DISCRIMINATING AMONG SCENARIOS TO RESOLVE THE SOLAR NEUTRINO PUZZLE

Report of the Working Group on Solar Neutrinos

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Summary

The properties of neutrinos may account for the difference between the measured flux of neutrinos emitted by the sun and the flux predicted by the standard solar model. This work summarizes the particle physics explanations of this discrepancy and the characteristics by which they may be distinguished from each other and from modifications to the standard solar model. New experiments which will soon come into being are discussed with respect to the different types of information they will bring to bear on the problem. Future experimental data should determine the flux of neutrinos emitted by the sun and the properties of neutrinos which may modify the flux which is detected on earth.

I. Introduction

In 1970 R. Davis, Jr., and collaborators began operation of an experiment designed to detect neutrinos emitted by the sun. At that time the principles of stellar evolution and nucleosynthesis were believed to be well understood, but all the astronomical data from which the model was constructed were based on observations of the surfaces of the sun and other stars. Detection of neutrinos would probe the interior of the sun and provide direct information on the region of the sun where the solar fuel is burned. The experiment observed approximately three times fewer neutrinos than the standard solar model predicted,[1] leading to the so called "solar neutrino puzzle": Is the discrepancy due to incomplete understanding of the evolution and nature of the sun, or are the properties of neutrinos not understood?

Fifteen years after the first solar neutrino experiment began operation there is data from only the original experiment. Many experimental checks of the apparatus have been performed, all of which support the established experimental result. In this paper it is assumed that this result is correct. Within the next few years several new experiments with different energy acceptance will begin operation. The interpretation of the results of these experiments is complicated by a plethora of suggested explanations of the result of the single existing experiment. The present work is intended to bring order to what may appear to many particle physicists to be a chaotic situation. Of further interest to particle physicists is the recent observation that matter oscillations in the sun may enhance the vacuum oscillations of neutrinos.[2] This observation opens a new region of neutrino mass and mixing space to experimental investigation. The sun may possibly be a unique source of information about fundamental properties of elementary particles.

The four principal sections of this paper provide background information for non-specialists, describe the experiments which are likely to bring new data to bear on the problem in the coming decade, discuss the various scenarios which have been put forward to "explain" the solar neutrino puzzle, and discuss what experimental data will discriminate among the various scenarios in the absence of "scenario mixing".

II. Background and Recent Developments

A review of the standard solar model is beyond the scope of the present work. The interested reader can find the basics in Reference 3. For the purpose at hand, the sun can be described as being in hydrostatic and radiative equilibrium. The transport of the energy liberated by the burning of nuclear fuel in the interior is dominated by radiation, with convection making a small contribution near the solar surface. The energy production is dominated (98.5 per cent) by nuclear reactions which convert four protons into ^4He by the three reaction chains shown in Table I. The dominant *ppI* chain terminates with the reaction

$$^3He + {}^3He \rightarrow {}^4He + 2\,{}^1H$$

The *ppI* chain is reponsible for the largest flux of neutrinos, albeit neutrinos of very low energy. These neutrinos are produced by the so called *pp* reaction ($p + p \rightarrow d + e^+ + \nu_e$) of

Table I

The *pp* Reaction Chains

ppI		*ppII*		*ppIII*
$p + p \rightarrow d + e^+ + \nu_e$				
or $p + e^- + p \rightarrow d + \nu_e$				
$d + p \rightarrow {}^3He + \gamma$				
$^3He + {}^3He \rightarrow {}^4He + p + p$	or	$^3He + {}^4He \rightarrow {}^7Be + \gamma$		
		$^7Be + e^- \rightarrow {}^7Li + \nu_e$	-or-	$^7Be + p \rightarrow {}^8B + \gamma$
		$^7Li + p \rightarrow {}^4He + {}^4He$		$^8B \rightarrow {}^8Be^* + e^+ + \nu_e$
				$^8Be^* \rightarrow {}^4He + {}^4He$

Table I. The *ppII* and *ppIII* chains of Table I involve elements heavier than ^4He and occur in the central core of the sun. The rate for the *ppI* chain is determined by the well measured solar luminosity as well as the mass and age of the sun. The rates for the *ppII* and *ppIII* chains depend also on the density, temperature, and composition of the solar core, parameters which the standard solar model constrains strongly. The *ppII* chain produces ^7Be neutrinos ($e^- + {}^7Be \rightarrow {}^7Li + \nu_e$) while the *ppIII* chain produces high energy ^8B neutrinos ($^8B \rightarrow {}^8Be + e^+ + \nu_e$) The CNO cycle is responsible for the remaining 1.5 percent of the energy generated in the sun, and a small flux of low energy neutrinos.

The spectra of neutrinos predicted by the standard solar model are tabulated in Table II and shown in Figure 1. The ^{37}Cl experiment of Davis, *et al.*, has a detection threshold at 0.81 MeV, but the acceptance is large only for the ^8B neutrinos of the *ppIII* chain. The contribution of each of the chains to the ^{37}Cl capture rate is shown in Table III. From Table III, the ^8B decay neutrinos are responsible for about three quarters of the predicted capture rate:

$$R(\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-) = 5.8 \pm 2.2 \quad SNU \text{ (Theory, } 3\sigma) \tag{2.1}$$

$$1\ SNU = 10^{-36}\text{captures/sec} - \text{atom}$$

This is to be compared to the experimentally observed rate:

$$R(\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-) = 2.1 \pm 0.3 \quad SNU \text{ (Experiment, } 1\sigma) \tag{2.2}$$

The discrepancy between these two numbers is the solar neutrino puzzle.

