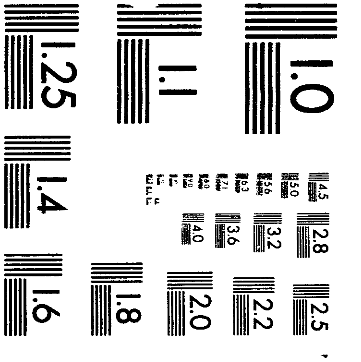
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TITLE: THE STATUS OF THE SOLAR NEUTRINO PROBLEM

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SUBMITTED TO: To be published by World Scientific in the Proceedings of the XVI Kazimierz Meeting on Elementary Particle Physics, Kazimierz, Poland, May 24-28, 1993.

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THE STATUS OF THE SOLAR NEUTRINO PROBLEM

Thomas J. Bowles
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ABSTRACT

Perhaps the most outstanding discrepancy between prediction and measurements in current particle physics comes from the solar neutrino problem, in which a large deficit of high-energy solar neutrinos is observed. Many Nonstandard Solar Models have been invoked to try to reduce the predicted flux, but all have run into problems in trying to reproduce other measured parameters (e.g., the luminosity) of the Sun. Other explanations involving new physics such as neutrino decay and neutrino oscillations, etc. have also been proffered. Again, most of these explanations have been ruled out by either laboratory or astrophysical measurements. It appears that perhaps the most likely particle physics solution is that of matter enhanced neutrino oscillation, the Mikheyev-Smirnov-Wolfenstein (MSW) oscillations. Two new radiochemical gallium experiments, which have a low enough threshold to be sensitive to the dominant flux of low-energy p-p neutrinos, now also report a deficit and also favor a particle physics solution The next generation of solar experiments promise to finally resolve the source of the "solar neutrino problem" by the end of this decade.

SOLAR NEUTRINO PRODUCTION

The solar neutrino spectrum, together with the thresholds for various detectors, is shown in figure 1. A number of Standard Solar Models (SSMs) that make somewhat different predictions for the fluxes have been published in the last few years, of which the two most widely reported are those of Bahcall and Pinsonneault (B-P) (1) and of Turck-Chieze and Lopes (T-C-L) (2).

The important point to realize concerning the SSMs is the temperature dependences of the neutrino fluxes. The effective temperature dependences have been found (3) to depend on the core temperature (T_c) as $\phi(^8B) \propto T_c^{18}$, $\phi(^7Be) \propto T_c^8$, and $\phi(p\text{-}p) \propto T_c^{-1.2}$. It is important to note that the flux of the p-p neutrinos is directly related to the observed solar luminosity in an essentially model-independent manner and is thus determined to an accuracy of about 2-3% (3). This is of particular importance to the results of the gallium experiments, as they are primarily sensitive to the p-p neutrinos. The calculated capture rates in SNU (1 SNU = 10^{-36} captures/atom/s) for the chlorine and gallium experiments together with the predicted ^8B flux for the Kamiokande experiment in the SSMs are given in Table I.

Table 1. Predicted capture rates and ^8B flux for the Bahcall-Pinsonneault and Turck-Chieze and Lopes Standard Solar Models. Quoted uncertainties are 1 σ.

Capture Rate (SNU)	Bahcall-Pinnsenault	Turck-Chieze and Lopes
^{37}Cl:	8.0 ± 1.0	6.4 ± 1.4
^{71}Ga:	$131.5 +7/-6$	122.5 ± 7
^8B Flux ($\nu/cm^2/s$)	$(5.69 \pm 0.82) \times 10^6$	$(4.43 \pm —) \times 10^6$

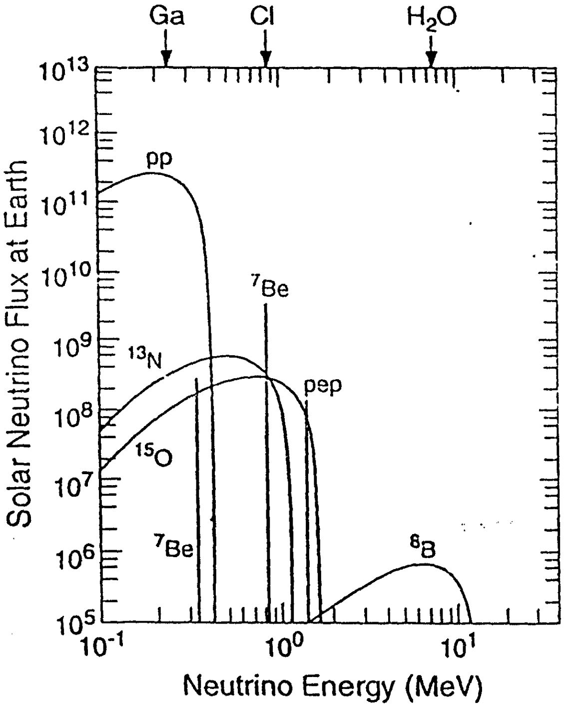

Figure 1. Solar neutrino spectrum. Thresholds for the operating detectors are indicated by the arrows. The flux is in units of neutrinos/cm^2/s/MeV.

One means to force agreement between the predictions and experiment is to incorporate possible new phenomena in order to reduce the core temperature, thereby reducing the predicted fluxes. For example, numerous Nonstandard Solar Models have been proffered that incorporate a variety of heavy element abundances, high magnetic fields, turbulent diffusion, continuous mixing, rapid rotation, convective mixing of hydrogen into the core, new equations of state, and other effects (3). However, none of the Nonstandard Models has been able to reproduce the observed ^8B flux without running into problems with reproducing other measured physical properties of the Sun. Yet one cannot rule out them possibility that there may be some additional physics not included in the SSMs which will resolve the problem.

