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Solar Neutrino Counters

N. W. Tanner

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Solar neutrino counters

By N. W. Tanner
Nuclear Physics Laboratory, University of Oxford, Keble, Oxford OX1 3RH, U.K.

This paper reviews the prospects of the next generation of solar neutrino counters which will come into operation in two or three years' time and are expected to provide much better information, both qualitatively and quantitively.

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1. Introduction

Neutrinos from the Sun have been detected in four experiments and, within a factor of two or so, the rates reconcile with the received wisdom of astrophysics and the energy generating nuclear reactions. Given that almost all that is known of the Sun is inferred from observation of the surface and that the neutrinos come from the central 1% of the volume there is reason to be pleased. However, the factor of *ca.* 2 discrepancy has persisted and all the neutrino detectors record rates lower than those required by astrophysics. Taking the experimental results at their face value it is necessary either to redesign the Sun or to make profound changes to the particle physics of neutrinos. This paper reviews the prospects of the next generation of solar neutrino counters which will come into operation in two or three years' time and are expected to provide much better information, both qualitatively and quantitatively.

In the Sun the dominant source of energy is the pp-chain,

$$p+p \rightarrow {}^2H+e^+ +\nu_e, \quad {}^2H+p \rightarrow {}^3He+\gamma, \quad {}^3He+{}^3He \rightarrow \alpha+2p,$$

driven by the thermal kinetic energy against the Coulomb repulsion and hence sensitive to the temperature. The pp-neutrinos have a maximum energy of 0.420 MeV and a flux of 6×10^{10} cm^{-2} s^{-1} at the Earth which can be confidently predicted from the energy output of the Sun. There are also important side branches for neutrino production:

(*a*) 15%: ${}^3He+\alpha \rightarrow {}^7Be+\gamma$, ${}^7Be+e^- \rightarrow {}^7Li+\nu_e$ giving mono-energetic neutrinos of 0.86 MeV, with an estimated flux at the Earth of 5×10^9 cm^{-2} s^{-1}.

(*b*) 0.01%: ${}^7Be+p \rightarrow {}^8B+\gamma$, ${}^8B \rightarrow 2\alpha+e^+ +\nu_e$ with a neutrino β-spectrum of maximum energy 14 MeV, and an estimated flux at the Earth's surface of 6×10^6 cm^{-2} s^{-1}.

The estimates of fluxes come from the standard solar model (SSM) (Bahcall 1989; Bahcall & Pinsonneault 1992) for which the inputs are the cross sections of the various nuclear reactions. Of these the least well established is the $p+{}^7Be$ reaction; ${}^7Be$ is radioactive with a 40 day half-life (terrestrially) and the measurement is unusually difficult.

There are huge numbers of solar neutrinos incident on the Earth but neutrinos are neutral, interact only weakly (in the sense of β-decay), and significantly are neutrinos rather than anti-neutrinos. At MeV energies the cross sections for neutrino scattering and reactions are of order 10^{-43} cm^2 and a detector with a sensitive mass of 1000 t might provide a count rate in the region of one per day for solar neutrinos.

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(*a*) *First generation detectors*

There are four solar neutrino detectors in operation at present, three of which employ radio-chemical techniques for extracting and counting the very few radioactive atoms produced by neutrino induced inverse β-decay in many tons of material. The fourth, Kamiokande, is a water Cherenkov counter, which will be discussed more fully in §2*b*. All are located deep underground to minimize the cosmic ray induced background, and the Cherenkov counter is subject to serious backgrounds from natural radioactivity.

In summary the measurements of these four detectors are as follows.

(*a*) Homestake Mine (Davis *et al.* 1990) (615 t of C_2Cl_4, extraction and counting of argon). The detection reaction is $\nu_e + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{A}$, which has an energy threshold of 0.814 MeV and is mainly sensitive to ^{8}B and ^{7}Be neutrinos (respectively about 77% and 14% of the detected neutrinos). The accumulated result from 25 years of operation is 26 ± 4% of the SSM prediction (Bludman *et al.* 1993), which itself is uncertain by 13%.

(*b*) Kamiokande (Hirata *et al.* 1990, 1991; Nakamura 1993) (water Cherenkov counter of 680 t; see §2*b*). The neutrinos are detected through the recoil electron from neutrino–electron scattering with an experimental threshold of 7.5 MeV which excludes all except ^{8}B neutrinos. The rate observed is 50 ± 7% of the SSM which itself has an uncertainty of 14%.

(*c*) Sage (Gavlin 1993) and Gallex (Anselmann *et al.* 1992) (each 30 t of Ga, extraction and counting of ^{71}Ge). The initial chemistry of the two experiments is different but they use the same reaction $\nu_e + {}^{71}\mathrm{Ga} \rightarrow e^- + {}^{71}\mathrm{Ge}$, which has a threshold of 0.233 MeV and is mainly sensitive to pp, ^{7}Be and ^{8}B neutrinos (respectively 54, 26 and 11%). The combined result of Sage and Gallex to date is 54 ± 11% of the SSM which is uncertain by 5%.

