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The Solar Neutrino Problem

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Abstract

A summary of the results of the Brookhaven solar neutrino experiment is given and discussed in relation to solar model calculations. A review is given of the merits of various new solar neutrino detectors that have been proposed.

INTRODUCTION

We would like to review the present status of the solar neutrino problem. First will be a report on the Brookhaven ^{37}Cl detector that has been in operation for 10 years. The results obtained during the last 7 years will be compared with the current solar model calculations. In recent years a number of new solar neutrino detectors have been proposed. These various detectors will be discussed in light of some of the current ideas on solar models and neutrino properties.

The sun is generating energy principally by the proton-proton chain of reactions. The neutrinos are produced by the P-P reaction and a few beta decay processes. These reactions and decay processes are listed in Table 1 along with the neutron energy spectra and fluxes at the earth. The highest flux (6×10^{10} cm^{-2} sec^{-1}) arises from the P-P reaction but these neutrinos have very low energies (<0.4 MeV). There are a group of processes emitting neutrinos with energies up to 1.7 MeV with fluxes in the range of 2-34 $\times 10^{8}$ cm^{-2} sec^{-1}. The neutrinos from ^{8}B decay have relatively high energies but the flux of these neutrinos is very low (3×10^{6} cm^{-2} sec^{-1}). Since the solar neutrinos have very low energies and the flux at the earth is low

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the only means of observing them that has been developed is a radiochemical technique based upon the inverse-beta processes. We developed a radiochemical detector based upon the neutrino capture reaction, $^{37}Cl(\nu,e^-)^{37}Ar$. A large detector capable of observing the calculated solar neutrino flux was built in the period 1964-1967. Actually at the time three direct counting detectors were built. Two were based on inverse beta processes, $D(\nu,e^-H)H$ and $^7Li(\nu,e^-)^7Be$, respectively, and one was based upon neutrino electron scattering.[1] It is interesting to note that these experimental approaches to observing the energetic ^8B solar neutrinos are now being reconsidered. We would like now to give you a summary of the present results from the ^{37}Cl experiment.

THE ^{37}Cl EXPERIMENT

Table 1 shows the flux-cross section product for each of the neutrino sources in the sun. The fluxes are those derived from the standard solar model,[2] and the cross sections are from Bahcall.[3] The total neutrino capture rate expected from the standard solar model calculation is 4.7 SNU where SNU represents a solar neutrino unit (SNU ≡ 10^{-36} captures/sec·^{37}Cl atom). The Brookhaven detector contains 615 tons of liquid C_2Cl_4 or 2.18 x 10^{30} atoms of ^{37}Cl. The expected solar neutrino capture rate is 0.88 per day from the current standard solar model calculations. The detector is located deep underground to reduce the production of ^{37}Ar in the liquid from cosmic ray muons. It is located in the Homestake Gold Mine at Lead, SD at a depth of 4850 feet, corresponding to 4400 hg/cm^2 of overhead shielding. The tank containing the liquid is also shielded with water to eliminate the production of ^{37}Ar from fast neutrons from the surrounding rock

Table 1. Solar Neutrino Fluxes[2] and Cross Sections[3] for $^{37}Cl(\nu,e^-)^{37}Ar$.

Neutrino Sources and Energies in MeV	Flux on Earth ϕ in cm^{-2} sec^{-1}	Cross Section σ in cm^2	Capture Rate in ^{37}Cl $\phi\sigma$ x 10^{36} sec^{-1} SNU
$H+H\rightarrow D+e^++\nu$ (0-0.42)	6.1 x 10^{10}	0	0
$H+H+e^-\rightarrow D+\nu$ (1.44)	1.5 x 10^8	1.54 x 10^{-45}	0.23
^7Be decay (0.86)	3.4 x 10^9	2.4 x 10^{-46}	0.80
^8B decay (0-14)	3.2 x 10^6	1.08 x 10^{-42}	3.46
^{15}O decay (0-1.74)	1.8 x 10^8	6.6 x 10^{-46}	0.12
^{13}N decay (0-1.19)	2.6 x 10^8	1.6 x 10^{-46}	0.04
			$\Sigma\phi\sigma$ = 4.65

wall.