NEUTRINO PROPERTIES

Another possible means of reducing the observed solar neutrino flux is to invoke new particle physics which either reduces the production rate of solar neutrinos or causes the neutrinos to "disappear" during their transit to the Earth. A plethora of possible extensions of the Standard Electroweak model has been presented, in which the neutrinos naturally acquire a mass, and lepton number is no longer strictly conserved. One of the implications of this is that the flux of neutrinos produced in the Sun may be accurately predicted by the SSMs, but the flux of electron-type neutrinos measured by the solar neutrino detectors at the Earth may be depleted due to oscillations.

Other mechanisms involving new physics have also been suggested to account for the observed deficit of solar neutrinos (3). Rather than changing the properties of the neutrinos, some of these hypotheses involve lowering the core temperature of the Sun, such as by Weakly Interacting Massive Particles (WIMPs). But all of these other mechanisms have been effectively ruled out by either laboratory measurements or astrophysical observations. Thus, it appears that the only viable candidate for new physics as the explanation of the solar neutrino problem is that involving neutrino oscillations.

The probability for oscillating, for example, from an electron neutrino to a muon neutrino is given by (4):

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2 2\theta \sin^2\{1.27 \times \Delta m^2 (eV^2) \times L(m)/E_\nu (MeV)\},$$

where θ is the mixing angle between the neutrino eigenstates ν_1 and ν_2 and $\Delta m^2 = |m_{\nu_2}{}^2 - m_{\nu_1}{}^2|$ is the mass squared difference of the neutrino eigenstates. Due to the long baseline (1 AU) and low energies (few MeV), solar neutrinos provide an improved sensitivity over terrestrial experiments to small values of Δm^2 of as much as eight orders of magnitude.

It was observed in 1985 (5) that the Sun also provides sensitivities to very small values of the mixing angle θ. This is due to the resonant amplification of the mixing in the high-matter densities of the Sun, which are called Mikheyev-Smirnov-Wolfenstein (MSW) oscillations. The physical process is due to the fact that the electron neutrinos that are produced in the core of the Sun can scatter from electrons by both the charged and neutral weak currents. However, muon and tau neutrinos can scatter only by the neutral weak current. As a result, as the neutrinos propagate, the index of refraction (or forward-scattering amplitude) depends on neutrino flavor. Under proper circumstances, the phases of the electron neutrino and muon or tau neutrinos will be such that full mixing can occur between the different flavors. This condition occurs when $L_{osc}/L_o = -\cos 2\theta$ where the L_{osc} is the oscillation length for the neutrinos in vacuum ($L_{osc} = 2\pi\, 2p_\nu/\Delta m^2$) and L_o is the oscillation length in matter and is given by:

$$L_o = 2\pi/(\sqrt{2}G_F N_e) \approx 1.7 \times 10^7/[\rho(g/cm^3)\, Z/A]\ m\ ,$$

where G_F is the Fermi constant, $N_e = \rho N_0 Z/A$, and N_0 is Avagadro's number. Thus, in the Sun, where $\rho \approx 150$ g/cm^3 and $Z/A \approx 2/3$, $L_0 \approx 200$ km, compared to the radius of the Sun of 7×10^5 km.

It is important to note two things about MSW oscillations. First, the probability for matter oscillations is dependent on the neutrino energy and therefore can result in a distortion of the energy spectrum from that predicted by the SSMs. Second, one finds that the solar neutrino experiments have sensitivities to mixing angles as small as $\sin^2 2\theta = 10^{-4}$, compared to sensitivities for oscillations in vacuum of $\sin^2 2\theta \approx 0.2$.

OPERATING SOLAR NEUTRINO EXPERIMENTS

Chlorine Experiment

The chlorine radiochemical experiment (6) employs 610 tons of perchlorethylene (C_2Cl_4) housed in a steel tank located 4900 mwe (meters water equivalent) underground at the Homestake Gold Mine in Lead, South Dakota. Solar neutrinos can produce ^{37}A by inverse beta decay reaction $^{37}\mathrm{Cl}(\nu_e,e^-)^{37}\mathrm{A}$ on the ^{37}Cl in the tank with a threshold of 814 keV. Thus, the chlorine experiment is sensitive to the ^{8}B, ^{7}Be, pep, and CNO solar neutrinos. The ^{37}A atoms (along with a few tenths of a cc of either ^{36}A or ^{38}A added as a carrier to measure the extraction efficiency) are chemically extracted about every 60 days. The extracted gas is purified, mixed with methane (to make a good counting gas), and then inserted into a small proportional counter. ^{37}A is detected in the proportional counter as it decays by electron capture with a 35-day half-life. The only way to observe this decay is to detect the low-energy 2.82-keV Auger electrons from K-shell capture produced during electron shell relaxation in the resulting ^{37}Cl atom. Pulse shape discrimination based on rise-timemeasurements is used to separate the ^{37}A decays from background. Each extraction is counted for about one year in order to allow an accurate determination of the background. The candidate events are fit to an exponential decay with a 35-day half-life and a time-independent background using a maximum-likelihood method (7).