Radio-chemical measurements are inherently more difficult than direct counting measurements to the extent that radio-chemistry provides little redundant information which can serve to check the reliability. However, in the case of the low energy pp neutrinos, but not ^{7}Be or ^{8}B neutrinos, it is possible to make a direct efficiency calibration with a β-decay neutrino source. Both Sage and Gallex plan to use neutrinos from a mega Curie of ^{51}Cr for calibration, which will eliminate the possibility that the 'hot atom' chemistry of neutrino induced ^{71}Ge is falsifying the results.

(*b*) *Interpretation*

There is a prima facie case that there is a deficiency in the number of solar neutrinos detected and that the deficiency varies with neutrino energy. It has proved difficult to find a plausible solar model variant which can explain the long standing Homestake result, and impossible to account for the deficiency in pp neutrinos (Sage and Gallex) and the difference between the Homestake (^{7}Be and ^{8}B neutrinos) and Kamiokande (^{8}B neutrinos) data (Bludman *et al.* 1993; Bahcall & Bethe 1993). Either the four measurements are wrong or particle physics is wrong.

It is well established that there are three 'flavours' of neutrinos (Mana & Martinay 1993), ν_e, ν_μ and ν_τ the neutral counterparts of the electron, muon and tau particles, and the standard model of particle physics holds that the neutrinos are massless and thereby independent one of another. If, however, either the ν_μ or ν_τ has a non-zero mass (the order of meV would be sufficient), then there would be little reason to assume that the neutrinos are independent, and neutrinos produced as ν_e in the Sun could arrive as ν_μ or ν_τ at the Earth and would not have been detected. In quantum mechanical terms the neutrino mass eigenstates would not correspond to the decay particles ν_e, ν_μ and ν_τ but to linear combinations of the decay states, so that a ν_e detector would record oscillations with distance from the source. Moreover the interaction of ν_e with electrons in the Sun or the Earth is different from that of ν_μ or ν_τ such that at a critical electron density N_e all ν_e of energy E_ν would convert to ν_μ or ν_τ:

$$N_e = \delta m^2/2\surd 2GE_\nu,$$

where δm^2 is the difference of the squares of the neutrino masses and G is the Fermi constant. This is the MSW effect (Mossaso 1991). Terrestrial limits on neutrino masses (Wilkerson 1993) ($\nu_e < 10$ eV, $\nu_e < 0.27$ MeV, $\nu_\tau < 35$ MeV) and oscillations (on length scales up to 10^3 m) do not reflect on solar neutrinos for which the length scale is 10^{11} m and the MSW effect is important.

There is nothing to exclude oscillations, aided by the MSW effect, as the explanation of the alleged solar neutrino deficiency and, with this added freedom, no great difficulty in fitting the measurements. However, it requires more concrete experimental evidence and less dependence on theoretical models to be wholly convincing.

2. Cherenkov and scintillation counters

There are two counters in existence, IMB and Kamiokande, and three, Borexino, SNO and Superkamiokande under construction. The latter have profited greatly from the experience of the former and might be considered second generation solar neutrino detectors which are expected to have higher sensitivity and better selectivity. For a broader review of solar neutrino detectors see Sinclair (1991).

For present purposes the schematic diagram of figure 1 will serve to illustrate the common features and mode of operation of the counters. All are installed underground to avoid cosmic rays and involve a large volume of liquid, the sensitive volume of figure 1, in which electrons energized by neutrinos one way or another can release Cherenkov or scintillation light for detection by an array of large (20 cm or 50 cm diameter) photomultipliers distributed over the full 4π solid angle. The water serves both as a 'light guide' between the sensitive volume and the photomultipliers and as a shield against the radioactivity of the photomultipliers and the surrounding rock.

An electron of a few MeV causes a multiple coincidence of photomultiplier hits (single photon pulses). In the case of Cherenkov light one obtains about 10 hits per MeV of electron energy for a generous provision of photomultipliers; scintillation light per MeV is about 50 times stronger. The best photomultipliers available exhibit a pulse height spectrum with a single photo-electron peak cleanly resolved from noise, a quantum efficiency approaching 30%, and transit time spread with a standard deviation close to 1 ns (the numbers refer to the EMI photomultiplier type 9351). The relative timing of the photomultiplier pulses can be used to reconstruct the position of the electron to an accuracy of a few tens of centimetres, and the number of hits recorded by the photomultipliers is proportional to the energy of the electron, with an uncertainty given by the statistics of the number of hits.