Over the years, a variety of solutions have been proposed for the solar neutrino puzzle. Generically they involve reducing the flux of ^8B neutrinos preferentially by reducing the temperature of the solar core where these neutrinos are produced, or changing the basic properties of neutrinos such that a depletion

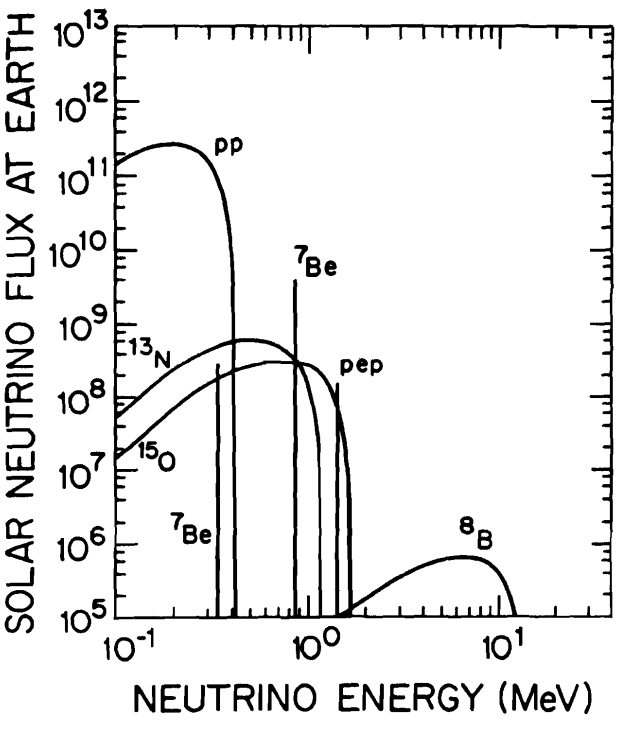

Figure 1. The energy spectrum of solar neutrinos predicted by the standard solar model. For monochromatic sources the height of the line represents the integrated flux.

Table II

Main Neutrino Producing Reactions in the Sun, Maximum Neutrino Energy, and the Integrated Flux Predicted by the Standard Solar Model.[a]

Solar Reaction	Max. Neutrino Energy (MeV)	Predicted Total Flux ($cm^{-2}sec^{-1}$)
$p + p \rightarrow d + e^+ + \nu_e$	0.42	6.1×10^{10}
$p + e^- + p \rightarrow d + \nu_e$	1.44	1.5×10^8
$e^- + {}^7Be \rightarrow {}^7Li + \nu_e$	0.86	4.0×10^9
$^8B \rightarrow {}^8Be + e^+ + \nu_e$	14.10	4.0×10^6
$^{13}N \rightarrow {}^{13}C + e^+ + \nu_e$	1.15	5×10^8
$^{15}O \rightarrow {}^{15}N + e^+ + \nu_e$	1.73	4×10^8

a) J. N. Bachall, B. T. Cleveland, R. Davis, Jr., and J. K. Rowley, Ap. J. Letters **292**, L179 (1985).

Table III

Typical Calculated Neutrino Capture Rates in Radiochemical Detectors (Uncertanties exist in calculated numbers, particularly for ^{81}Br)

	Capture Rate (SNU)		
	^{37}Cl	^{71}Ga	^{81}Br
$p + p \rightarrow d + e^+ + \nu_e$	0	70.2	0
$p + e^- + p \rightarrow d + \nu_e$	0.24	3.0	1.2
$e^- + {}^7Be \rightarrow {}^7Li + \nu_e$	0.9	31.2	10.6
$^8B \rightarrow {}^8Be + e^+ + \nu_e$	4.3	11.6	2.2
$^{13}N \rightarrow {}^{13}C + e^+ + \nu_e$	0.08	3.3	1.0
$^{15}O \rightarrow {}^{15}N + e^+ + \nu_e$	0.24	4.6	1.6
Total Rate	5.8	124	16.6
Reference	a	b	c

a) J. N. Bachall, B. T. Cleveland, R. Davis, Jr., and J. K. Rowley, Ap. J. Letters **292**, L179 (1985). (A more recent calculation of the ^{37}Cl rate gives 7.6 SNU. J. N. Bachall, private communication.)

b) G. J. Matthews, S. D. Bloom, G. M. Fuller, and J. N. Bachall, Phys. Rev. **C32**, 796 (1985).

c) G. S. Hurst, C. H. Chen, S. D. Kramer, and S. L. Allman, in *Solar Neutrinos and Neutrino Astronomy*, AIP Conf. Proc. **126**, p. 152 M. L. Cherry, W. A. Fowler, and K. Lande, eds., Am. Inst. of Physics, NY (1985).

of the ν_e flux occurs after production. Some of the latter scenarios are vacuum flavor oscillations, neutrino spin precession in solar magnetic fields, and neutrino decay. Although interesting, these solutions appear somewhat contrived because they require very specific neutrino mixing angles, magnetic moments and decay rates respectively. We discuss these possibilities and their testable consequences in Sections IV and V.