The ^{37}Ar is removed from the tank periodically by purging with helium gas. Argon is collected from the helium stream by a charcoal filter. It is finally purified by gas chromatography, gettered with hot titanium, and placed in a small low-level proportional counter to observe the ^{37}Ar decay events. The detailed procedures are described in earlier reports.[4] The small proportional counter (internal volume 0.6 cm^3) is operated in anticoincidence with a well-type sodium iodide scintillation counter to eliminate cosmic ray events. The counters are operated inside a 20 cm thick mercury shield. Pulse rise-time, pulse height and time of occurrence are recorded for each count, along with auxillary information to check the performance of the recording system. Argon-37 decay events produce a fast rising pulse that can be clearly distinguished from background events from beta rays and Compton electrons. The ^{37}Ar-like events are thereby characterized by their energy and pulse rise time. Individual samples are counted for long periods of time, usually 150 to 250 days, so that the decay of ^{37}Ar (half-life 35 days) could be observed. During the entire period only a small number of counts are recorded (12 on the average). The time of occurrence of the counts with the characteristic energy and rise-time was treated by a maximum likelihood statistical treatment developed by one of us (B.T.C.) to separate the 35 day decaying component from the presumed constant background counting rate. This treatment yields a most likely value for the ^{37}Ar production rate in the tank, and includes fluctuations (1) in the ^{37}Ar production in the tank, (2) in the decay during the production period, (3) during the extraction, and (4) in the counting. The errors were obtained by taking the upper and lower bounds defined by 34 percent of the total area under the likelihood function on either side of the most likely value. In the event that the most likely value is too low for this procedure to be followed, the upper error given corresponds to the bound that includes 68 percent of the area under the likelihood function. To obtain an average of a number of runs one uses the likelihood function formed by multiplying the separate likelihood functions for each run.

The ^{37}Ar production rates derived from this analysis are shown in Fig. 1. These are 30 individual runs, nos. 18 to 51, that were made from 1970 to 1977. Prior to run 18 we did not use pulse rise-time discrimination; results from these earlier experiments are given in reference 5. Every long exposure run is given except run no. 23; it was a poor run due to a valve leak. The missing run numbers correspond to runs in which special tests were performed. The average ^{37}Ar production for all runs shown is 0.41 ± 0.06 ^{37}Ar atoms per day in 615 tons of C_2Cl_4. There is a cosmic ray background production of ^{37}Ar in the tank from muons and cosmic ray produced muon-neutrinos that must be subtracted to