Cherenkov light is emitted by an electron at an angle to its direction of $\cos 1/n$, 42° for water, where n is the refractive index of the liquid. At MeV energies this simple pattern is smeared by multiple Coulomb scattering of the electron which limits the

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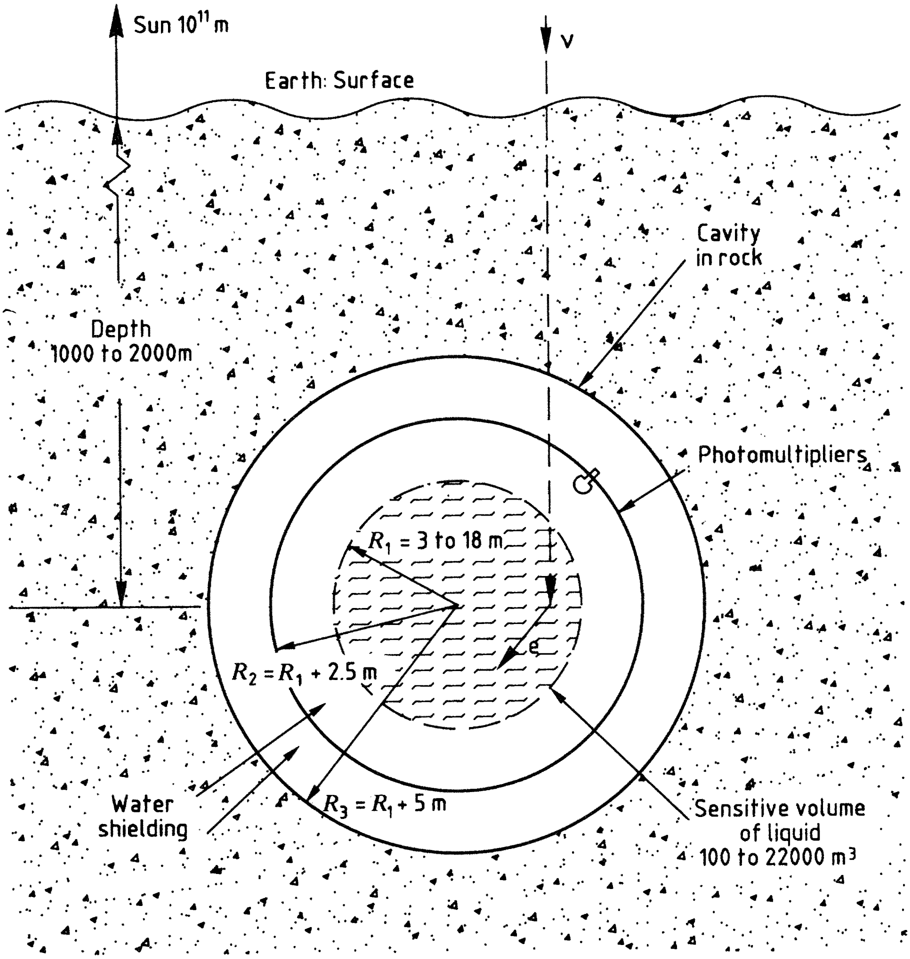

Figure 1. A schematic representation of the various Cherenkov/scintillation counters designed for the detection of solar neutrinos. The liquid in the sensitive volume is either H_2O, D_2O or liquid scintillator. Neutrinos are detected via the Cherenkov or scintillation light radiated by MeV electrons released by reactions. Typically some thousands of photomultipliers are used.

accuracy with which the initial direction of the electron can be inferred to a standard deviation of 20 or 30°. Scintillation light is isotropic so the directional information is lost, but the position and energy resolution is better, and for sub-MeV neutrinos Cherenkov light is not an option.

It should be noted that there are two limiting features which are common to all solar neutrino counters: (*a*) it is impossible to shield any radioactivity which resides in the sensitive volume itself; (*b*) it is impossible to switch off the neutrinos from the Sun to measure the background. External backgrounds can be assessed by comparing event rates near the centre and near the outside of the sensitive volume, but internal backgrounds are a much less tractable problem.

(*a*) *IMB*

The IMB water Cherenkov counter of 2000 m³ sensitive volume was built to search for proton decay but is at too shallow a depth and has too few photomultipliers (the photocathodes cover only about 2% of 4π) for the detection of solar neutrinos.

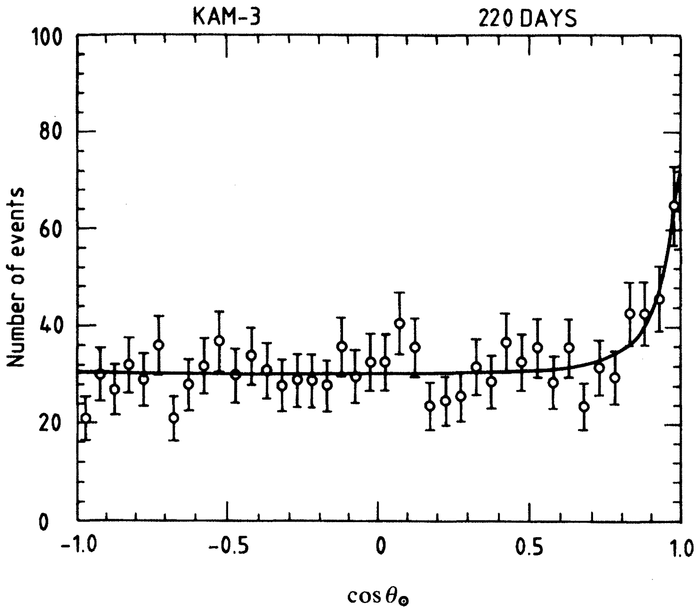

Figure 2. The angular distribution of electrons of energy greater than 7.5 MeV, relative to the direction of the Sun, recorded by Kamiokande. The peak on the right is identified as elastic scattering of ^{8}B neutrinos by electrons.