Recently, a new ingenious solution to the solar neutrino puzzle has been proposed by Mikheyev and Smirnov.[2] Employing an analysis of matter effects on neutrino oscillations, they showed that for a large range of neutrino masses and mixing parameters neutrino oscillations between ν_e and ν_μ or ν_τ in the sun's interior could be significantly enhanced. In fact, for some neutrino energies one can get a nearly complete transformation of ν_e into another neutrino flavor. That scenario (henceforth referred to as the MS effect) provides an elegant natural solution to the solar neutrino puzzle and hence has become very popular. It will certainly enter into the planning for future solar neutrino experiments as well as their interpretation. We describe below some of its salient features and potential implications.

The basic mechanism responsible for the MS effect is contained in the coupled evolution equation for two neutrino flavors propagating through matter. (The generalization to three flavors is straightforward but cumbersome.[4])

$$i\frac{d}{dt}\begin{pmatrix}\nu_e(t)\\ \nu_l(t)\end{pmatrix} = \begin{pmatrix}\frac{-\Delta m^2}{2p}\cos 2\theta + \sqrt{2}G_F N_e & \frac{-\Delta m^2}{4p}\sin 2\theta \\ \frac{-\Delta m^2}{4p}\sin 2\theta & 0\end{pmatrix}\begin{pmatrix}\nu_e(t)\\ \nu_l(t)\end{pmatrix} \tag{2.3}$$

$$l = \mu, \tau ...$$

where $\Delta m^2 \equiv m_2^2 - m_1^2$, p is the neutrino momentum, $G_F = 1.16636 \times 10^{-5}\ GeV^{-2}$ is the Fermi constant, N_e is the electron number density in matter and θ is the vacuum mixing angle between neutrino mass eigenstates ν_1 and ν_2

$$\nu_e = \nu_1 \cos\theta + \nu_2 \sin\theta \tag{2.4}$$

$$\nu_l = \nu_2 \cos\theta - \nu_1 \sin\theta$$

The $\sqrt{2}\ G_F N_e$ term arises from the $\nu_e - e$ charged current interaction. In a vacuum where $N_e = 0$, an initial ν_e state will oscillate into a ν_l state with a characteristic vacuum oscillation length

$$L_V = \frac{4\pi p}{\Delta m^2} \tag{2.5}$$

such that the probability of observing it as a ν_l at a distance x from the source is given by

$$P_{\nu_e\to\nu_l}(x) = \sin^2 2\theta\ \sin^2\left(\frac{\pi x}{L_V}\right) \tag{2.6}$$

For large mixing $\theta \approx \pi/4$, one gets a depletion ($\approx 50\%$) for $x \gg L_V$. (In the case of 3 neutrinos, the reduction can be even larger.) However, theoretical prejudice favors small mixing as suggested by quark mixing angles where $\sin^2 2\theta \approx 0.16$. In those cases $P_{\nu_e\to\nu_l}(x)$ is much too small to account for the ^{37}Cl results.

The effect of matter can cause dramatic changes. Indeed, for fixed density N_e, Eq. (2.3) gives

$$P_{\nu_e\to\nu_l}(x) = \sin^2 2\theta_m\ \sin^2\left(\frac{\pi x}{L_m}\right) \tag{2.7a}$$

where

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{1 - 2\frac{L_V}{L_o}\cos 2\theta + \frac{L_V^2}{L_o^2}} \tag{2.7b}$$

$$L_m = \frac{L_V}{\left(1 - 2\frac{L_V}{L_o}\cos 2\theta + \frac{L_V^2}{L_o^2}\right)^{1/2}} \tag{2.7c}$$

$$L_o = \frac{2\pi}{\sqrt{2}\,G_F N_e} \tag{2.7d}$$

The matter mixing angle θ_m can become quite large even if θ is small. In fact, if the condition

$$L_V/L_o = \cos 2\theta \quad \text{(Resonance Condition)} \tag{2.8a}$$

which corresponds to

$$N_e = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2}G_F p} \tag{2.8b}$$

is satisfied, one finds $\theta_m = 45^o$, maximal mixing.

The MS effect derives from a changing electron density profile in the sun. Neutrinos produced in the solar core start out at high electron density, but experience a decreasing density as they propagate outward. If the resonance condition is satisfied during that transit, they can resonate completely into ν_l. Assuming that the vacuum angle θ is small, they will tend to remain as ν_l as they propagate to the earth. Matter effects due to solar neutrinos traversing the earth are also potentially interesting for $10^{-5} \lesssim \Delta m^2 \lesssim 10^{-7} eV^2$.

To analyze the MS resonance effect on the solar neutrino spectrum requires a realistic solar density profile and numerical solution of the coupled evolution equation in (2.3). Several detailed computer aided studies have been carried out. Here, we illustrate some of the results obtained by Rosen and Gelb[5] and analytic results due to Parke.[6] In Figure 2, the probability for a ν_e created at the center of the sun to reach the earth as a ν_e is plotted as a function of its energy for the case of very small mixing, $\sin^2 2\theta = 0.01$. Notice that a range of neutrino energies have small survival probabilities, some are partially suppressed and other energies are unaffected. Requiring 70% of the ^{37}Cl rate to be suppressed by this effect leads to the approximate solutions in Figure 3. There are three classes of solutions which we describe briefly here and discuss in detail later:

1) The solutions in the horizontal line correspond to:

$$\Delta m^2 \approx 1 \times 10^{-4} eV^2$$

$$0.001 < \sin^2 2\theta \leq 0.4 \tag{2.9}$$

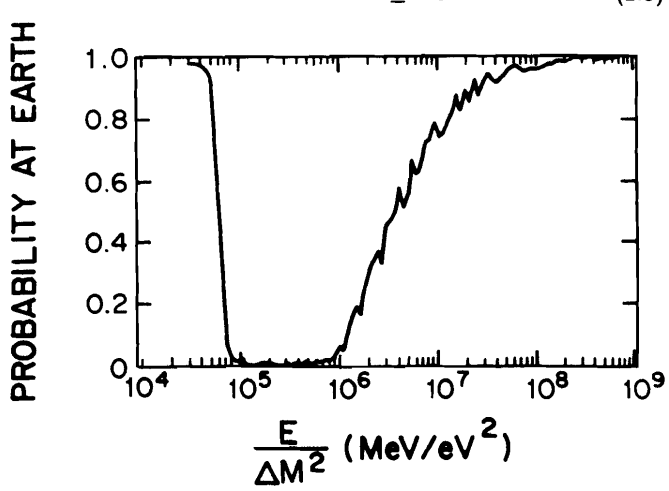

Figure 2. The survival probability for a single ν_e created at the center of the sun to arrive at earth as ν_e for $\sin^2 2\theta = 0.01$. The figure is taken from the work of Rosen and Gelb, Reference 5.

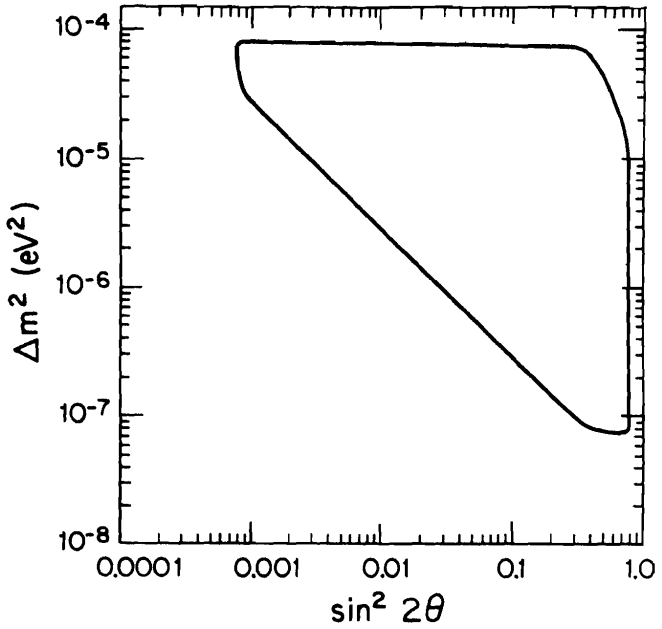

Figure 3. Schematic representation of the contour in $\Delta m^2 - \sin^2 2\theta$ corresponding to 30% survival of ν_e emitted by the sun. It is assumed that neutrino oscillations are responsible for the discrepancy between the measured flux and that predicted by the standard solar model. The suppression of the flux is greater than 70% inside the contour. The three straight segments of the contour correspond to the three classes of solution discussed in the text. The figure is adapted from the work of Parke, Reference 6.

In this case the high energy ^8B neutrinos are almost completely depleted while the low energy ones are unaffected.
2) The diagonal line corresponds to:

$$\Delta m^2 \sin^2 2\theta \approx 3 \times 10^{-8} eV^2$$

$$0.001 \leq \sin^2 2\theta \leq 0.4 \qquad (2.10)$$

In this class of solutions with $\Delta m^2 \leq 10^{-5} eV^2$ essentially all the low energy neutrinos are lost and the high energy ^8B neutrinos are partially depleted.
3) The vertical line corresponds to:

$$8 \times 10^{-8} eV^2 < \Delta m^2 < 1 \times 10^{-5} eV^2$$

$$\sin^2 2\theta \simeq 0.8 \qquad (2.11)$$

For this set of solutions, 70% of the flux is lost independent of energy. It corresponds to the effect of matter on vacuum oscillations with large mixing. For values of $\sin^2 2\theta$ between 0.4 and 0.8 there is a smooth interpolation between the diagonal and vertical line.

Including the experimental uncertainty in the ^{37}Cl experiment spreads all the above lines into narrow bands of solutions in Figure 3. Note also that experiments which are sensitive primarily to lower energy solar neutrinos are, through the MS resonance condition, sensitive to smaller values of Δm^2 than those displayed in Figure 3.

The above set of solutions illustrate the elegance of the MS effect and the reason for its popularity. One can explain the ^{37}Cl results for a large range of Δm^2 and $\sin^2 2\theta$ values. Those ranges include the types of values suggested by grand unified theories. Indeed, the MS effect provides a unique window to very small neutrino masses and mixing parameters, an exciting development.

III. The Experiments

One new solar neutrino experiment is operational, two more are under construction, at least two more are in advanced stages of design, and many new techniques are in developmental stages. These experiments are classified as direct counting experiments, radiochemical experiments, and geochemical experiments. The Snowmass '86 Workshop included talks by proponents of those techniques which are well established, and certain techniques which are in the developmental stage. Details can be found in the contributions to these proceedings. In this section we provide a short summary of the various experiments which can be used as a reference to correlate a particular experiment with the energy interval of the solar spectrum to which it is sensitive, to indicate the charged and neutral current capabilities, and to indicate the present status of the experiment.