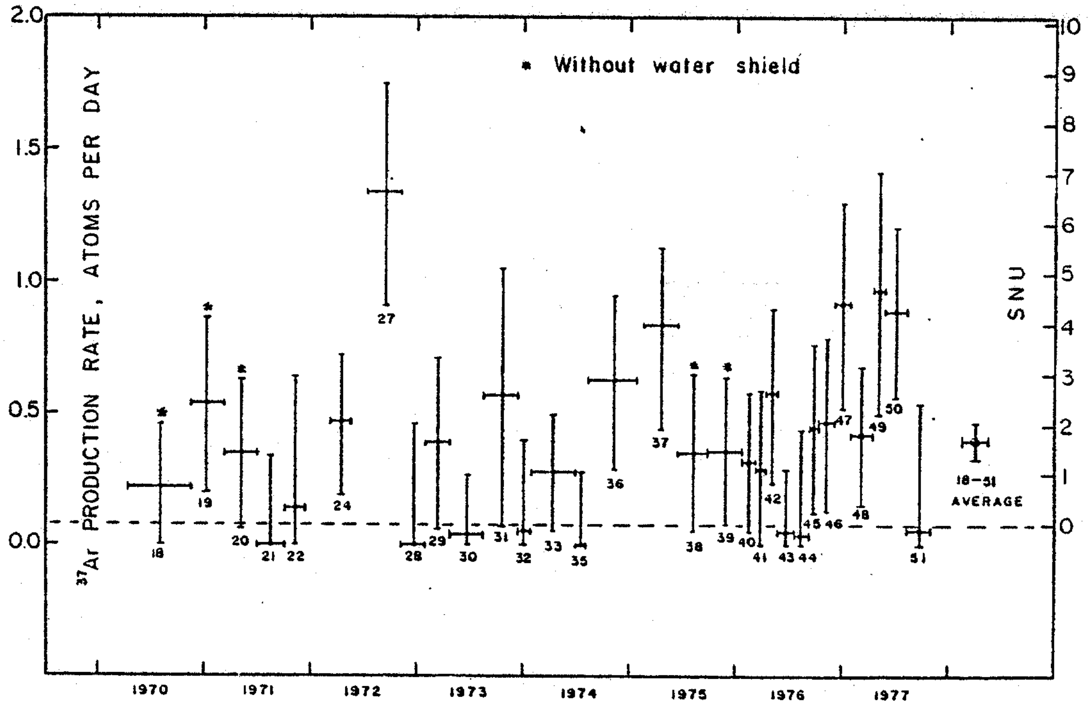

Figure 1. Summary of results

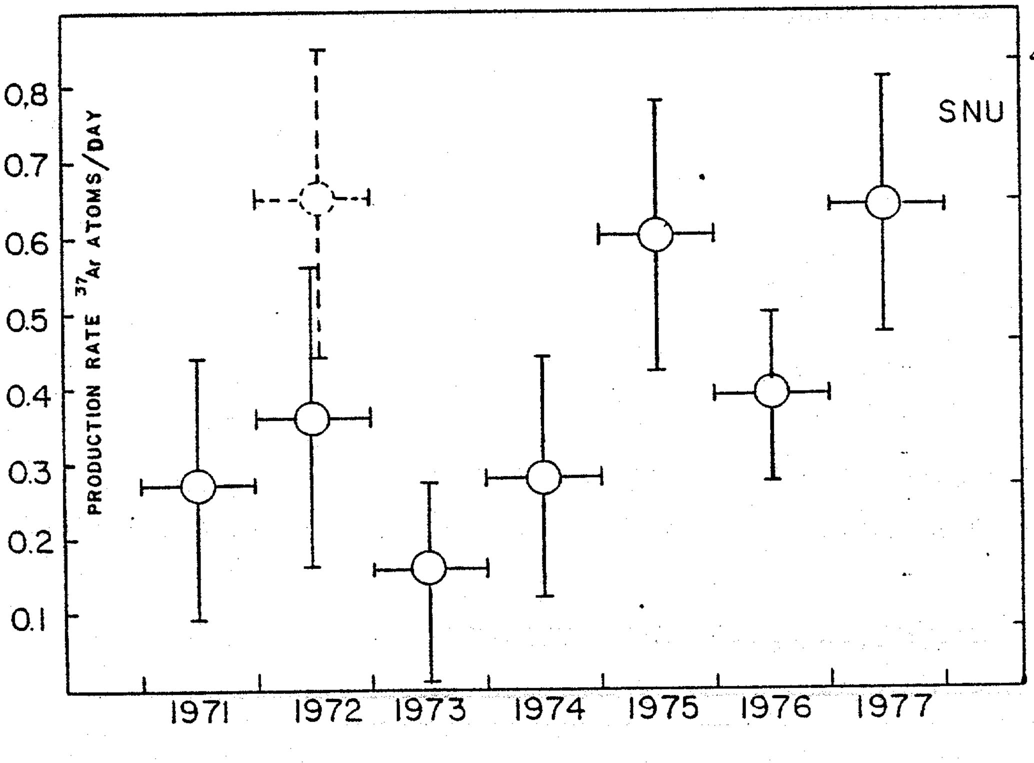

Figure 2. Yearly averages

obtain the ^{37}Ar production rate that we could assign to solar neutrinos.[6] The results are as follows:

^{37}Ar atoms/day

Average ^{37}Ar Production Rate (18-51) = 0.41 ± 0.06
Cosmic ray background (muons and ν_μ) = 0.08 ± 0.03

Rate above known backgrounds 0.33 ± 0.03

Possible solar neutrino rate =
$5.31 \times (0.33 \pm 0.07) = 1.75 \pm 0.4$ SNU

It is interesting to see if there is any change in the neutrino flux during the last 7 years that is observable with the ^{37}Cl experiment. Theoretically there is no reason to expect any change in the solar neutrino flux on time scales less than about 10^4 years. We have made yearly averages and these are presented in Fig. 2. Run no. 27, our highest experiment, was a long exposure and therefore dominates the 1972 value. Shown for 1972 are two values, one including run 27 (dotted), and one without it. From this plot it is evident that there has not been any change in the ^{37}Ar production rate outside of our statistical errors.