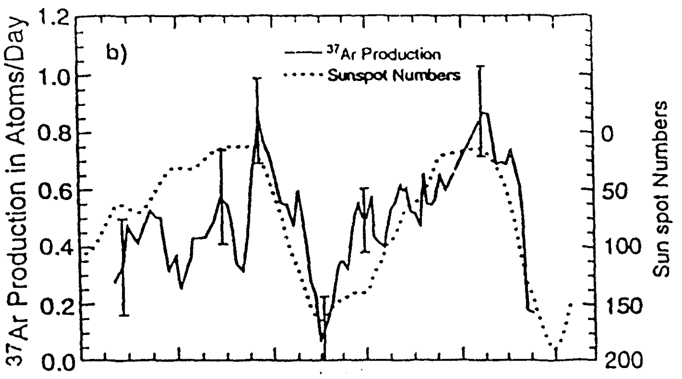

Figure 2. Chlorine data (solid line) smoothed by 5-point running average technique showing the apparent anticorrelation with the number of sunspots (dotted line).

The average production rate of ^{37}A from 1970 to 1990 was 0.49 ± 0.03 atoms per day, as shown in figure 2. A background due to cosmic-ray muon interactions of 0.08 ± 0.03 ^{37}A atoms per day must be subtracted from this rate. Making this subtraction results in a value of 2.2 ± 0.3 SNU attributed to solar neutrinos for the chlorine experiment for the period from 1970 to 1990.

Also plotted on figure 2 is the number of sunspots during this period. An apparent anticorrelation between the production rate of ^{37}A and the number of sunspots was claimed from these data (6), although various analyses differ in the statistical significance of the effect (8). Such an inverse correlation was attributed to the possible existence of a magnetic moment of the neutrino, causing a spin flip of the neutrino as it traverses the magnetic fields of the convection zone (9). While the magnitude of the magnetic moment required (about 10^{-10} Bohr magnetons with 10-kGauss fields in the convection zone) is just slightly below laboratory limits, it appears to be ruled out by astrophysical observations (10).

Kamiokande

The Kamiokande experiment (11) is a water Cherenkov detector which is sensitive to ^{8}B neutrinos. The detector is located at the Kamioka mine in the Japanese Alps at a depth of 1000 m (2700 mwe). The signature for solar neutrinos in this experiment is by the elastic scattering (ES) reaction: $\nu_x + e^- \rightarrow \nu_x' + e'^-$ and observing the Cherenkov light cone radiated by the scattered electron. Timing and pulse-height information from the photomultipliers (PMTs) that register the Cherenkov photons allows one to determine the position, direction, and energy of the recoil electron, thereby providing a measure of the neutrino energy and direction.

The elastic scattering cross section can proceed via both charged and neutral current interactions. However, as the ratio of the cross sections for the neutral current to charged current at these low energies is $\sigma(NC)/\sigma(CC) \approx 1/6$, Kamiokande is predominately sensitive to electron neutrinos.

The Kamiokande detector consists of a cylinder 14.4 m diameter by 13.1 m high holding 4,500 tons of pure water. The inner volume is viewed by 948 50-cm-diameter photomultipliers (PMTs) and a 2-m-thick outer water volume is used as a veto for cosmic-ray muons and is viewed by 123 PMTs.

The results from Kamiokande II and III are shown in figure 3. A clear signature for events correlated with the direction of the Sun ($\cos\theta = 1$) is observed, but the flux is less than that predicted by the SSM. Combining the three data sets (12), one finds a value of the flux relative to the B-P SSM prediction of ϕ(Kamiokande)/ϕ(B-P SSM) = 0.49 ± 0.04 (stat) ± 0.06 (syst). As the Kamiokande experiment can point back to the direction the neutrinos come from, this capability has provided the first direct observation of neutrinos coming from the Sun, and confirms the long-held belief that fusion reactions are occurring in the Sun.

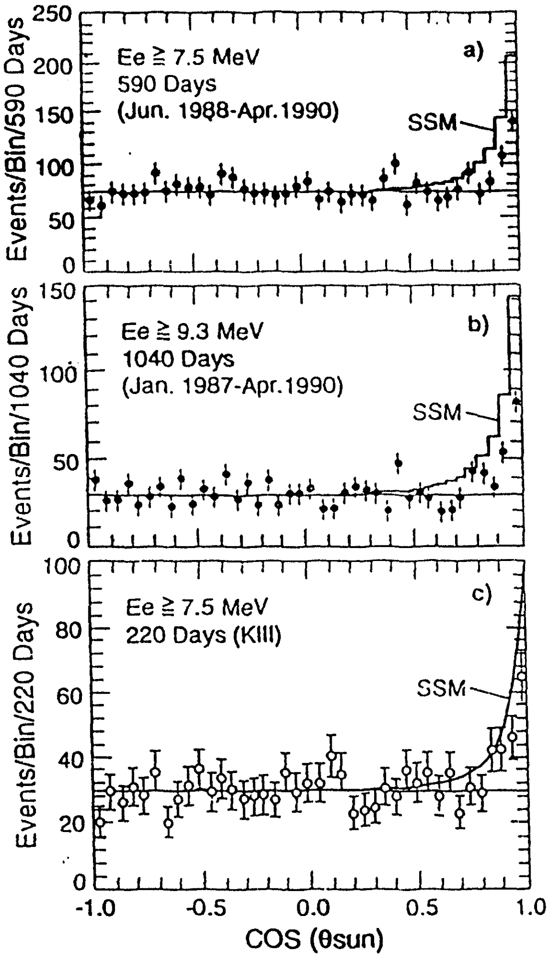

Figure 3. a) Kamiokande II results with 7.5-MeV threshold, b) Kamiokande II results with 9.3-MeV threshold, and c) Kamiokande III results with 7.5-MeV threshold.