Radiochemical Experiments

The radiochemical experiments[7] all detect neutrinos through inverse beta decay processes which transform the target nucleus into a different species and are therefore only sensitive to charged current neutrino interactions. The ^{37}Cl experiments have a threshold of 0.81 MeV and are not sensitive to the neutrinos from the *pp* reaction of the *ppI* chain. Furthermore, the detection cross section rises dramatically above the threshold for the superallowed transition to the 5 MeV analog state of ^{37}Ar. In the standard solar model, the ^{37}Cl experiment is expected to detect 4.3 SNU (1 SNU = 10^{-36} capture per target per second) from the ^8B flux, out of a total 5.8 SNU with most of the remaining rate due to the ^7Be line at .86 MeV. The ^{71}Ga experiment has an energy threshold of 0.233 MeV. With this low threshold, 70 SNU are expected from the *pp* reaction, an additional 31 SNU from the two ^7Be lines and only 12 SNU from the ^8B decays. A third radiochemical experiment, which is under development uses ^{81}Br as a detector. The threshold of 0.47 MeV is above the endpoint of the dominant *pp* reaction. This experiment is expected to detect a total of 17 SNU, of which 11 SNU are from the 0.86 MeV ^7Be line. A summary of standard solar model predictions for radiochemical detectors is given in Table III.

The three types of radiochemical experiments discussed above measure the integral of the flux times the cross section above the detection threshold.The principal advantage of these experiments is the very low level of background to which they are sensitive.

The ^{37}Cl experiment of Davis and others is expected to continue running in the Homestake mine until a new ^{37}Cl experiment which is five times larger is commissioned in the Baksan laboratory in the early 1990's. At that time it is hoped that the ^{81}Br experiment is sufficiently developed that it can replace the ^{37}Cl experiment in the Homestake detector. Two ^{71}Ga experiments are under construction. A Soviet-U.S. collaboration plans to begin taking data in the Baksan laboratory in 1987, and the European GALLEX collaboration will begin taking data in the Gran Sasso laboratory about two years later.

Direct Counting Experiments

The direct counting experiments are all isotropic volume targets with detection instrumentation mounted on the surface. They include water Cerenkov counters and large volume scintillation detectors in which Cerenkov or scintillation light is detected by photomultiplier tubes, liquid argon time projection chambers, and a variety of detectors which exploit techniques more familiar to the condensed matter physicist than the elementary particle physicist.

The KAMIOKANDE II light water Cerenkov detector[8] has been operational since the beginning of 1986 and expects the backgrounds to solar neutrino detection to be reduced to an acceptable level by early 1987. The detector is sensitive to the recoil electrons from neutrino-electron scattering above a threshold of 7 MeV. The detection reaction is directional, which will verify that the source is the sun, and detects neutrinos of all flavors. The expected rate of solar neutrino interactions in the fiducial volume is about 0.5 per day, comparable to the rate in the ^{37}Cl detector.

The Sudbury Neutrino Observatory (SNO), which is in an advanced stage of design study,[9] uses a similar technique, but with a heavy water fiducial volume. The neutrino-electron scattering detection capability is similar to the KAMIOKANDE II experiment, but the deuterium in the heavy water is also a useful neutrino target sensitive to the pure charged current reaction $\nu_e + d \rightarrow p + p + e$. The event rate for this process is 12 times larger than the neutrino-electron scattering rate, but the directional sensitivity is poorer. The detector is also sensitive to the pure neutral current reaction $\nu + d \rightarrow n + p + \nu$, followed by the capture reaction $n + d \rightarrow {}^3H + \gamma$ where the 6.25 MeV photon conversion is the signature for the reaction. Any source of neutrons which capture on the deuterium produces a background for this latter reaction.

The proposal for a liquid argon time projection chamber[10] (known as ICARUS) has been approved for construction in the Gran Sasso laboratory in Italy. The detector measures the ionization of charged particles moving through the liquid argon with sufficient information to reconstruct the trajectory of the particle in the analysis. The threshold for electron detection is 5 MeV. This detector is sensitive to both neutrino-electron scattering and inverse beta decay. The inverse beta decay acceptance is dominated by transitions to the isotopic analog state of ^{40}K at an excitation energy of 4.38 MeV above the ground state. Conversion in the liquid argon of photons emitted during the de-excitation of the ^{40}K provide an additional signature which reduces the background to the inverse beta decay process and may allow a reduction of the detection threshold for this reaction. At the present time it is proposed that the first phase of this work would deploy a 2000 ton detector. The event rate for this mass is about 4 events per day for both the elastic scattering and the inverse beta decay.

Another ionization detector, which is in an early stage of design,[11] is a large volume of liquid scintillator located in a deep mine, and shielded by water. The scintillation light yield is sufficiently large that if the detector materials can be made pure enough, it appears possible to detect electrons from neutrino-electron scattering with energies as low as 0.25 MeV. In a very deep mine where cosmic ray induced backgrounds can be made negligible, a sufficiently well shielded detector containing 100 tons of scintillator would be sensitive to neutrinos from the ^7Be electron capture in the sun through measurement of the recoil electron energy spectrum. Such a measurement provides information similar to the ^{81}Br radiochemical experiment, but in real time. If background radioactivity does not permit operation at a threshold of 0.25 MeV, an alternative 1000 ton detector operating at a threshold of 2-3 MeV would produce a unique measurement of the ^8B energy spectrum through measurement of neutrino-electron scattering.