COMPARISON WITH THE STANDARD SOLAR MODEL

One can compare this result with the generally accepted solar model calculation of 4.7 SNU. It is difficult to assign an error to the standard solar model calculation. If the errors in the various input data used in the calculation are evaluated one can estimate an error of about ±30 percent.[7] The standard solar model presumes that the sun is a spherical non-rotating body with an initial composition identical to that observed now in its photosphere. The structure is derived from a set of differential equations for hydrostatic equilibrium, for radiation transport, and for energy production. It is assumed that the energy is derived solely from the thermal fusion reactions of the P-P and CNO chains. An ideal equation of state is used and the kinetic velocities are considered to be accurately Maxwellian. Various data are used in these calculations, some are very well determined like the mass, age and luminosity of the sun, and others are not as well known. The laboratory derived nuclear reaction cross sections are used, and the theoretically calculated opacities. The standard model predicts that the sun is operating on the P-P cycle and less than 2 percent of the energy is produced by the CNO cycle. This prediction agrees with our experiment, since if the sun were operating on the CNO cycle the neutrino capture rate would be 25 SNU. Another conclusion is that the luminosity of the sun increases with time at the rate of 5 percent per billion years. This result has been discussed in relation to the earth's climate,[8] and some have concluded that if the earth's atmospheric composition has not changed a 5 percent drop in solar luminosity would cause the oceans to freeze.

During the last 10 years almost all of the basic ideas of solar structure have been reexamined. Many effects such as rapid internal rotation, periodic mixing, pure helium core, and intense magnetic fields have been invoked in an effort to reduce the temperature in the central regions and thereby reduce the ^{8}B flux. These models are not satisfactory in that they are not consistent with observation, are not stable for long periods, or violate some concepts generally accepted in stellar evolution. There has been an extensive examination of the possibility that the sun is periodically mixed. However, as this question now stands there is no satisfactory mechanism. Furthermore to reduce the ^{8}B flux sufficiently to account for our observation requires mixing a large fraction of the interior of the sun. One of the most reasonable models that is consistent with our results is one in which the interior of the sun is essentially devoid of heavy elements. This reduces the opacity and allows radiation to escape more readily from the interior. The reduced central temperature results in a dramatic reduction in the ^{8}B flux. For this model to be convincing one needs a mechanism for adding the heavy elements to the solar surface after the sun becomes a stable main-sequence star. Several mechanisms have been proposed, the infall of cometary-like debris or the collection of material by the sun during its travel around the galaxy. These various non-standard models have been discussed in various review articles.[9] However, there is to date no critical review of all the aspects of the solar neutrino question.

There has been an extensive examination of the laboratory measurements of nuclear reaction cross-sections of specific interest to the P-P chain and possible variations. At the present time the nuclear physicists feel content that all the questions of cross-section values, possible resonances in critical reactions, and possible new nuclear reactions have been answered.[10] Neutrino properties are another question that has been with us for about 10 years. Since the travel time for the neutrino and the amount of matter that the neutrino must pass through are large for solar neutrinos it is possible that neutrino decay, oscillations, and small scattering processes could effect the terrestrial flux. All of these possible processes have been considered.[9] Neutrino oscillations have been discussed considering both vacuum oscillations[11] and matter oscillations.[12] If either of these oscillations occur it could severely alter the interpretation of any solar neutrino observation. In fact this is an important consideration in our thinking about new solar neutrino experiments.

NEW EXPERIMENTS

A number of new experimental approaches have been proposed in recent years. The ^{37}Cl experiment is relatively easy and simple to carry out and the target element is rather inexpensive. This will not be the case for the next solar neutrino experiment! In addition to the usual difficulties, there are some added requirements imposed by our theoretical interest. The rate of the initiating P-P reaction in the sun is essentially independent of the variations in the solar structure. All solar models forecast the same flux of these low energy neutrinos (0-0.42 MeV). From the viewpoint of astrophysics one has great confidence that these low energy neutrinos are being produced in the sun at the calculated rate. This is an important consideration if one uses a solar neutrino experiment to test for neutrino oscillations. Needless to say a solar neutrino experiment tests for oscillation lengths much greater than is possible with experiments at reactors or accelerators. With these considerations in mind we favor an experiment that is capable of observing the P-P reaction neutrinos, though any with sufficient sensitivity to observe any part of the solar neutrino spectrum would be very important. The ultimate goal is to determine the energy spectrum of neutrinos from the sun, and a way of obtaining this information is to use several radiochemical detectors with different thresholds. The ultimate technique would be a direct counting method that observes the energy of the neutrino and its direction.