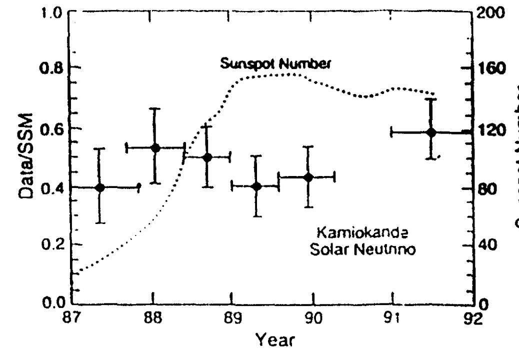

Figure 4. Kamiokande data (crosses) and number of sunspots (dotted line).

The Kamiokande experiment has now run during a period of five years, during which the solar cycle went from a minimum in 1986 to a maximum in 1990. The flux of ^{8}B neutrinos, as measured by Kamiokande, is shown in figure 4, which also shows the number of sunspots during this period. It is clear that Kamiokande does not see any temporal variation of the flux of ^{8}B neutrinos.

SAGE

The two gallium experiments (SAGE and GALLEX) both observe the reaction ^{71}Ga(ν_e,e$^-$)^{71}Ge produced by solar neutrinos by chemically extracting and observing the subsequent decay of the ^{71}Ge atoms. The threshold for this reaction is 233 keV, so that the gallium experiments are sensitive to all of the neutrino-producing reactions in the Sun. In particular, 54% of the total rate predicted by the B-P SSM is due to the p-p neutrinos. Thus, the prospect exists that the gallium experiments may be able to unravel solar physics from particle physics effects, as the flux of p-p neutrinos is essentially independent of solar modeling.

SAGE uses the Gallium-Germanium Neutrino Telescope situated in an underground laboratory specially built at the Baksan Neutrino Observatory of the Institute for Nuclear Research of the Russian Academy of Sciences in the Northern Caucasus Mountains (13). It is located under Mount Andyrchi and has an overhead shielding of 4700 mwe.

SAGE initially used 30 tons and presently employs 57 tons of gallium in the form of the liquid metal. The individual ^{71}Ge atoms, along with about 700 μg of natural Ge (added as a carrier to measure the extraction efficiencies) are chemically extracted, purified, and synthesized into germane (GeH_4). A measured quantity of xenon is then added, and this mixture is inserted into a sealed proportional counter. The SSM predicts a production rate of 1.2 ^{71}Ge atoms/day in 30 tons of Ga. Taking into account all efficiencies, SAGE expects to detect only about 4 ^{71}Ge atoms from 30 tons of gallium in each run, assuming the SSM flux. Thus, the counting backgrounds must be kept to a small fraction of a count/day.

^{71}Ge decays with an 11.4-day half life by electron capture to the ground state of ^{71}Ga. The only way to observe this decay is to detect the low-energy K- and L-peaks from Auger electrons and X-rays produced during electron-shell relaxation in the resulting ^{71}Ga atom. The low-energy electrons and X-rays are detected in a small-volume proportional counter. The proportional counter is placed in the well of a NaI detector (used as a veto) inside a large passive shield and counted for 2–4 months. Pulse-shape discrimination based on rise-time measurements is used to separate the ^{71}Ge decays from background. The data analysis selects events that have no NaI activity in coincidence within the ^{71}Ge K-peak acceptance window. A maximum likelihood analysis is then carried out on these events by fitting the time distribution to an 11.4-day half-life exponential decay plus a constant rate background. Due to considerably higher backgrounds in the L peak, only the K peak has been used in the analysis presented by SAGE.

The experiment began operation in May of 1988, when purification of the 30 tons of gallium commenced. Large quantities of long-lived ^{68}Ge (half life = 271 days) produced by cosmic rays while the gallium was on the surface had to be removed. By January 1990, the backgrounds had been reduced to levels sufficiently low to begin measurements of the solar neutrino flux. Twelve runs taken between January 1990 and May 1992 have completed counting. The results of these runs are shown in figure 5, together with the best combined fit value.