The experiments discussed above utilize conventional technology. New suggestions, such as those discussed by Cabrera in these proceedings,[12] exploit the very small energy required to cause measurable effects typically studied by condensed matter physicists. The detectors may be sensitive to phonon excitations or transitions in superconductors, but the unique feature in terms of neutrino physics is that they are sensitive to coherent neutral current neutrino-nucleus scattering, $\nu + A \rightarrow \nu + A$. Although these detectors require substantial development, they would have the capability to detect the neutrinos emitted by the sun with equal cross section independent of flavor.

The discussion above is summarized in Table IV.

Table IV

Summary of Solar Neutrino Experiments

Location	Target	Detection Reaction	Charged or Neutral Current	Status
Homestake	^{37}Cl	$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$	CC	Operational (since 1970)
Kamioka	H_20	$\nu + e^- \rightarrow \nu + e^-$	CC + NC	Operational (since 1986)
Baksan	^{71}Ga	$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$	CC	Install 1987
Gran Sasso	^{71}Ga	$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$	CC	Install 1989
Baksan	^{37}Cl	$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$	CC	Planning
Sudbury	D_2O	$\nu + e^- \rightarrow \nu + e^-$	CC + NC	Proposal 1987
		$\nu + d \rightarrow p + p + e^-$	CC	
		$\begin{cases} \nu + d \rightarrow p + n + \nu \\ \rightarrow n + d \rightarrow {}^3H + \gamma \end{cases}$	NC	
Gran Sasso	LAr	$\nu + e \rightarrow \nu + e$	CC + NC	Approved
		$\nu_e + {}^{40}Ar \rightarrow {}^{40}K + e^-$	CC	R&D
Homestake	^{81}Br	$\nu_e + {}^{81}Br \rightarrow {}^{81}Kr + e^-$	CC	R&D
USA	Scintillator	$\nu + e \rightarrow \nu + e$	CC + NC	R&D
US, Europe	Cryogenic	$\nu + e \rightarrow \nu + e$	CC + NC	R&D
	Detectors	$\nu + (Z, A) \rightarrow \nu + (Z, A)$ (coherent)	NC	

IV. Catalog of Scenarios

In this section we list the various proposed solutions to the solar neutrino puzzle and comment briefly on their characteristic features and predictions. It is to serve as a prelude to Section V where the impact of various measurements on sorting out and eliminating some of these scenarios is discussed.

Solar Model Modifications

The flux of ^8B neutrinos is sensitive to the temperature of the solar core. Attempts to modify the standard solar model to account for the Davis result produce, in general, lower temperatures for the solar core, for example by changing the abundance of elements heavier than helium, or mixing more hydrogen into the core by convection. Again, it is beyond the scope of this work to review solar model variations. One statement can be made independent of solar model modifications: If the sun is powered by nuclear fusion, and if the rate of fusion in the sun's core has remained constant over the time required to transport energy from the core to the sun's surface, then a minimum of $6 \times 10^{10}\ \nu_e\ cm^{-2}sec^{-1}$ must be produced by the basic *pp* reaction itself. Observation of *ppI* neutrino fluxes below this limit (70 SNU in the ^{71}Ga experiment) are definite evidence for a solution involving modification of neutrino properties; *ppI* fluxes above this limit have an ambiguous interpretation in the absence of additional information.

Vacuum Oscillations

In this scenario, ν_e oscillates into one or more other flavors during its sun-earth journey. In either case relatively large mixing angles are required to obtain the observed reduction in ^8B neutrinos. If the vacuum oscillation lengths are small compared to the earth-sun distance, and there is large mixing between all flavors, the neutrino flux reduction will be approximately energy independent. For example, three generations of neutrinos with all Δm^2 combinations $> 10^{-8}eV^2$ and large mixing will produce the ^{37}Cl result. It is also possible to have only 2 neutrinos with large mixing and pick the oscillation length (or Δm^2) such that high energy neutrinos are near a maximum in $P_{\nu_e \to \nu_\mu}(x)$ when x is the sun-earth distance. In that case the flux reduction will be very energy dependent.

Matter Enhancement of Vacuum Oscillations

If vacuum neutrino oscillations occur, but with small mixing angles, the neutrino oscillations may undergo enhancement by matter when travelling through the sun. As discussed in Section II, there are three classes of solutions in this category corresponding to the three straight portions of the closed curve in Figure 3.

1) $\Delta m^2 \approx 1 \times 10^{-4}eV^2,\ 0.001 < \sin^2 2\theta \leq 0.4$

The horizontal set of solutions corresponds to an essentially complete conversion of high energy solar neutrinos into ν_μ or ν_τ while low energies are unaffected. This scenario leads to the standard unsuppressed prediction for the gallium experiments; *it cannot be differentiated from the lower solar core temperature scenarios by the results of the gallium and chlorine experiments alone.* Measurement of the energy spectrum of the surviving ν_e is a crucial test of this flavor oscillation scenario. A further verification of flavor conversion is the measurement of the energy spectrum or the interaction rate of all flavors of neutrinos via a neutral current interaction. Comparison of the spectrum or flux of ν_e with the spectrum or flux of all neutrino flavors provides direct evidence for flavor conversion. We also observe that the IMB experiment[13] has excluded this solution for mixing parameters $\sin^2 2\theta \geq 0.3$ through the measurement of atmospheric neutrino interactions.