Nothing came of the proton decay but IMB made a major contribution to astrophysics by observing, in time coincidence with Kamiokande and in advance of the optical observation, a burst of 10 anti-neutrinos of about 30 MeV energy over a period of a few seconds from the supernova SN1987A. Decades of theoretical speculation about supernovae were validated in a flash.

(*b*) *Kamiokande*

Like IMB, Kamiokande is also a water Cherenkov counter built for proton decay, but at a rather greater depth and with photocathodes covering 20% of 4π surrounding the 680 m^3 sensitive volume. It was adapted for solar neutrinos by improving the radioactive cleanliness of the water and reducing the electron energy threshold to 7.5 MeV which permitted the detection of ^{8}B neutrinos.

The only interaction of solar neutrinos (as opposed to anti-neutrinos from supernovae or reactors) in ordinary water is neutrino–electron scattering. The energy spectrum of the recoiling electrons is uniform between zero and $E_{\mathrm{v}}(1+m_{\mathrm{e}}/2E_{\mathrm{v}})$ for a neutrino energy E_{v} and, for detectable electrons which have energy greater than $\frac{1}{2}E_{\mathrm{v}}$, the angle of the electron relative to the neutrino is inside 15°, less than the multiple scattering angle. Figure 2 shows a recent angular distribution of electrons of energy greater than 7.5 MeV (cf. the end point of 14 MeV of the ^{8}B β-spectrum) where the angle, relative to a line between the counter and the Sun, is inferred from the multiply scattered Cherenkov distribution. The background in figure 2 is made up of similar contributions from the β-decay of ^{214}Bi which is a member of the ^{238}U chain, various radioactive species produced by cosmic ray muons, and external γ-rays. Solar neutrinos were observed at a rate of 0.13 per day which is interpreted as 50 ± 7% of the SSM, a result which is notably sensitive to the energy calibration of the counter.

(c) *Superkamiokande*

This is a scaled-up version of the Kamiokande water Cherenkov counter at the same depth, with a sensitive volume of 22000 m^3, 32 times larger than Kamiokande, and 1100 photomultipliers. It is expected to improve on the signal to background ratio of figure 2 by more than an order of magnitude, partly because scaling reduces the surface to volume ratio which is important for muons and external γ-rays, and partly by eliminating from the water ^{222}Rn which is a precursor of the β-decaying ^{214}Bi. A lower electron energy threshold and a neutrino count rate 100 times Kamiokande have been mentioned, but the β- and γ-decays of ^{208}Tl in the ^{232}Th chain and photomultiplier noise could impose a limitation.

(d) *Borexino*

The proposal envisages using 100 m^3 of liquid scintillator, roughly in the manner of figure 1, for the counting of ^{7}Be neutrinos from the sun via neutrino–electron scattering. The decay of ^{7}Be is via electron capture giving a monoenergetic group of neutrinos, with $E_\nu = 0.86$ MeV, and a uniform electron recoil energy distribution between 0 and 0.66 MeV.

There are a thousand times as many ^{7}Be neutrinos as ^{8}B neutrinos from the Sun according to the SSM. The predicted count rate for Borexino for a recoil electron energy threshold of 0.25 MeV is 50 per day, and external γ-rays and cosmic ray muons are unlikely to contribute significantly to the background, particularly as Gran Sasso, where Borexino will be installed, is substantially deeper than Kamioka.

The difficulty that Borexino faces is that the neutrino signal has no distinguishing features (cf. the internal radioactivity of the liquid scintillator), including α-decays, which also give signals in scintillators similar to electrons of about a tenth the energy. By ordinary standards organic materials are radioactively clean, but the required purity of 10^{-16} ^{232}Th and ^{238}U by mass is a new world. That concentration of ^{232}Th and ^{238}U in equilibrium with their daughters in 100 t of scintillator would give 212 decays per day from 25 radioactive species. As equilibrium cannot be guaranteed it will be a formidably difficult task to determine the background although it may be possible to suppress signals from α-decays by pulse shape discrimination. The experiment may have to rely on the small eccentricity of the Earth's orbit to recognize the ^{7}Be signal.