If one examines all beta emitters with allowed or superallowed transitions and low disintegration energies that could be used for observing low energy neutrinos one finds only very few that are suitable. Table 2 is a list of the ones that are considered reasonably satisfactory and are now being considered in various laboratories. The table is divided into radiochemical detectors and direct counting neutrino detectors.

Let us first discuss the various radiochemical approaches. The reaction with the lowest threshold is the one with thallium in which ^{205}Tl (70.9%) captures a neutrino to form $^{205\mathrm{m}}$Pb which rapidly decays to ^{205}Pb. The product ^{205}Pb has a very long half-life (1.6×10^{7} y), so it is necessary to use a very old mineral as the target material. Mel Freedman and his associates at Argonne National Laboratory propose using 3-10 kg of a mineral low in lead that has been exposed at depth underground.[13] There is some difficulty in obtaining the mineral, and there is at present an uncertainty in knowing the exact value of the cross-section. Another similar case is the neutrino capture in ^{81}Br to form $^{81\mathrm{m}}$Br that decays to the long-lived ^{81}Kr (half-life 2.1×10^{5} y). The target material suggested is a salt deposit that has a small amount of bromine present.[14] These experiments have the unique ability of measuring the neutrino flux in the past, the thallium

Table 2. Proposed Solar Neutrino Detectors

Neutrino Capture Reaction	Half-life Product	Threshold Energy, MeV	Tons of Element needed for 1 ν-capture/day (For the standard solar model) All Sources
$\nu + {}^{205}\mathrm{Tl} \rightarrow e^- + {}^{205m}\mathrm{Pb} \rightarrow {}^{205}\mathrm{Pb}$	1.6×10^7 years	0.048	13
$\nu + {}^{55}\mathrm{Mn} \rightarrow {}^{55}\mathrm{Fe} + e^-$	2.6 years	0.231	290
$\nu + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$	11 days	0.233	38
$\nu + {}^{81}\mathrm{Br} \rightarrow e^- + {}^{81m}\mathrm{Kr} \rightarrow {}^{81}\mathrm{Kr}$	2.1×10^5 years	0.490	660
$\nu + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$ (present system)	35 days	0.814	603
$\nu + {}^{7}\mathrm{Li} \rightarrow {}^{7}\mathrm{Be} + e^-$	53 days	0.862	5
$\nu + {}^{115}\mathrm{In} \rightarrow e^- + {}^{115m}\mathrm{Sn} \rightarrow {}^{115}\mathrm{Sn} +$	Direct counting	0.128	3.1
$\nu + D \rightarrow 2H = e^-$	Direct counting	∿5	∿6 (^{8}B flux only)
$\nu + e^- \rightarrow \nu + e^-$		∿7	∿2000 (^{8}B flux only)

experiment measures the H-H reaction, and the bromine experiment could measure the ^{7}Be decay occurring in the sun. However, any experiment that uses a natural deposit can have serious built-in background effects.

A very attractive reaction is the one using gallium. It has a low threshold and therefore the dominant signal would come from the low energy neutrinos from the H-H reaction. The product ^{71}Ge has a convenient half-life and its decay is relatively easy to observe in a gas-proportional counter using germane (GeH_4) as the counting gas. The chemical procedures for efficiently extracting ^{71}Ge from gallium metal or gallium chloride solution have been developed.[16] The major problem with this approach is to obtain the use of 50 tons of gallium for a few years. The material is produced on a sufficient scale, but it is expensive. Of course it can be returned to the industrial market at the end of the experiment and thus recover the cost of the material. A solar neutrino detector based on the $^7\mathrm{Li}(\nu,e^-)^7\mathrm{Be}$ reaction has many advantages. The neutrino capture reaction has a relatively high cross-section (super allowed). The threshold is slightly higher than chlorine, but because of the superallowed character of the transition this experiment would have a high sensitivity to the medium energy neutrinos from the $H + H + e^- \rightarrow D + \nu$ reaction, and from the decay of ^{13}N, ^{15}O, and ^{8}B. Because of the superallowed character of the $^7\mathrm{Li}(\nu,e^-)^7\mathrm{Be}$ transition the lithium experiment requires the least amount of material, only 5 tons for 1 capture per day-standard model! The major difficulty with the lithium experiment is in measuring the ^{7}Be produced. There are several techniques that could be used, but as yet no really satisfactory method has been developed. Table 3 compares the relative sensitivity of the three radiochemical detectors using gallium, chlorine, and lithium as target material. Examining this table makes clear that the gallium detector responds mainly to P-P neutrinos, the chlorine detector responds primarily to the energetic neutrinos from ^{8}B, and the lithium detector has a more uniform response to all neutrino sources. If we had results from all three of these radiochemical detectors there would be sufficient information to determine the solar neutrino spectrum. This is the goal of the Brookhaven program.