2) $\Delta m^2 \sin^2 2\theta \simeq 3 \times 10^{-8}eV^2,\ 0.001 < \sin^2 2\theta \leq 0.4$

The diagonal set of solutions in Figure 3 produce almost complete conversion of low energy solar ν_e for $\Delta m^2 \leq 3 \times 10^{-6}$ and no conversion of the low energy ν_e for larger values of Δm^2. In the former case, the ν_e survival probability increases slowly with energy to about 0.5 at the 14 MeV endpoint of the ^8B spectrum, while in the latter case the survival probability drops to almost zero rapidly at some critical energy up to 4 MeV and then rises slowly to about 0.3 at 14 MeV. Spectral information and neutral current information are again critical in determining the solution.

For this solution and the following one, earth matter oscillation effects can convert some of the ν_l back to ν_e,[14] particularly for Δm^2 in the range 10^{-5} to $10^{-7}eV^2$ and $\sin^2 2\theta \geq 0.01$. Thus one can expect seasonally modulated diurnal variations in the measured flux of ν_e. Radiochemical experiments would average these effects over some hours while real time experiments would be able to calculate the amount of terrestrial mass between the detector and the sun at the time of each event candidate. Observation of modulated regeneration of ν_e would constitute compelling evidence for matter oscillations.

3) $8 \times 10^{-8}eV^2 \leq \Delta m^2 < 1 \times 10^{-5}eV^2,\ \sin^2 2\theta \simeq 0.8$

This vertical set of solutions corresponds to an energy independent conversion over the entire neutrino spectrum into other neutrino flavors. It leads to an intermediate prediction for the gallium capture rate (about 30% of the standard model prediction) and predicts a large flux of ν_μ and ν_τ. Regeneration of ν_e in the earth is again important for appropriate values of mass and mixing parameters as discussed above.

Spin Precession

The toroidal magnetic fields in the convective outer layer of the sun would cause the ν_e to precess into an effectively sterile right-handed neutrino if the neutrino has an appropriate magnetic moment.[15] Such a precession can only occur for Dirac 4-component neutrinos and requires a magnetic moment of order $10^{-10}e/2m_e$. Such a large moment is close to the experimental limit. This mechanism for depleting the ν_e flux is energy independent and would lead to the same reduction in all charged current processes.

The main argument in favor of this scenario is the possible correlation between the changes in the ^{37}Cl flux measurements and cycles in the sun's magnetic field activity. It has also been suggested that a semiannual periodicity could exist in the ^8B neutrino flux. The toroidal solar field reverses direction at the solar equator and the line of flight from the solar core to the earth passes through the solar equator twice each year due to the seven degree inclination of the solar rotation axis to the normal to the ecliptic plane. These scenarios are disfavored theoretically because the required magnetic moment is much larger than the moment one generally gets from quantum loop

corrections. Confirmation of a correlation between ν_e flux and solar magnetic activity or a semiannual ^8B neutrino flux variation would strongly support this scenario. If that should occur, direct measurements of the neutrino magnetic moment at low energy neutrino facilities would become extremely important.

Neutrino Decay

A somewhat contrived scenario suggests that ν_e decays during its flight from the sun to the earth.[16] The decay lifetime in this scenario must be adjusted to reproduce the single solar neutrino measurement. The most natural decay is $\nu_e \rightarrow \bar{\nu}_l + M$ where M is the so-called Majoran, a spin 0 pseudoscalar. This mechanism is similar to spin precession in that a potentially observable right-handed anti-neutrino of a different flavor appears in the final state. This scenario is very energy dependent, i.e. the low energy spectrum should be almost totally depleted by decay. In addition, the final state $\bar{\nu}_l$ will retain only about 1/2 of the ν_e energy. The neutral current interaction rate of the low energy neutrinos will be substantially less than the interaction rate of the parent ν_e. This scenario is easily tested by gallium and neutral current measurements.

V. Discriminating Among Scenarios

To what extent can the future solar neutrino experiments discriminate among the scenarios we have described? In discussing this question, we make two assumptions: (1) The ν_e flux generated by the pp reaction is as predicted by the standard solar model. (2) The ν_e flux detected by a ^{37}Cl detector is three times smaller than that predicted by the standard solar model. We then consider a set of possible results for the ^{71}Ga experiment.

I. Suppose the gallium experiment indicates no suppression of pp neutrinos. Then either the treatment of ^8B by the solar model needs to be modified, or else MS neutrino mixing is occurring, but without affecting the ν_e flux from pp. The latter flux is not reduced either in the MS scenario discussed by Bethe[17] with $\Delta m^2 \approx 10^{-4} eV^2$ and a broad range of possible mixing angles, or in another MS scenario with $\Delta m^2 = (1-6) \times 10^{-5} eV^2$ and a value of $\sin^2 2\theta$ between 10^{-2} and 10^{-3}.

Study of the ^8B neutrino spectrum would distinguish clearly among the various possibilities. If a modification of the solar model is the explanation of the low ^8B neutrino counting rate, then there is no distortion of the spectrum. By contrast, in the Bethe-MS scenario the spectral shape is distorted greatly, with the high-energy ^8B neutrinos almost completely suppressed. Discrimination between these two possibilities requires only a crude measure of the spectrum between 6 and 14 MeV. To obtain a measure of the mixing angle in the Bethe-MS scenario requires a more refined measurement of the ^8B spectrum.