3. SNO

The Sudbury Neutrino Observatory collaboration is constructing a Cherenkov counter 2000 m underground at Sudbury, Ontario, with a sensitive volume of 1000 m^3 which can be filled either with ordinary water or heavy water. The purpose of the heavy water is to serve as a target of nearly free neutrons (the deuteron is bound by only 2.2 MeV) which permits neutrinos to be detected with an order of magnitude greater sensitivity than that available from neutrino–electron scattering, and provides other important advantages. It will be sensitive only to ^{8}B neutrinos and is expected to be operated with an electron energy threshold of about 5 MeV.

The neutrino interactions which will give rise to signals from the heavy water Cherenkov counter are as follows, including the count rates expected for the neutrino flux according to the SSM and an electron energy threshold of 5 MeV.

(*a*) Neutrino-elastic scattering:

$$\nu_e + e^- \rightarrow \nu_e + e^- \quad 1100 \text{ per year.}$$

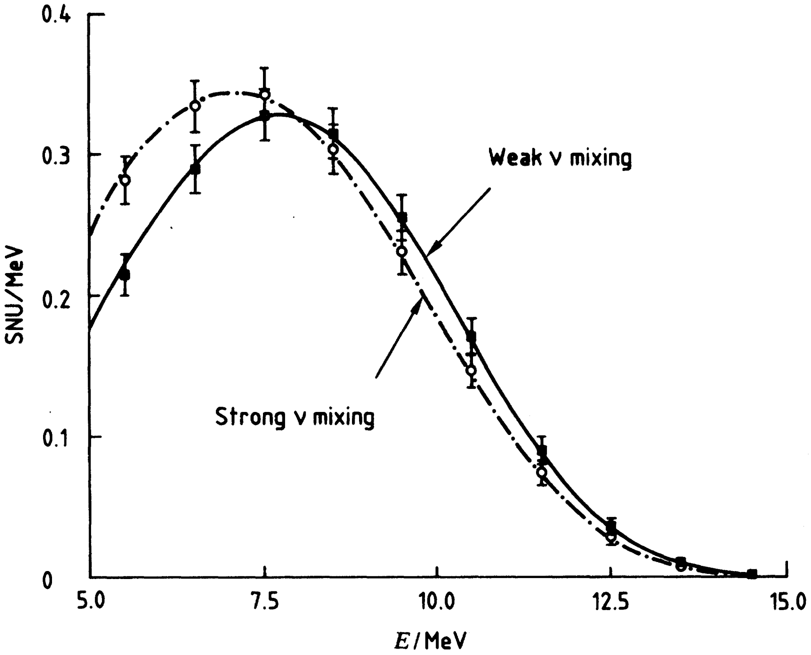

Figure 3. The predicted electron energy spectrum of $\nu_d d \rightarrow ppe^-$ events from SNO after two years operation, assuming the MSW explanation of the existing data. There are two solutions, here called weak and strong coupling. (SNU, solar neutrino unit, is defined as an event per 10^{36} s per detector atom.)

For neutrinos which arrive at the earth as ν_μ or ν_τ the scattering cross section is six to seven times smaller.

(*b*) The 'charged current' reaction (CC):

$$\nu_e + d \rightarrow p + p + e^- \quad 9750 \text{ per year,}$$

which has an angular distribution $1 - \frac{1}{3}\cos\theta_e$ and a cross section known to 10%. This reaction is analogous to the reaction

$$\bar{\nu}_e + p \rightarrow n + e^+,$$

which has been used to detect anti-neutrinos from reactors and, by IMB and Kamiokande, from the supernova SN1987A. The energy of the electron from the deuterium reaction is approximately $E_\nu - 1.44$ MeV. There is no charged current reaction for low energy ν_μ and ν_τ.

(*c*) The 'neutral current' reaction (NC):

$$\nu + d \rightarrow p + n + \nu \quad 2800 \text{ per year,}$$

for which the event rate is independent of whether the neutrino is ν_e, ν_μ or ν_τ. The cross-section is uncertain to 10%, but only $\frac{1}{2}$% relative to (*b*). The neutrino energy threshold for this reaction is 2.23 MeV. The neutron which is released can be detected in the Cherenkov counter by adding a $\frac{1}{4}$% NaCl to the D_2O so that the neutron after thermalization (about 5 ms) undergoes radiative capture by the Cl giving 8 MeV worth of γ-rays which convert to electrons by Compton scattering or otherwise and give Cherenkov radiation.

