the detector response, and an energy-measuring capability that might provide a unique identifying signal. Experiments beyond those currently under way will probably be needed, and development of real-time detectors is particularly important.

In this article we discuss the various experiments under way, proposed, or under discussion that are designed to shed light on the possible causes of the discrepancy between the solar neutrino flux predicted by the so-called "standard" model of the sun and the result of the ^{37}Cl experiment, the only solar neutrino flux measurement to date (*1*). As discussed in the preceding article (*2*), explanations of the discrepancy fall into two classes—those invoking deviations from the standard solar model and those based on transformations of neutrinos during propagation from the central region of the sun to Earth. To distinguish between these two possibilities is a prime objective of the much discussed ^{71}Ga experiment (*3*) now under development. It was thought until recently that the ^{71}Ga experiment would enable researchers to make this distinction clearly. As a consequence of the possibility of matter-induced neutrino oscillations (*4*), the ^{71}Ga experiment may not lead to such a clear-cut decision. We will therefore discuss briefly all proposed solar neutrino experiments that we are aware of and that show some promise of developing into real detectors, and examine what additional insight they can provide on the need for modifications in the standard solar model or on neutrino properties.

Background Processes

The common feature that makes all solar neutrino experiments difficult is the extremely low cross section for neutrino interactions—in the range of 10^{-46} to 10^{-42} cm^2 at solar neutrino energies. Two important consequences are as follows: (i) Very large detector masses (10^3 to 5×10^6 kg) are required and the experiments are therefore major engineering undertakings. (ii) Even in such huge detectors, expected event rates are at most one to ten per day and therefore background processes that give rise to products or signals indistinguishable from the neutrino reaction products or signals must be scrupulously excluded.

It follows immediately that "off-line" methods (that is, methods that rely on isolation and subsequent identification of neutrino capture products) can be contemplated only if these product species do not normally occur in nature. Even when this condition is fulfilled, for example, when the capture product is a radioactive nuclide detected by its radioactive properties or other unique isotopic signature, the nuclide may be produced by other processes in concentrations so high as to mask the minute traces made by neutrino capture. The (p,n) reaction always produces in the target material the same product nuclide as does neutrino capture. Consequently, any source of energetic protons must be carefully excluded. Since protons are the principal component of cosmic rays at Earth's surface, solar neutrino detectors must be placed deep underground (shielded typically by at least the equivalent of 3000 m of water). Even at these depths the penetrating component of the cosmic radiation, consisting mainly of energetic μ mesons, can produce the sought-after neutrino capture product by secondary processes. The magnitude of this background must be evaluated.

Protons are also produced by (α,p) reactions and, in hydrogenous media, by collisions of alpha particles with hydrogen. Alpha particles are emitted from impurities such as uranium, thorium, and radium in the target material or in its container wall. Specifications for the maximum permissible levels of such impurities, typically in the part-per-million to part-per-billion range, must therefore be established and monitored for each detector system. Levels of other impurities may also be of concern if they can give rise to the neutrino capture product by nuclear reactions such as (α,n) or (α,p).

Other sources of protons that must be carefully evaluated are (n,p) reactions in the detector itself, induced by fast neutrons from sources such as (α,n) processes and spontaneous fission of uranium in the surrounding rock walls. If necessary, these fast neutrons can be sufficiently attenuated by water shielding around the detector.

For "on-line" experiments (that is, experiments in which each neutrino interaction is detected in real time) the background problems are of a somewhat different nature than for radiochemical experiments. Here, too, one must go deep enough underground to minimize total event rates from cosmic-ray interactions. The choice of fiducial volumes to ensure event observation away from the walls helps suppress backgrounds. Beyond that, the severity of background problems depends strongly on the uniqueness of the signature used to detect neutrino interactions. Radioactive contamination must be rigorously controlled. However, it can never be completely eliminated, so it is always necessary to discriminate against residual background from radioactivity by setting energy thresholds; therefore, the electronic techniques for detecting solar neutrinos by neutrino-electron scattering or inverse β processes can in practice be made sensitive to only the high-energy (^8B) neutrinos.

Solar Neutrino Detector Sensitivities

In any discussion of detectors it is important to consider their response to the different components of the solar neutrino spectrum. The relative responses are shown in Table 1. In considering what can be learned from each experiment, on the basis of the entries in

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this table, we should keep in mind two points. (i) In the context of astrophysics, it is the reaction mechanism in the interior of the sun that is important; specifically, the pp and pep fluxes are fairly independent of the details of astrophysical models, whereas the contributions from the other neutrino sources are strong functions of temperature and thus quite model-dependent. (ii) On the other hand, if we wish to understand neutrino properties, the important parameters are the neutrino energy and, for matter-induced neutrino oscillations, the point of origin; in this sense ^{8}B neutrinos (with energies up to 14 MeV) are in a class by themselves, whereas the other neutrinos have relatively low energies.