Finally, in the MS scenario with $\Delta m^2 = (1-6) \times 10^{-5} eV^2$ and $\sin^2 2\theta$ somewhere between 10^{-2} and 10^{-3}, the ^8B spectrum is distorted differently, with the maximum suppression at an energy of 2 to 6 MeV. In this scenario, the MS resonant condition holds for nearly all of the ^8B spectrum (although not for pp), but for the higher energies the adiabatic condition begins to fail, so that at these energies the ν_e flux is less suppressed.

The information obtained from the ^8B spectrum would be enhanced by measurement of the ^7Be neutrinos. In the case of a modified solar model, the ^7Be measurement would add to our knowledge of solar physics. In the case of the MS solution discussed by Bethe, the ^7Be neutrinos are not suppressed, but in that of the MS solution with Δm^2 around $2 \times 10^{-5} eV^2$, they may be, and the ratio of the ^7Be and pp fluxes might yield a relatively precise determination of Δm^2.

II. Assume now that the gallium experiment indicates very large suppression of pp neutrinos. Then either MS mixing which practically eliminates the low energy ν_e flux from pp is occurring, or else there is neutrino decay with a lifetime such that about one-half of the average ^8B neutrinos and all of the pp neutrinos decay before reaching the earth. MS mixing of the indicated character is expected if $\Delta m^2 = (1-10) \times 10^{-7} eV^2$ and $\sin^2 2\theta \sim 0.1$, and in a "three-neutrino" solution[18] in which high-energy ν_e becomes ν_τ, and low energy ν_e becomes ν_μ.

In the first of these MS scenarios, the ^8B ν_e survival probability increases with energy, while in the second scenario the survival probability peaks at intermediate energies. Neutrino decay, like the first MS scenario, also yields a ν_e survival peaked at the high energies (where the neutrinos do not have time to decay before reaching the earth), but could perhaps be distinguished from the MS scenario by a ^8B spectrum with some detail. (Such a spectrum could also roughly determine Δm^2 and $\sin^2 2\theta$). Neutrino decay can also be distinguished from both MS scenarios by the observation of neutral current interactions, since in the case of decay the final state neutrinos have lower energies, and consequently lower cross sections for neutral current interaction.

If the pp neutrinos are highly suppressed, one expects the same for the ^7Be neutrinos, but it would be interesting to check this. Terrestrial regeneration of ν_e at night for appropriate mass and mixing parameters discussed previously is a further signature of the MS effect. This leads to the unusual situation that the gallium experiment only detects solar neutrinos at night!

III. Assume that the gallium experiment indicates some, but not complete, suppression of pp neutrinos. Then either vacuum oscillation is occurring, perhaps with matter effects modifying the solution as in the discussion of the vertical solution of Figure 3, or there is MS neutrino mixing with Δm^2 and $\sin^2 2\theta$ in a narrow range somewhere in the region $\Delta m^2 = (2-10) \times 10^{-6} eV^2$, $\sin^2 2\theta \sim 10^{-2}$, or else a large neutrino magnetic moment is responsible. In particular, if the pp suppression is consistent with being the same as the ^8B suppression, then vacuum oscillation is the most natural explanation. Such oscillation does not distort the ^8B spectrum, except in the special event that the oscillation length is comparable to the astronomical unit, in which case the high-energy part of the spectrum is suppressed. By contrast, the above MS scenario distorts the ^8B spectrum by suppressing the low-energy part. Thus, the ^8B spectrum distinguishes vacuum oscillation from the MS possibility. So too does the ^7Be counting rate, which is much more suppressed in the relevant MS scenario than by typical vacuum oscillation. In the range of Δm^2 where terrestrial regeneration of ν_e is important, there is no ambiguity in the mechanism which is operating.

If vacuum oscillation appears to occur, then it is important to look for neutral currents to distinguish flavor oscillation from oscillation to sterile neutrinos. The observation of flavor oscillation via neutral current measurements would provide direct confirmation that neutrino oscillation is indeed taking place.

If a neutrino magnetic moment precession reduces the ^8B and pp counting rates, the neutrino spectrum is not distorted, any more than in the case of typical vacuum oscillation. However, a magnetic moment effect, unlike oscillation, leads to a correlation between the counting rates and solar activity, and may also produce a *semiannual* periodicity in the ^8B counting rate, but not in the pp counting rate.

VI. Conclusion

For nearly all possibilities the gallium experiment plus the ^8B spectrum can identify the solution of the solar neutrino puzzle. An experiment sensitive to ^7Be neutrinos is important both to confirm and to narrow down some of the solutions. It is also important so that by subtraction the gallium experiment measures pp neutrinos and the chlorine experiment measures ^8B neutrinos. Assuming the solution involves neutrino physics, a neutral current experiment is a crucial experiment for particle physics to see if the ν_e end up as ν_μ or ν_τ or as sterile neutrinos. In the former case, this experiment would provide direct confirmation of neutrino flavor transitions.

Which experiments will bring spectral data to bear on the solar neutrino puzzle? The first experiment should be KAMIOKANDE II, with crude information on the high energy end of the ^8B spectrum and real time data on the flux of ν_e. This data will be refined and extended by the Sudbury heavy water experiment and the Gran Sasso liquid argon project. The experiments under construction and those in an advanced stage of planning can, when taken together, measure the spectrum of neutrinos emitted by the sun. Furthermore, there is a potential that these measurements will also produce unique information on a fundamental problem of elementary particle physics, namely the masses and mixing of neutrinos. With an aggressive program *the solar neutrino puzzle can be solved in the next ten years.*

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