The attraction of using D_2O is clear. Not only can better statistical accuracy be

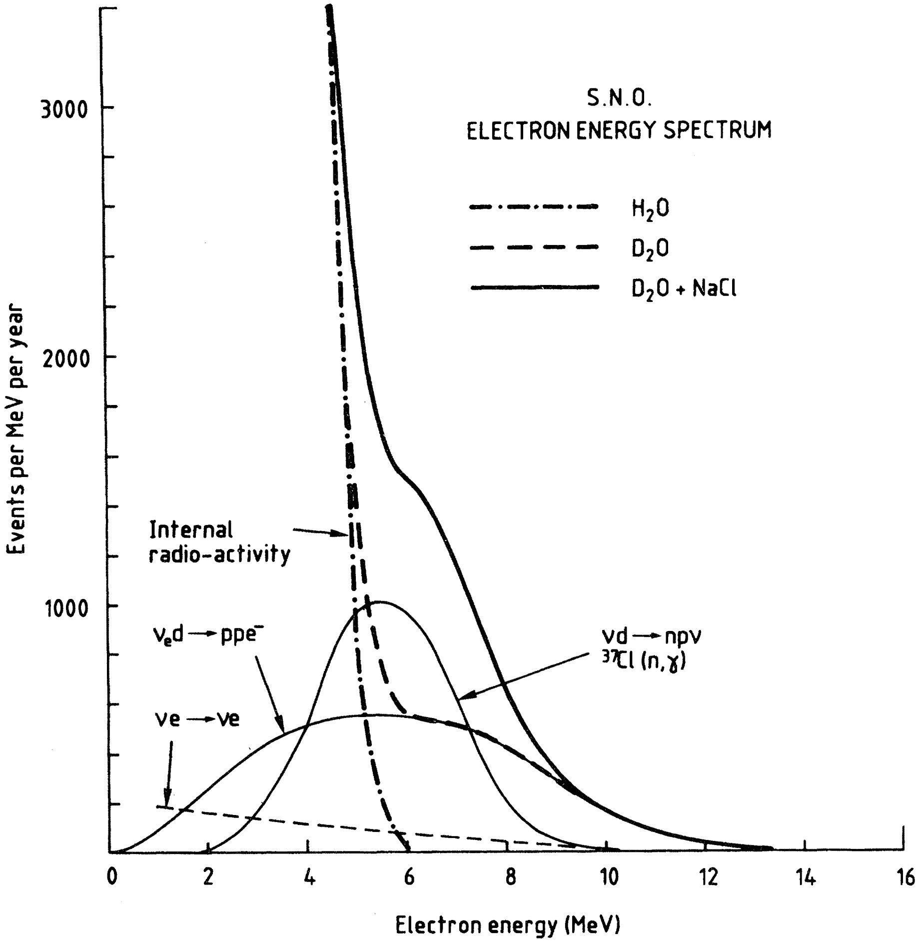

Figure 4. The simulated energy spectra, from solar neutrinos plus background, for events reconstructed within the sensitive volume of SNO filled with H_2O, D_2O and $D_2O+NaCl$ respectively. It is assumed that the sun provides its full SSM quote of ^8B neutrinos of which one third arrive as ν_e, and that the water contains 10^{-15} ^{232}Th and 10^{-14} ^{238}U. The recognizable elastic scattering events have not been added into the totals for H_2O, D_2O and $D_2O+NaCl$ and the photodisintegration background in the case of $D_2O+NaCl$ has been ignored.

obtained than is the case for H_2O but, if indeed the apparent neutrino deficiency has its origin in oscillations enhanced by the MSW effect, this will appear as a factor of two difference from the expected ratio of the count rates for the charged current reaction (*b*) and the neutral current reaction (*c*), independent of any assumption made about the Sun. In addition the neutrino energy spectrum as determined by the charged current reaction (*b*) will in general be distorted: figure 3 shows the predictions by Bludman *et al.* (1993) of the SNO data for the value of δm^2 and the two values of the coupling $\sin^2 2\theta$ preferred by the existing solar neutrino measurements. In principle there is a third test, namely the comparison of the charged current rate (*b*) and the ν–e scattering rate (*a*) from SNO or Superkamiokande since the latter responds to ν_μ and ν_τ with a cross section about one sixth that for ν_e; in practice it may not be very useful because of the uncertainty of 10% in the cross section for (*b*) and the sensitivity of the interpretation of the scattering data to the energy calibration.

Figure 4 shows a simulation of the energy spectrum expected from the SNO Cherenkov counter. The energy is inferred from the number of photomultipliers recording hits with a calculated calibration of 8 hits per MeV. It is assumed that the sun produces the full SSM number of ν_e but that at the Earth only one third are ν_e and two third ν_μ or ν_τ. The background is dominated by the radioactivity within the sensitive volume which in figure 4 is assumed to include mass concentrations of 10^{-15} ^{232}Th and 10^{-14} ^{238}U in equilibrium with their chains. Three fillings of the sensitive volume are presented in figure 4: (i) H_2O which should exhibit only the radioactive background and ν_e elastic scattering, recognizable as in Kamiokande by the directionality of the recoil electron. (ii) D_2O which adds the β-spectrum from $\nu_e d \rightarrow ppe^-$ to (i). It has been assumed that a neutron 'poison', e.g. a small quantity of boron, has been added to the D_2O to suppress the reaction $n+d \rightarrow t+\gamma$. (iii) $D_2O+\frac{1}{4}\%$ NaCl (without boron) which adds to (ii) the neutron capture γ-rays.