Radiochemical Experiments

^{71}Ga: A probe for low-energy solar neutrinos. An experiment that uses a ^{71}Ga detector is widely considered as the next logical step in solar neutrino research (*3, 5*). Because of the low threshold (233 keV) and relatively large cross section of the reaction $^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$, ^{71}Ga primarily detects the abundant pp neutrinos, as shown in Table 1 for the standard model. As in the ^{37}Cl experiment, detection of neutrino capture is based on chemical separation of the product (^{71}Ge) and measurement of its radioactive decay. The use of gallium as a detector was first suggested by Kuzmin (*6*) at a time when amassing the necessary multiton quantity was practically unthinkable. After gallium arsenide became an article of commerce, development work toward a gallium detector was initiated in several laboratories, principally Brookhaven National Laboratory and the Institute for Nuclear Research (Moscow). Two methods for separating a few atoms of ^{71}Ge (half-life, 11.43 days) from large quantities of gallium were developed at Brookhaven (*3, 7*). In one method, closely patterned after the successful technique for separating argon from C_2Cl_4, volatile $GeCl_4$ is swept out of an acidic, concentrated $GaCl_3$ solution by a stream of air or helium. In the other technique, ^{71}Ge is extracted from liquid gallium with aqueous dilute HCl containing an oxidizing agent such as H_2O_2. In both systems ^{71}Ge has been shown to be removable with >95% yield even without addition of stable germanium as a carrier. In the gallium system this is surprising since one is dealing with a heterogeneous mixture of metal and aqueous solution. However, in the presence of oxidizing agent a stable dispersion is formed, with finely divided gallium in the form of oxide-coated particles and with germanium concentrated in the oxide coat. When the dispersion is broken by increasing acid concentration, the oxide dissolves, the gallium metal settles out, and the germanium is in the aqueous phase. Volatile $GeCl_4$ is then swept out of this aqueous solution as described above.

In both systems, the $GeCl_4$ in the gas stream is absorbed in a small volume of water. Subsequent treatment consists of extraction from 8*N* to 9*N* HCl into CCl_4 and back-extraction into tritium-free water (tritium can ultimately give undesirable background counts). Reduction from $GeCl_4$ to GeH_4, a gas suitable for use in a proportional counter, is accomplished with borohydride, and the GeH_4 is purified by gas chromatography and introduced into a small (<1 ml) proportional counter of the type used in the ^{37}Cl experiment. The electron capture decay of ^{71}Ge is measured in these counters, with discrimination against background events achieved by both pulse height (energy) and pulse shape analysis (*8*). The pulse shape discrimination is based on the fact that the Auger electrons and photoelectrons associated with ^{71}Ge electron capture decay have short (<1 mm) ranges in the counter gas and thus the counts take the form of rapidly rising pulses, whereas the ionization produced by particles traversing the counter is distributed over larger distances and leads to more slowly rising pulses.

Two gallium experiments are being prepared. One at the U.S.S.R. Institute for Nuclear Research, with 60 metric tons of gallium metal, will be set up in the underground facility being constructed in the Baksan Valley (Caucasus). The other, the European GALLEX collaboration (with West German, Italian, French, Israeli, and U.S. participation), with 30 tons of gallium as $GaCl_3$ solution, is being prepared for the Gran Sasso tunnel in Italy. Pilot experiments at 4 to 10% of full scale have been successfully done for both systems (*8, 9*). Tests that involve in situ production of a small, known number of ^{71}Ge atoms, from the decay of radioactive ^{71}As, and their subsequent removal and measurement, have validated the $GaCl_3$-$GeCl_4$ system on this scale.

With germanium "milked" out of 30 to 60 tons of gallium every 1 to 2 half-lives, each sample will contain only between 5 and 15 atoms of ^{71}Ge. As a result the experiments will have to be done over a period of years to obtain statistically significant results.