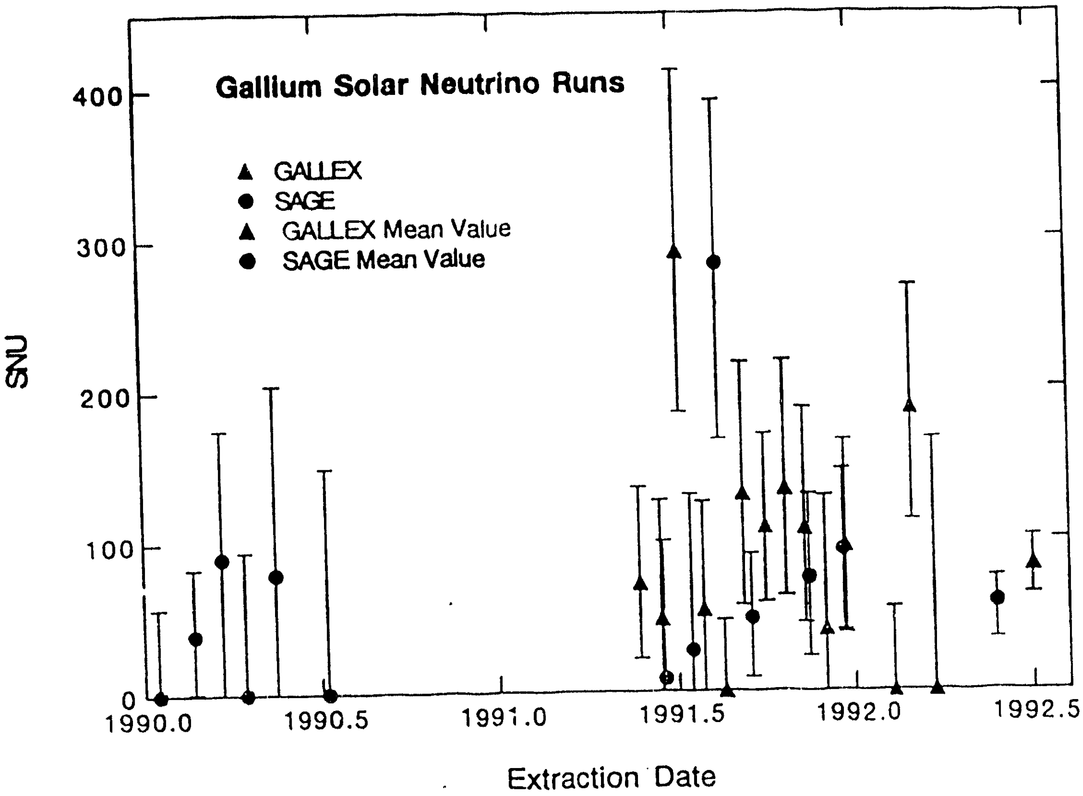

Figure 5. Best fit values for each of the SAGE and GALLEX solar neutrino runs and combined mean values of the ^{71}Ge capture rate. All uncertainities shown are 1-σ.

SAGE reported an initial value (14) of 20 +17/-20 ± 32 SNU, which resulted in a quoted upper limit of 79 SNU (90% CL). For the combined 1990–91 data, which SAGE takes as the best measure of the capture rate, the results are (15):

$$^{71}\text{Ga Capture Rate} = 58 + 17/-24\ (\text{stat}) \pm 14\ (\text{syst})\ \text{SNU},$$

assuming that the extraction efficiency for ^{71}Ge atoms produced by solar neutrinos is the same as that measured using natural Ge carrier. This corresponds to 24 counts assigned to ^{71}Ge decay, compared to the SSM prediction of 55 counts.

As SAGE observed a low signal in the first data, a great deal of effort was expended to check that the experiment was working correctly. The first test consisted of extracting Ge carrier doped with a known number of ^{71}Ge atoms from 7 tons of gallium. The results indicated an extraction efficiency of 101 ± 5% for the natural Ge carrier and of 99 + 6/–8% for the ^{71}Ge.

In inverse beta decay, the resultant ^{71}Ge atom may be in an excited state or in some fraction, the ^{71}Ge atom is ionized. It is possible, albeit very unlikely, that inverse beta decay may drive some chemical reaction, which results in a low extraction efficiency. To test this, SAGE looked at the beta decay of Ga isotopes. A few grams of Ga was taken from the reactors and irradiated to form ^{70}Ga and ^{72}Ga by (n,γ) reactions. The ^{70}Ga and ^{72}Ga subsequently decay to stable ^{70}Ge and ^{72}Ge, which were then extracted from the irradiated gallium using the same procedure as in the solar neutrino runs and were measured by mass spectroscopy. The preliminary results showed 98 ± 10% and 92 ± 10% extraction efficiencies for the ^{70}Ge and ^{72}Ge, respectively.

Finally, an experiment using a neutrino source is planned in order to test the overall extraction efficiency *in situ*. A suitable neutrino calibration source can be made using ^{51}Cr, which decays with a 27.7-day half-life by electron capture, emitting monoenergetic neutrinos. A 1-MCi ^{51}Cr source can produce a few hundred atoms of ^{71}Ge in 20 tons of Ga. An engineering test run with a low-intensity ^{51}Cr source was carried out during the fall of 1990 and demonstrated feasibility but did not yield any physics results.

With the combined 1990–91 data sets, SAGE is now observing a signal consistent with ^{71}Ge produced by solar neutrinos. Intensive work has been carried out to reduce noise pulsing and backgrounds in the L peak, and SAGE appears to be able to count the L peak beginning with the September 1992 extraction, which would almost double the counting efficiency. SAGE is continuing to study possible systematic effects from the data. Finally, plans are under way for a full-scale ^{51}Cr calibration experiment in 1994.

GALLEX

The GALLEX experiment is located in Hall A of the Gran Sasso National Laboratory in central Italy (16). The laboratory is located 6.3 km from the entrance of the tunnel at a depth of 3300 mwe. Many of the physical principles involved in the GALLEX experiment have been treated in the previous section on SAGE and will not be discussed again.

GALLEX employs 30.3 tons of Ga in 101 tons of 8.13 molar aqueous gallium chloride solution. ^{71}Ge atoms and the (isotopic) Ge carrier are chemically extracted by a simple process and germane is then synthesized from this solution and purified by gas chromatography. The germane is then mixed with xenon and inserted into a small proportional counter. The pulses from the counters are amplified and multiplexed into a GHz transient digitizer to provide rise-time information. In addition, the pulse waveform is also recorded at slower speeds to check for delayed coincidences in the counters and to allow identification of noise events.