The background 'wall' has its origin in the βγ decays of ^{208}Tl in the ^{232}Th chain and ^{214}Bi in the ^{238}U chain, and rises with a slope of about one decade per MeV. It will not be easily moved.

The neutron background (not shown in figure 4) is dominated by the photodisintegration of deuterium by the 2.6 MeV γ-ray from the ^{208}Tl activity and for a 10^{-15} ^{232}Th concentration is expected to yield *ca.* $\frac{1}{30}$ of the neutral current neutrino signal from $\nu d \rightarrow np\nu$. The background is of course indistinguishable from the NC neutrino signal.

(*a*) *Special features of the SNO Cherenkov counter*

SNO owes much to the experience of Kamiokande but has particular additional requirements and, like Superkamiokande, has taken the opportunity to design for a much lower level of radioactivity, as is desirable for a solar neutrino counter.

The schematic diagram of figure 1 is in fact drawn to the proportions of SNO, but the actual construction, figure 5, looks rather different. The sensitive volume is enclosed within an acrylic sphere which isolates the volume from the shielding water. The acrylic sphere is to be fabricated from bonded panels and will be, by nearly an order of magnitude, the largest acrylic vessel ever made, 12 m diameter with a wall thickness of 50 mm which is a delicate container for the very valuable 1000 tons of D_2O (on loan from AECL). Buoyancy of the H_2O will reduce the net load to 100 t plus 30 t of acrylic, and by a judicious choice of H_2O and D_2O levels it will be possible to maintain the sphere under compression and avoid the risk of crazing.

The other special features of SNO, namely radioactivity and light detection, are described in the following two sections, but this is not to overlook a great deal of high class engineering, mining and mechanical, which is going into the project.

(i) *Backgrounds*

At 2000 m underground cosmic rays are negligible and radiations from the 1 p.p.m. of Th and U in the rock are adequately suppressed by the water shielding. All the materials to be used in the construction of the counter, down to the level of the tiny ceramic insulators use in the photomultipliers, have been subjected to tests for (*a*) radioactive content by low level γ-ray counting, usually Th, U and ^{40}K, (*b*) emanation of radon, and (*c*) leaching of radioactive species in water. The nature of the problem may be judged from the specifications for the Th concentration of some of the major components of the counter: glass of photomultiplier bulbs, Th $\lesssim 10^{-8}$, which was achieved by the development of a special glass; acrylic for the vessel,

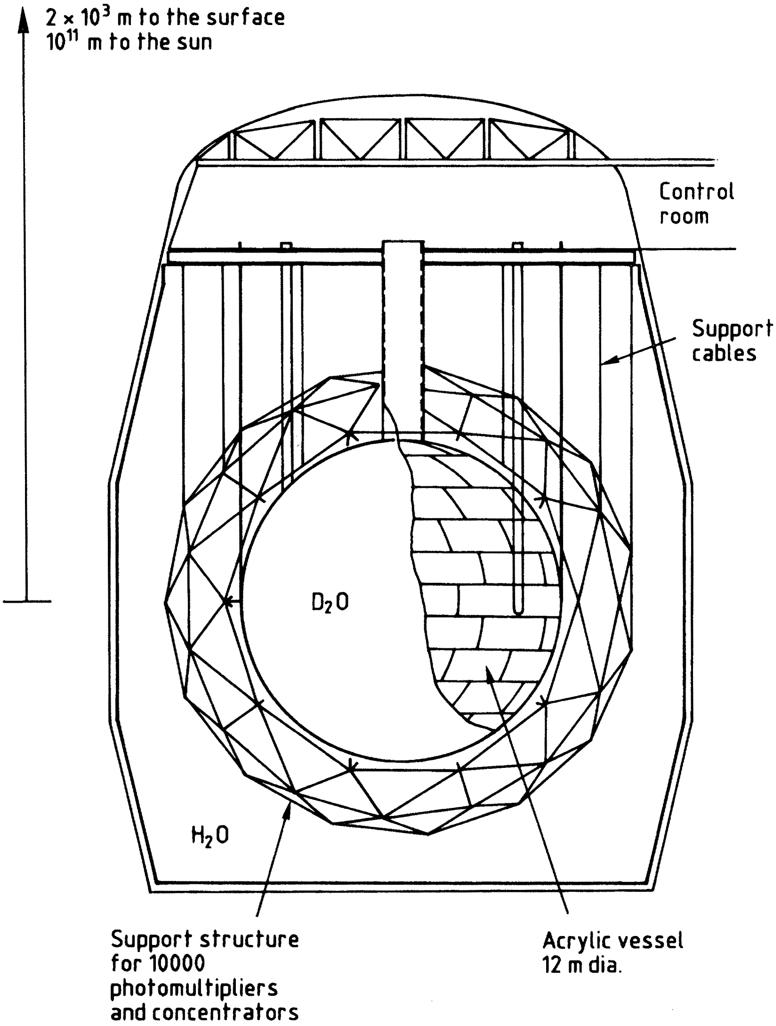

Figure 5. A drawing of the SNO Cherenkov counter showing the cavity 22 m diameter by 30 m deep 2000 m below the surface, the support structure 17.5 m diameter for 10000 photomultipliers, and the acrylic vessel for D_2O, 12 m diameter.