As originally conceived, the ^{71}Ga experiment was to give decisive information about the cause of the low ^{37}Cl result. Since ^{8}B and ^{7}Be neutrinos contribute only 10 and 22.5%, respectively, of the captures in ^{71}Ga, a result within 10 to 40% of the standard solar model prediction would strongly indicate difficulties with this model. A capture rate about one-third or less of that expected from the standard model would be clear evidence for a neutrino transformation mechanism; neutrino decay (*10*) is expected to lead to a near-null result because of the much shorter effective lifetime of the

Table 1. Relative capture rates of various detectors for the components of the solar neutrino spectrum in the standard model. The relative capture rates are based on those given in (*30*) but modified to reflect the revised fluxes in column 2.

Neutrino source	Neutrino flux* (10^{10} cm^{-2} sec^{-1})	Fraction of total captures (%)							
		^{37}Cl	^{71}Ga†	^{98}Mo	^{81}Br‡	^{7}Li	^{205}Tl§	^{115}In‖	Electronic¶ detectors
pp	6.1	0	59	0	0	0	~82	76.5	0
pep	0.015	4	2.5	0	7.5	24	1	1.5	0
^{7}Be	0.40	16	22.5	0	64.5	9.5	~13.5	16.5	0
^{8}B	0.00040	74	10	100	12	37	0	1.5	100
^{13}N	0.05	1.5	2.5	0	6	5.5	1.5	2	0
^{15}O	0.04	4.5	3.5	~0	10	24	2	2	0

*These values are taken from (*31*) and include the effects of recent measurements of neutron decay and nuclear reactions. †Calculated from the rates given in (*32*), corrected for an increase in the ground-state cross section, the Q-value, and the effects of the excited states. The excited state effects are estimated from the (p,n) work of Krofcheck *et al.* (*33*). ‡Since the effect of excited states in ^{81}Kr is not known at this time, we follow the procedure of Hurst (*15*) and use the results of a model calculation by Haxton (*34*), but with the fluxes in column 2. §These entries are approximate at best. Only the transition to the ^{205}Tl ground state is taken into account, and the strength of this transition has only been estimated from systematics. Although nothing is known of the transitions to excited states, they are not likely to make a qualitative difference. ‖The cross sections for ν_e capture are as determined by (p,n) studies (*13*). The percentages listed are calculated under the assumption that no biases are introduced beyond those inherent in the nuclear physics. However, detection of neutrino capture depends on measurement of the product electron, and the actual detector response is determined by the effective energy threshold, which in turn is dictated by background and other experimental conditions. With an effective threshold of 3 MeV, ^{115}In would become another detector of ^{8}B neutrinos only. ¶Because the thresholds are chosen above 3 MeV, sensitivity to all but the ^{8}B part of the solar neutrino spectrum is lost.

lower energy neutrinos; the spin-flip mechanism (*11*), being energy-independent, would predict the same diminution of flux as observed for ^{37}Cl.

Although the conclusion from a low result ($\leq 1/3$ of the standard prediction) continues to be valid, the interpretation of a high value (≥ 0.6 of the standard prediction) is no longer as definitive, since there is (*2*) a region of neutrino mass differences and mixing angles that would cause high-energy (^8B) but not low-energy ν_e's to be transformed into other ν's during transit through the sun. In other words, a "high" (60 to 80% of standard) ^{71}Ga result would still leave an ambiguity, indicating either astrophysics problems or matter-induced neutrino oscillations, whereas a low result for ^{71}Ga would definitely point to some neutrino transformation mechanism.

^{98}Mo: An experiment to measure average solar activity over millions of years. A geochemical experiment is now under way to test the hypothesis that accounts for the low yield of the ^{37}Cl experiment in terms of a temporal variation in the central solar region (*12*). In this hypothesis, the present sun is presumed to be performing differently than it has in the past, because of either recurring or one-time fluctuations.

The reaction that forms the basis of this experiment, $^{98}Mo + \nu_e \rightarrow {}^{98}Tc + e^-$, creates a nuclide with a half-life of 4.2 million years. Measurements of the ^{98}Tc accumulated in geologically undisturbed ore determine an average of the sun's neutrino output over times of the order of the half-life. The high reaction threshold, 1.68 MeV, together with the small values of the transitions to low-lying excited states in ^{98}Tc, makes the experiment effectively responsive only to ^8B neutrinos; the reaction rate as a function of excitation energy has been carefully mapped in a set of measurements of the high-energy charge-change reaction (p,n) (*13*). As in the chlorine detector, only the electron-neutrino is capable of initiating the nuclear reaction. This ^{98}Mo-based experiment is, then, sensitive to much the same part of the solar neutrino spectrum as the chlorine (although the higher energy ^8B neutrinos are somewhat more heavily weighted); the integration of the signal over several million years is the new piece of information being sought.