GALLEX began solar neutrino runs on May 14, 1991 and has carried out a total of 16 solar neutrino runs in the first phase, called GALLEX I. In addition, 5 blank runs were carried out. From these data, it appears that GALLEX is seeing a definite signature for the presence of ^{71}Ge in the extractions. The data are fit using a maximum likelihood function that has components due to the decay of ^{71}Ge, the decay of ^{68}Ge, and a constant background.

It is necessary to correct for backgrounds that produce ^{71}Ge, ^{69}Ge, ^{68}Ge, and Rn. While the ^{71}Ge and ^{69}Ge backgrounds are small, ^{68}Ge and Rn presented unexpected backgrounds for GALLEX. The residual levels of ^{68}Ge during the solar neutrino runs result in a background of 9 ± 5.5 SNU, which is used as an input to fix the ^{68}Ge level in the maximum likelihood fitting procedure. Radon was also found to be present in the extraction samples at an average level about three ^{222}Rn atoms per run, corresponding to a background of about 25 SNU. Cuts result in a residual radon background of 2 ± 1 SNU. Thus, the total ^{71}Ge rate observed by GALLEX is corrected by 9 ± 5.5 SNU for ^{68}Ge and by 6.85 ± 1.80 SNU for other backgrounds.

Following completion of the counting of all 15 runs, GALLEX finds (17):

$$^{71}\text{Ga Capture Rate} = 83 \pm 17\ (\text{stat}) \pm 8\ (\text{syst})\ \text{SNU}.$$

The results of the runs are shown in figure 5. A number of consistency checks have also been carried out. The data were fit allowing the mean life of the ^{71}Ge decay to be a free parameter with a fit of 13.5 + 5.2/-3.5 days, in agreement with the known ^{71}Ge mean life of 16.49 days. The values for the K- and L-peaks agree at 70 ± 23 SNU and 104 ± 31 SNU, respectively. Additional runs were made by extracting "blank" samples immediately after a solar neutrino extraction. This tests for any effects that do not depend on exposure time. The result was 8 + 16/−8 SNU, consistent with no additional sources of ^{71}Ge in the chemical extraction. GALLEX also investigated possible loss mechanisms due to hot-atom effects. In one test, ^{69}Ge was produced in situ via the ^{69}Ga(p,n)^{69}Ge reaction. The extraction efficiency was determined to be > 99%. In a second test, ^{71}Ge was produced in situ by electron capture of ^{71}As. The resultant ^{71}Ge was extracted with an efficiency of 99.8 ± 3.7%.

A program of improvements was carried out by GALLEX during the summer of 1992. GALLEX resumed normal solar neutrino running in September 1992 on a monthly basis. Finally, a test of the extraction efficiency is planned for 1994 using a 2-MCi ^{51}Cr source (17).

IMPLICATIONS OF THE SOLAR NEUTRINO DATA

All four operating solar neutrino experiments observe significant deficits below the SSM predictions. The chlorine data by itself can be accommodated by lowering the core temperature of the Sun by about 7%. Many Nonstandard Solar Models have been put forward to provide a means of reducing the core temperature. However, these have proven to be ad hoc solutions, which run into problems in trying to reproduce other measured quantities of the Sun. Nonetheless, if one believes the quoted errors in the SSM have been underestimated, or that some known physics that is not included in the SSMs may prove important, then it becomes possible to reconcile the chlorine result.

The Kamiokande result by itself can also be accommodated along the same lines. However, it is difficult to reconcile the combination of the chlorine and Kamiokande results with an astrophysical explanation. The gist of the argument is: Kamiokande is sensitive only to ^{8}B neutrinos and directly determines the flux of ^{8}B neutrinos. Using this as input to the SSM, one can then determine T_c in the SSMs and one finds that for the B-P SSM, T_c is reduced by 4%. Using the lowered value for T_c, the SSMs can now predict the rate for the chlorine experiment and both make about the same prediction of roughly 4.4 SNU, compared with the chlorine result of 2.23 ± 0.23 SNU. The fact that the chlorine experiment is sensitive to the ^{7}Be neutrinos, which have a weaker temperature dependence than the ^{8}B neutrinos, makes it difficult to reconcile the two experiments by lowering T_c. The conclusion is that the Kamiokande and chlorine data are inconsistent with any variation of the SSM that invokes a lower T_c, and the data are consistent with MSW oscillations.

The gallium experiments, in principle, can provide a model-independent determination of the origin of the solar neutrino problem. Assuming only that the Sun is in thermal equilibrium, the gallium experiments must observe at least 80 SNU (3). An observation of significantly less than this requires one to invoke new physics in order to resolve the solar neutrino problem.

The initial results presented by SAGE indicated quite a low rate, but with such large uncertainties that it was impossible to claim that the solution to the solar neutrino problem involved new physics. Subsequently, GALLEX announced their measurement of 83 SNU and, with additional running, SAGE observed 58 SNU. But, again, the uncertainties are sufficiently large that it is not possible to entirely rule out astrophysical solutions to the solar neutrino problem. However, the latest GALLEX result is 2.6 σ away from the B-P SSM prediction, while the SAGE result is 3.3 σ away.