A direct observation of the neutrino interaction itself could give information on the energy of the neutrino and its direction. These features are only possible if the neutrino energy is relatively high. Direct counting experiments to observe solar neutrinos have been discussed for 15 years.[1,17] However, it is very difficult to reduce the background counting rate of a few ton detector sufficiently low to observe the feeble signal from solar neutrinos. The only hope of success is to take advantage of a very unique signal from the neutrino interaction or to observe a neutrino interaction with energy release above that of background

Table 3. Relative Sensitivities of Ga, Cl, and Li Detectors to the Neutrino Sources in the Sun

Neutrino Source	Neutrino Energy MeV	Percentages of the total rate from each Neutrino Source in the Sun-standard model		
		$^{71}Ga(\nu,e^-)^{71}Ge$	$^{37}Cl(\nu,e^-)^{37}Ar$	$^{7}Li(\nu,e^-)^{7}Be$
$H + H \rightarrow D + e^+ + \nu$	0-0.42	71	0	0
$H + H + e^- \rightarrow D + \nu$	1.44 line	2	5	33
^{7}Be decay	0.861	23	17	11
^{13}N decay	0-1.20	1	1	4
^{15}O decay	0-1.74	2	3	15
^{8}B decay	0-14	<1	74	36
$\Sigma\phi\sigma$ in SNU		92	4.7	27.3

All cross sections from J. N. Bahcall (ref. 16).

processes. Recently R. S. Raghavan of Bell Labs has proposed using the neutrino capture in ^{115}In to produce an isomeric state in ^{115}Sn that rapidly decays (3.2 μsec) by emitting two successive characteristic gamma rays. This unique delayed triple coincidence process could identify the neutrino capture event sufficiently to distinguish the process from various background events. The reaction has a low threshold and could observe the neutrinos from the H-H reaction. A particular arrangement of indium loaded liquid scintillation counters has been suggested,[18] but background effects must be carefully studied before feasibility can be clearly demonstrated. A detector based upon this reaction can in principle also measure the energy spectrum of low energy neutrinos.

One of the early processes considered for observing ^{8}B neutrinos was the capture in deuterium producing an electron with an energy above 7 MeV. A detector was built by T. L. Jenkins (Case) about 10 years ago that used 2000 liters of D_2O, but various background processes limited its sensitivity. We know now that the ^{8}B flux is below 1×10^6 cm^{-2} sec^{-1} from the chlorine experiment so that observing ^{8}B neutrinos by this method is extremely difficult. Recently A. Fainberg (Brookhaven-Syracuse) has proposed building a D_2O Cerenkov detector of high resolution.[19] His present aim is to study backgrounds to determine if such a detector is capable of observing the low fluxes of ^{8}B neutrinos. A deuterium detector of this design is needed for observing pulses of neutrinos from collapsing stars. Present theories of stellar collapses predict an initial pulse of neutrinos a few hundredths of a second duration followed by a continued pulse of neutrino-antineutrino pairs that may last many tens of seconds. A 10-30 ton D_2O Cerenkov detector of the type proposed by Fainberg is the best means of observing this sharp characteristic pulse from a super nova event. Such a detector could observe the constant flux of energetic solar neutrinos.

Neutrino-electron scattering also has been regarded as a promising means of observing energetic ^{8}B neutrinos.[1] Observing the scattering event by a sandwich detector system made of alternating layers of thick plastic scintillator slabs and spark chamber modules has been recently suggested by H. Chen of the University of California, Irvine.[20] Studies of background processes have been made with a pilot system at the LAMPF accelerator that indicate a detector of this design would have a sufficiently low background to allow observing the ^{8}B flux. A detector of this design with the ability of defining the direction of the scattered electron would identify the sun as the source of the neutrinos that are observed. These various direct counting experiments look promising and perhaps in a future neutrino '80-'90 conference the direct observation of solar neutrinos will be reported.

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