This experiment clearly involves a difficult technology that depends vitally on the existence of a clean natural molybdenum target. A suitable ore body has been found in an operating commercial mine in Colorado that meets the exacting criteria for a definitive interpretation: (i) sufficient shielding from cosmic rays over the experiment's long time period; (ii) freedom from the effects of natural radioactivity originating in the ore, its host material, and the natural surroundings; and (iii) geochemical stability for the produced technetium. The experiment will require the extraction of the order of 10 tons of molybdenite from a much larger amount of mined ore; from this still enormous quantity the 10^6 to 10^8 atoms of ^{98}Tc must be extracted and concentrated without appreciable loss. Negative-ion mass spectrometry will be used in the final determination of the number of ^{98}Tc atoms. All of these requirements appear to have been met. The possibility of a simultaneous additional experiment based on ^{97}Tc (half-life, 2.6×10^6 years) production from ^{97}Mo is still under investigation (*12*).

The experiment is now in its initial steps; results are expected in several years. If the result shows that the integrated signal is in substantial agreement with the standard model, it would be a strong argument for believing that the sun is now "cooling" in the central regions where the conditions were previously right for ^8B production; this would indeed be a striking discovery. If, however, the time-averaged neutrino flux agrees with the low result of the chlorine experiment, little that is new will have been learned about solar processes or neutrino physics. Because of limitations on statistical accuracy, this is true even though the ^{98}Mo is sensitive to ^8B neutrinos only, whereas the chlorine experiment has small additional contributions from other, lower energy solar neutrinos. Confirmation of the chlorine result by an independent experiment would, of course, be welcome.

^{81}Br: A detector for the mid-energy range. We now turn to other proposed, but less fully developed radiochemical experiments. A detector based on the reaction

$$^{81}Br + \nu_e \rightarrow e^- + {}^{81}Kr^m \xrightarrow{13 \text{ seconds}} {}^{81}Kr$$

was originally proposed (*14*) as a method of investigating the neutrino flux integrated over $\sim 10^5$ to 10^6 years, since ^{81}Kr has a half-life of 2.1×10^5 years and bromine occurs in minerals deep underground. Although this approach has not been pursued actively in recent years, the possibility of detecting a small number of krypton atoms by resonance ionization spectroscopy (RIS) with pulsed lasers (*15*) has led to consideration of ^{81}Br as a detector of the present-day neutrino flux. This method is interesting in that ^{81}Br has a different spectral response from other proposed detectors: it is primarily sensitive to ^7Be neutrinos, which in the standard model account for ~64% of captures. Furthermore, the removal of krypton from a bromine-containing liquid such as $CHBr_3$ or $C_2H_2Br_4$ is analogous to the extraction of argon from C_2Cl_4. In fact, the present C_2Cl_4 tank in the Homestake mine (*1*) could presumably be used for a ^{81}Br experiment; the expected ^{81}Kr production rate would be one to two atoms per day, with background processes probably contributing ~0.1 atom per day.

Some uncertainties about the nuclear physics of a ^{81}Br detector remain, particularly cross sections for neutrino capture to higher excited states of ^{81}Kr. However, it may well be that these questions can be answered by studies of the $^{81}Br(p,n)^{81}Kr$ reaction similar to those done for other (p,n) reactions at the Indiana University cyclotron. The RIS technique for detection of a few hundred atoms of ^{81}Kr has been demonstrated in principle, but further development is needed before a full-scale ^{81}Br experiment can be undertaken. Preliminary work is being actively pursued.

The result of a ^{81}Br experiment could be illuminating in conjunction with the ^{37}Cl and ^{71}Ga experiments. If the ^{71}Ga result should turn out to be 60 to 80% of the standard model value—a result that would be compatible with either solar model problems or matter-induced neutrino oscillations—^{81}Br with its sensitivity to ^7Be neutrinos (low energy, but temperature-dependent) will discriminate between the two hypotheses. If the astrophysics is incorrect (central temperature lower than predicted by the standard model), the ^{81}Br result will be low (<50% of standard prediction). Matter-induced oscillations, on the other hand, will lead to a high (>50% of standard) ^{81}Br result. If the ^{71}Ga result is low, indicative of a neutrino transformation mechanism of one sort or another, ^{81}Br is not likely to add decisive new information.