Recent analyses (18, 19) of the consistency of the combined chlorine, Kamiokande, and gallium results concludes that the results are highly inconsistent with any astrophysical explanations and in fact are best attributed to Mikheyev-Smirnov-Wolfenstein (MSW) neutrino oscillations. Any astrophysical explanation invoking a cooler Sun is ruled out at the 99.99% CL (19). The range of mass difference squared and mixing angles allowed by the chlorine, Kamiokande, and gallium results for MSW oscillations are shown in figure 6. The conclusion is that MSW oscillations appear to be the most attractive explanation for the observed deficit and the nonadiabatic region gives

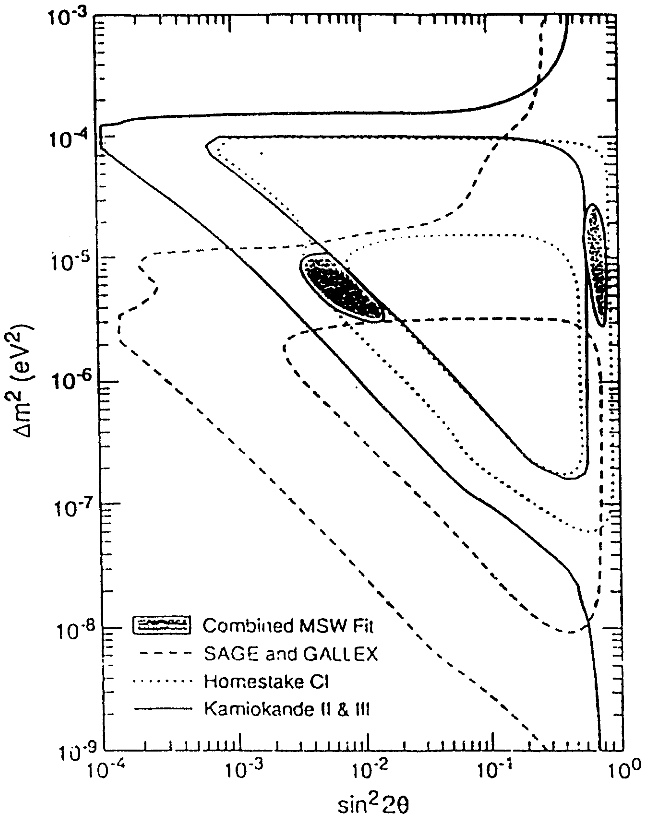

Figure 6. The allowed region for the chlorine (dotted lines), Kamiokande II + III (solid lines), and the combined SAGE and GALLEX (dashed lines) results. The shaded region is the combined fit of the four experiments (90% CL).

a better fit to the data than does the large mixing angle solution. The values of $\Delta m^2 = 10^{-5}$ eV^2 for both fits imply (absent sterile neutrinos) that either m_{ν_μ} or m_{ν_τ} = 3 meV. The mass and mixing angles implied by the MSW solutions are in reasonable agreement with GUT predictions.

The MSW solutions to the two allowed regions provide quite different energy dependences. The nonadiabatic solution (around $\Delta m^2 = 6 \times 10^{-6}$ eV^2 and $\sin^2 2\theta = 7 \times 10^{-3}$) essentially does not affect the p-p flux, but strongly suppresses the ^{7}Be flux and to a lesser extent the ^{8}B flux. The large-mixing solution has a gentler energy dependence and suppresses all of the fluxes by about a factor of two to three. In order to resolve which (if either) of the two solutions is correct, it is necessary to independently measure the flux of the ^{7}Be neutrinos and/or measure the energy dependence of the ^{8}B neutrinos.

FUTURE SOLAR NEUTRINO EXPERIMENTS

Sudbury Neutrino Observatory (SNO)

SNO is now under construction at the Creighton #9 nickel mine at Sudbury, Ontario, Canada (20). A 22-m-diameter x 34-m-high chamber is being excavated at the 6800-ft level (5900 mwe) to house the detector. One kiloton of D_2O will be housed inside a 12-m-diameter, 6-cm-thick acrylic sphere. The D_2O sits within a 5-m-thick H_2O shield to provide shielding of external photons and neutrons. A photomultiplier support assembly holds 9500 20-cm-diameter PMTs (fitted with reflectors to increase light collection) on a 17-m-diameter.

SNO will be sensitive to and able to discriminate electron neutrinos from muon and tau neutrinos by the following reactions:

1) $\nu_e + d \rightarrow p + p + e^-$	[Charged Current reaction (CC)]
2) $\nu_x + e^- \rightarrow \nu_x + e^-$	[Elastic Scattering reaction (ES)]
3) $\nu_x + d \rightarrow \nu_x + p + n$	[Neutral Current reaction (NC)]

The CC reaction is sensitive only to electron neutrinos, has very good spectral information and has some directionality. The ES reaction is primarily sensitive to electron neutrinos, provides good directionality, and contains spectral information. The NC reaction is equally sensitive to all types of neutrinos, has a 2.2-MeV threshold, but has no directionality or spectral information.

Assuming a 5-MeV threshold, the rates per year will be about 2600 for the CC, 780 for the ES, and 2400 for the NC reactions (assuming B-P SSM fluxes). These rates are sufficient to get good spectra to allow analysis for MSW energy distortions, and are also sufficient to observe the secular variation of the NC signal with 2-σ accuracy, thereby confirming the solar origin of the NC signal.

The primary difficulty in SNO is the reduction of backgrounds necessary to observe the CC reaction with a low threshold and to observe the NC signal. Extensive Monte Carlo calculations indicate that the threshold should be about 5 MeV for the CC and ES reactions. For the NC reaction, U and Th in the detector present significant backgrounds. The design goals (in pg/g) are levels of U and Th in the detector of about 10^{-14} in the D_2O and H_2O, and about 10^{-12} in the acrylic.