^{7}Li: A broad mix of spectral sensitivity. The use of the reaction $^7Li + \nu_e \rightarrow {}^7Be + e^-$ for solar neutrino detection has been discussed for many years, and feasibility studies have been done both with aqueous lithium salt solutions (*16*) and with molten lithium metal (*17*) as targets. The response of ^7Li to the various components of the solar neutrino spectrum (Table 1) would make a ^7Li experiment harder to interpret than an experiment primarily sensitive to the neutrinos from a single source or in a more confined energy region—$^{37}Cl(^8B)$, $^{71}Ga(pp)$, or $^{81}Br(^7Be)$. In fact, it is not clear that, even in conjunction with other experiments, decisive information concerning the major open questions can be derived from a future ^7Li experiment.

The cross section for neutrino capture in ^7Li is relatively high and well known. Chemical isolation of beryllium appears feasible both in the aqueous and metal systems. The levels of α-emitting impurities that can be tolerated in the aqueous solution may be hard to achieve; in a metal system the problem is much less severe. The largest unsolved problem in the ^7Li-^7Be system is efficient, low-background measurement of ^7Be. Only 10% of decays are accompanied by γ emission; in the other 90% of decays the only emissions are 50-eV Auger electrons. An alternative detection method that has been suggested but not yet proven feasible is RIS.

^{205}Tl: A problematic proposal. An experiment for measuring a time-averaged neutrino flux, proposed by Freedman *et al.* (*18*), would use the reaction $^{205}Tl + \nu_e \rightarrow {}^{205}Pb + e^-$. The long half-life of ^{205}Pb (1.5×10^7 years) means that the neutrino flux would be integrated over geologic times, and requires, as with ^{98}Tc, detection by means other than radioactive decay, most likely by mass spectrometry. Since the energy required for neutrino capture to the first excited state of ^{205}Pb is only 43 keV (the 41-keV transition to the ground state is too highly forbidden to be of interest), a ^{205}Tl detector, in contrast to ^{98}Mo, is sensitive to pp neutrinos; in fact, some 82% of captures in ^{205}Tl are expected to be due to this primary neutrino source. Thus a ^{205}Tl experiment might be particularly interesting when coupled with a gallium experiment, although it is hard to invent a credible model for large time variations in the pp neutrino flux.

Unfortunately, a ^{205}Tl experiment has several serious difficulties and at present it is not clear whether any or all of these can be overcome to the point of making a ^{205}Tl experiment worth attempting. The difficulties lie in the areas of geology, nuclear physics, and product detection.

The only suitable thallium deposit known, a deposit of the mineral lorandite ($TlAsS_2$) in southern Yugoslavia, has an overburden of only 120 m of rock, which would not provide adequate shielding from cosmic-ray muons. Although geologists are confident that the rock cover was appreciably thicker (>300 m) in the past ($>10^6$ years ago), the exact cosmic-ray exposure history is difficult to estimate, which makes any correction for cosmic-ray–produced ^{205}Pb quite uncertain. Other background sources can probably be adequately estimated and are thought to be sufficiently small.

The neutrino capture rate of ^{205}Tl is at present known only from theoretical considerations. The use of (p,n) reaction data for deducing cross sections for inverse β decay, successful for the ^{71}Ga-^{71}Ge case, may not be applicable to nuclear transitions of the type involved here (a "forbidden" transition). Theoretical (shell model) calculations of the requisite matrix elements cannot be expected to give the needed accuracy.

Finally, the isolation and measurement of ^{205}Pb from lorandite is far from easy. Lorandite contains one to a few parts per million of lead so that, from 10 to 100 kg of lorandite, one will separate a sample with up to 1 g of lead. Assuming an ore age of 5×10^6 to 1×10^7 years, this lead sample will contain 10^6 to 10^7 ^{205}Pb atoms; it will also presumably still have at least nanogram quantities of thallium so that the $^{205}Tl/^{205}Pb$ ratio may be 10^5 to 10^6. Recent experiments have shown that determination of ^{205}Pb in the presence of both ^{206}Pb and ^{205}Tl in these relative abundances can probably be achieved by accelerator mass spectrometry. But to do this at the level of 10^6 to 10^7 ^{205}Pb atoms will require greatly improved ion source efficiencies.

The feasibility of a ^{205}Tl experiment is far from established. Nevertheless, several groups in Germany, Yugoslavia, and the United States are pursuing various aspects of the method (*18*).

Real-Time Experiments

All radiochemical detectors have one serious limitation: they can at best give a value for the total number of neutrino interactions during the collection time, without giving any direct information on the energies and directions of the neutrinos and possible correlations with other solar phenomena. Measurements done event by event in real time and with the potential of yielding information on one or more of these additional parameters would be of great interest.

^{115}In: Potentially a neutrino spectrometer. A real-time detection scheme based on the reaction, $^{115}In + \nu_e \rightarrow {}^{115}Sn^*$ (613 keV) + e^-, has been proposed (*19*). It makes use of the fact that the 613-keV excited state of ^{115}Sn decays to the stable ground state with a half-life of 3.26 μsec by the successive emission of two γ rays of 116 and 497 keV. A triple coincidence between the emitted electron and the two delayed γ rays is the characteristic signature. The low (128 keV) threshold of the reaction makes ^{115}In a detector primarily of pp neutrinos, with a response like that of ^{71}Ga but with the added advantages that, at least in principle, the electron energy and hence the neutrino energy is measurable and in fact measurable in real time. The technical feasibility of an indium detector remains to be established. Approaches under investigation include indium-loaded liquid scintillators, sandwiches of indium foils and plastic scintillators, multiwire proportional counters, and superconducting indium tunnel junctions (*20*). Any of these approaches needs considerable development before a full-scale design can be contemplated, where full scale means a device containing at least 1 ton of indium. A 1-ton detector would be expected to detect ~85 pp neutrinos and ~15 ^7Be neutrinos per year. One of the intrinsic problems in an indium detector is the natural radioactivity of ^{115}In; despite its half-life of 4.4×10^{14} years, this β^- decay produces about 10^{11} times as many electrons per unit time as solar neutrino capture in a given quantity of indium. The triple coincidence requirement has been the basis for the strategy for suppression of this background, but it remains to be shown that adequately low backgrounds can be achieved.

A heavy-water detector—the possibility of decisive information. One of the most advanced proposals for real-time measurement of solar neutrinos is based on a large-volume heavy (deuterated) water detector (*21*). Three basic neutrino detection mechanisms occur via the reactions:

$$\nu_e + d \rightarrow p + p + e,\ RT = 1.44\ \text{MeV};\ \nu_e \text{ only} \quad (1)$$

$$\nu + d \rightarrow p + n + \nu,\ RT = 2.22\ \text{MeV};\ \sigma_{\nu_e} = \sigma_{\nu_X} \quad (2)$$

$$\nu + e \rightarrow \nu + e,\ RT = 0;\ \sigma_{\nu_e}/\sigma_{\nu_X} \sim 6 \quad (3)$$

where RT is the reaction threshold and ν_X denotes any neutrino species other than ν_e.

Reaction 1 provides the main method of measurement. The product electron carries off the incoming neutrino energy except for a variable amount that is given to the two protons (of the order of 1 MeV); it is the electron that is actually detected by the Čerenkov light that it emits in its flight through the water. The effective threshold, determined by the electron observation, is stated to be close to 7 MeV. Therefore, this process limits the measurements to the upper part of the ^8B spectrum, not very different from the weighting of the chlorine experiment; further, since the reaction is an inverse β-decay, only electron-neutrinos can activate it. However, there are some impressive advantages: (i) measurement in real time, (ii) electron energy determination with, perhaps, 20% accuracy, and (iii) rough directionality.

The proposal calls for 1000 to 1500 tons of heavy water as the fiducial volume (encased in a shield of light water), to achieve a count rate of the order of 10^4 per year for the standard model prediction. The Čerenkov light signals from the emitted electrons are to be read out by about 2400 phototubes and fed into computer programs for event reconstruction. Careful avoidance of radioactive contaminants, suitable shielding, and placement in a deep mine complete the detector installation.

Reaction 2 has the potential for providing a straightforward test of the oscillation hypothesis. Because it is a neutral-current reaction (that is, mediated by the neutral Z^0 boson) of the weak interaction, it is equally effective for the originally emitted electron-neutrino as for any oscillation partner. For this reason, reaction 2 could be used to measure the total neutrino flux which, in comparison with the results of the inverse β reaction 1, would directly confront the oscillation hypothesis. One catch in this scenario is the need to distinguish between the neutrons produced in this reaction and background neutrons; it is not yet known whether this can be done well enough.

The spin-flip mechanism (*11*) would make the interaction of the transformed neutrino zero for the first process, negligible for the second, and small for the third.

Reaction 3, elastic electron scattering, is the weakest mechanism in the deuterated water detector: it has a cross section an order of magnitude smaller than that of the inverse β reaction and is less efficient at converting the neutrino energy into the recoil electron energy. It is not known at present whether this reaction can provide a useful additional signal for the heavy water detector, but it is the basic mechanism in other proposed systems we will briefly discuss later.