The CC and ES reactions are directly observable from the Cherenkov light, allowing a determination of the energy, position, and direction of the track. NC detection is done by adding 10 tons of NaCl to the D_2O and capturing the neutron on ^{35}Cl, yielding an 8.6-MeV gamma ray that is detected. The detector will be run for 6 months without NaCl, then 6 months with NaCl. The two spectra will then be subtracted from each other, leaving a pure NC spectrum.

An alternate method is now under development. The plan is to deploy an array of 112 proportional counters filled with ^3He in the D_2O. The neutrons are detected by the $^3He(n,p)t$ reaction. It appears it may be possible to measure the NC reaction this way with a signal to background of 10 to 1. If this scheme proves feasible (and is funded), it would provide 100% duty factor for the NC reaction, an effective increase in the NC counting rate of a factor of four, and identification of NC reactions on an event-by-event basis.

The excavation of the chamber is well under way and it is expected that the detector will come on the air in the fall of 1995. Assuming that the ^{3}He counters prove feasible, it is expected they will be installed in early 1996.

SuperKamiokande

SuperKamiokande is an improved and enlarged version of the Kamiokande detector (21). It will be located at the Kamiokande site at a depth of 2700 mwe. It will consist of a detector 39.3-m diameter and 41.4-m high with a 2-m-thick water shield that also serves as an active anti-counter to veto cosmic-ray muons. The inner detector will contain 32 kilotons of H_2O with a 22-kton fiducial volume viewed by 11,200 50-cm diameter PMTs fitted with reflectors. Excavation of the chamber is well advanced, the PMTs, electronics, and other equipment are being produced, and SuperKamiokande anticipates initial operation in the spring of 1996.

SuperKamiokande will provide event rates of 8400 ES events/yr (assuming fluxes of 0.46 × B-P SSM). In addition, the quality of the data will be substantially improved over Kamiokande: 1) the threshold is expected to be about 5 MeV, 2) the energy resolution will be 14% (at 10 MeV), and 3) the vertex resolution will be 0.5 cm (for 10-MeV e^-). Reductions by a factor of several for U and Th, and by a factor of 100–1000 for ^{222}Rn are also planned.

The impressive statistics that SuperKamiokande will achieve will permit precise measurements of any possible time variations of the ^{8}B solar neutrino flux, with an accuracy of ±3% for day/night or seasonal variations and ±1–2% for yearly variations. SuperKamiokande expects to provide a more accurate measurement of the energy spectrum of the scattered electrons, permitting a determination of the spectral distortion caused by MSW oscillations. In the ES reaction, the MSW distortions are diluted by kinematics, so that the difference in spectral shapes between the nonadiabatic and large mixing-angle MSW solutions is only about 10% at 10 MeV and almost zero at 5 MeV. Thus, the ability to discriminate between these two solutions will require a great deal of attention to systematic effects in the detector.

Borexino

Borexino (22) is envisaged as a 300-ton (100-ton fiducial) volume detector using liquid scintillator in an acrylic vessel surrounded by a 2-m-thick water shield. The scintillator is composed primarily of 1-2-4 trimethylbenzene doped with fluors to provide efficient light output. The fiducial volume will be viewed by 1650 20-cm PMTs fitted with reflectors. The scintillator, PMTs, and support structure will be inside a 16.4-m-diameter steel vessel filled with ultrapure water that serves as a passive shield. The detector will be installed in the Gran Sasso National Laboratory at a depth of 3700 mwe.

The detector will have a very low threshold of 250 keV and will be predominantly sensitive to the ES reaction with a rate of 18,000 events/yr (B-P SSM) from ^{7}Be neutrinos.

The important contribution of Borexino will be the direct detection of ^{7}Be neutrinos. The signature comes from a combination of the Compton edge observed in the scintillator from the monoenergetic ^{7}Be line and from the 7% modulation in count rate due to the Earth's orbital eccentricity. As the ^{7}Be flux is much less temperature dependent than the ^{8}B flux, their observation provides a strong means of verifying the origin of the solar neutrino problem and in determining which of the allowed MSW solutions is the correct one.

The primary difficulty facing Borexino is to achieve extremely low levels of radioactivity in the scintillator. Unlike SNO and Kamiokande, which are water Cherenkov detectors and thus have an intrinsic Cherenkov threshold, Borexino is sensitive to all radioimpurities. The levels of U and Th must be at the 10^{-16} level, while K must be at the 10^{-14} level. Other possible background sources include ^{14}C, ^{7}Be, and ^{10}Be. A great deal of development effort has gone into demonstrating these purity levels, and it seems likely that they will be reached. A 20-ton test detector is now being installed at the Gran Sasso Laboratory to demonstrate feasibility in 1994. Assuming that it is successful, with full funding Borexino could be constructed to turn on in 1996.

CONCLUSIONS

Possible evidence for neutrino oscillations is observed in the solar neutrino experiments. Various analyses indicate it is unlikely that changes to the Standard Solar Models can accommodate the results. The most likely consistent explanation is that we are observing matter-enhanced MSW neutrino oscillations. Yet, given the extreme dependence of the neutrino fluxes on the core temperature of the Sun, it is difficult to definitively rule out astrophysical solutions. But a new round of experiments will provide model-independent tests, which should provide the solution to the solar neutrino problem in the next five to seven years.

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