What are the results of this experiment likely to tell us? Even if the only feasible measurements are those based on reaction 1, the impact is likely to be substantial. The advantages of real-time event recording and directionality are clear. The determination of the response rate will provide a useful check of the ^{8}B ν_e flux, under experimental conditions quite different from those of the ^{37}Cl experiment. However, the rate determination is not likely to provide a clear distinction between hypotheses; the high effective threshold, ~7 MeV, combined with the cross-section weighting, means that the experiment is sensitive to the upper part of the ^{8}B spectrum, much as in ^{37}Cl; we estimate that the distinction would be lost in the statistical errors. However, the promised energy-measuring capability offers the exciting possibility of determining the neutrino spectrum shape well enough to give a decisive answer: If the observed deficit in ^{8}B neutrinos is of astrophysical origin, the spectrum shape should be unchanged. If the reduction in flux results from matter-induced neutrino oscillations, the spectrum will be distorted. Assuming 2-MeV resolution, we estimate that the fairly sharp cutoff of high-energy neutrinos produced by oscillations in the "high-mass" regime [left-hand branch of the graph in figure 2 of (*2*)] will be reflected in a readily measurable distortion of the electron spectrum. If the "low-mass" solution (right-hand branch of the graph) pertains, the cutoff is more gradual and hence the distortion of the electron spectrum will be less pronounced and a decisive result may not be attainable.

Another major payoff depends on the realizability of reaction 2, with its capability to measure both emitted and transformed neutrinos and so directly confirm or contradict the oscillation hypothesis.

Other large electronic detectors. A number of other, new, and very large detectors are being discussed in the form of proposals to various funding agencies. Solar neutrino detection is only one of several proposed applications of these devices. Their solar neutrino detection capability depends on neutrino-electron scattering, reaction 3; as such, there is no specific identification of the nature of the neutrinos (electron-neutrino or otherwise). However, all neutrinos are not equal: the electron-neutrino scattering cross section (mediated by both the charged and neutral bosons) is about six times that of other neutrinos (mediated only by neutral bosons). Therefore, much as in the D_2O detector, a positive identification of neutrino oscillations is possible from the spectrum shape if neutrino energy resolution is good enough. Such resolution has not been clearly established. Spin-flipped neutrinos (*11*) would be almost undetectable, but those turned into antineutrinos of a different family would scatter as a result of the neutral current, with a sixfold smaller cross section.

A large volume detector (*22*), based on 1800 tons of liquid scintillator, is planned for the Gran Sasso (Italy) underground laboratory. An ambitious program of neutrino and antineutrino astrophysics has been outlined, including as one component the detection of solar neutrinos. Since this is a real-time experiment, all of the advantages provided by the capability to correlate with other solar phenomena will follow. The energy of the recoil electron is to be measured, subject to a threshold of about 3 MeV (therefore restricted to ^{8}B neutrinos). Directionality information is to be obtained with electron streamer tubes, but whether the recoil electron direction can be measured with accuracy sufficient to determine the original neutrino energy is not clear to us. If only a total event rate can be determined, the results would be similar, whether the chlorine result arose from astrophysical or oscillation phenomena. In a total event determination, only the extra scattering on the detector electrons produced by the neutrinos transformed into ν_X would make the difference, a difference that may be too small to be statistically significant.

Programs to develop a liquid argon detector have been under way for some years. By combining electronic readouts of the ionization tracks with a large target mass, such a detector acts basically as an electronic bubble chamber and offers all the advantages of track recognition in real time. A huge detector of this type encompassing 6.5×10^3 tons of liquid argon is proposed, ICARUS (*23*) (Imaging Cosmic and Rare Underground Signals), as yet another tenant of the Gran Sasso underground laboratory. Some fraction of its program is to be devoted to solar neutrino studies. Its very large mass assures an event rate large enough to overcome the statistics problem (4.5×10^3 per year for the standard model prediction), if background problems can be surmounted. In addition to detecting electrons from neutrino-electron scattering (for any neutrino species), this device will also detect the electrons from ν_e capture in ^{40}Ar, principally to the region of the isospin analog state of ^{40}K at 4.38 MeV (that is 5.89 MeV above the ground state of ^{40}Ar). Since background considerations impose a threshold of ~5 MeV on the electron energies that can be measured, only ^{8}B neutrinos of ≥ 11 MeV will be detected by the capture reaction. To sort out these electrons from those produced by neutrino-electron scattering, the ICARUS proposal includes the suggestion of replacing the argon with methane (CH_4) that will "see" only scattering (with the same cross section per e^- as argon). The two measurements together would give direct information on the ν_e and ν_X fluxes, thus decisively confronting the oscillation hypothesis. Furthermore, the high effective energy threshold (~11 MeV) for the capture reaction should lead to an even greater reduction in signal from the standard model expectation than in the ^{37}Cl experiment if the Mikheev-Smirnov mechanism is operative with the "high-mass" solution. If the "low-mass" solution holds, the observed flux would be similar to that deduced from the ^{37}Cl experiment, and alternate hypotheses then could not be differentiated.

Water detectors. Proposals have been made and exploratory work is under way to develop large pure water detectors to measure neutrinos by means of the Čerenkov radiation that follows their scattering from electrons. As in the other electronic detectors, only the high-energy portion of the ^{8}B spectrum is accessible. We have heard of such plans in Australia (*24*) for a 100-ton detector. The Japanese water detector (Kamiokande II) designed and used in the search for proton decay, has been modified for neutrino work, of which solar neutrino measurements are to be an important part. Early reports (*25*) on this 3000-ton detector describe recent progress and indicate that present limits are not far from the standard model prediction. Thus one may hope for useful results if further efforts toward reducing backgrounds are successful.

Interesting new ideas. It is encouraging that new ideas for solar neutrino experiments are being proposed, although their realizability as actual experiments is far from established. Cabrera, Krauss, and Wilczek (*26*) have proposed a detector based on direct measurement of the recoil energy deposited in a large (1 to 10 tons) block of pure silicon by neutrino-electron scattering and neutrino-nuclear scattering. At very low temperatures the specific heat is so small that the recoil energy, on the order of a fraction of 1 MeV, is sufficient to produce an appreciable temperature rise—a few millikelvin in a kilogram. An energy resolution of 10 keV is envisioned, which can be compared with the electron recoil spectrum maximum of 0.66 MeV for ^{7}Be neutrinos and 0.26 MeV for pp neutrinos. As noted before, neutrino-electron scattering is mainly sensitive to ν_e's; however, neutrino scattering from nuclei occurs by the neutral-current interaction and is therefore sensitive to ν_X as well as ν_e. The recoil energy of the struck silicon nuclei is small, up to 14 keV, but, it is hoped, measurable; as such it could serve directly as a detector of the oscillation-transformed neutrino. Much development work is required before such a detector can be shown to be feasible. Another idea for detecting nuclear recoils from neutral current coherent scattering of neutrinos (of any type) has been suggested by Drukier and Stodolsky (*27*); it would utilize the loss of superconductivity in small grains of a suitable medium. Here, too, much development is needed before feasibility can be established.

Recently it has been suggested (*28*) that excitation of nuclear levels in certain target nuclei through neutral-current interactions and comparison with transitions to the analogous levels in the isotopic-spin mirror nuclei by charged-current interactions would offer a useful tool for analysis of the solar-neutrino spectrum—whether transformed or not. The underlying considerations are similar to those discussed for the heavy-water detector. A particularly good candidate for such a detector appears to be ^{11}B.

Summary

A solution to the "solar neutrino puzzle" created by the discrepancy between astrophysicists' model calculations and the results of the ^{37}Cl experiment requires additional solar neutrino measurements. The ^{71}Ga experiments now funded and in advanced planning stages will show whether the neutrinos from the primary pp reaction reach us with the predicted intensity. If not, a neutrino transformation mechanism will have been proven and thus it will have been established that neutrinos have nonzero rest mass or a magnetic moment or both. The other currently funded experiment, which uses geologic molybdenum deposits, has the potential of determining whether the sun has undergone variations that make the present a special time in its history. Such outcomes would be important for particle physics and astrophysics. But beyond that, much remains to be learned, and a third generation of solar neutrino experiments is needed—experiments done with real-time detectors capable of giving information on energies, directions, and types of incoming neutrinos.

Note added in proof: An interesting consequence of the Mikheev-Smirnov mechanism recently pointed out by several authors (*29*) is the effect of transit through Earth on the mix of neutrinos arriving at a target. This raises the intriguing possibility of observing seasonal and diurnal variations in some solar neutrino measurements. This is an example of the ferment in this field. It is quite possible that important new ideas will have surfaced by the time this article appears, although we have touched on all those known to us at time of submission (August 1986).

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