Th $< 10^{-12}$, which has been satisfied but not without some difficulty with the measurement; H_2O, Th $\leqslant 10^{-14}$, which is not expected to be a serious problem, cf. D_2O; D_2O, Th $\leqslant 10^{-15}$, for which the techniques of assay are still under development.

A ^{232}Th concentration of 10^{-15} means 40 decays per day in 100 t and it is necessary to concentrate an appropriate member of the decay chain (the chain may be out of equilibrium) from 100 t down to *ca.* 1 kg for counting, possibly after further concentration. The appropriate members of the chain for analysis are two year ^{228}Th or four day ^{224}Ra as all subsequent members of the chain down to the damaging ^{208}Tl are short lived. As the chemistry of thorium is unspeakable (it both deposits out on surfaces and forms a variety of complexes which are difficult to extract) the practical choice is ^{224}Ra, an alkaline earth.

Two absorber systems for extracting radium at a flow rate of 100 l min^{-1} are being studied, packed bed and seeded ultrafiltration. Figure 6 shows a schematic diagram

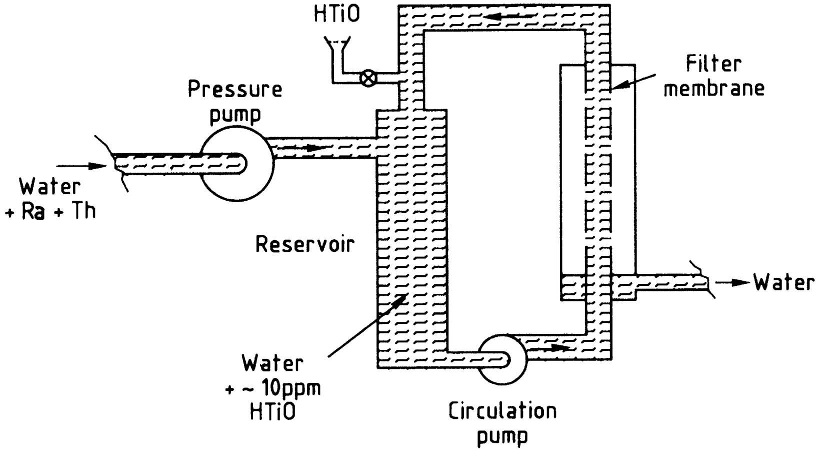

Figure 6. Schematic diagram of the system for seeded ultrafiltration using *ca.* 10 p.p.m. of finely divided hydrous titanium oxide (abbreviated HTiO) to absorb Ra and Th in water and extract via a filter of pore size *ca.* 10 nm.

of a seeded ultrafiltration system which was developed for extracting activities from reactor waste streams. The favoured 'seed' is finely divided hydrous titanium oxide at a concentration of *ca.* 10 p.p.m. in the reservoir which absorbs both radium and ionic thorium with high efficiency. The Ra can be redissolved with acid and subjected to further chemical processing for any of a variety of low background counting techniques. The hydrous titanium oxide ultrafiltration technique is indifferent to the presence of NaCl and can provide a salt free concentrate of radium. Naturally it will also remove 1600 year ^{226}Ra in the ^{238}U chain, and therefore effectively remove ^{214}Bi.

Both the D_2O and H_2O will be recirculated via degassing (to remove four day ^{222}Rn) and purification plants and cooled to 10 °C, the operating temperature of the counter. The H_2O flow will be outwards through the photomultiplier support structure, figure 6, which will provide an appreciable flow impedance to discourage reverse flow driven by convection currents.

(ii) *Photon detection*

The SNO counter will be equipped with nearly 10000 Hamamatsu 20 cm photomultipliers, not the best but the maximum photocathode area for the funds available. Each photomultiplier will be equipped with a non-imagining light concentrator which increases the effective photomultiplier area by a factor of 1.65 at a cost of 10% of a photomultiplier. The total effective coverage of 4π, in the geometry of figure 1 with $R_1 = 6$ m, provided by the 10000 enhanced photomultipliers amounts to 65% and is limited by the mechanical mounting.

The $1/\lambda^2$ Cherenkov spectrum is cut off at about 330 nm by the acrylic vessel (cf. 300 nm for the photomultiplier glass) but otherwise the light is not much disturbed by absorption or scattering in the water or reflection from the acrylic–water interfaces. The light concentrators (Welford & Winston 1989) are a development of the Winston cone, commonly used for Cherenkov counters, for non-planar photomultipliers. Figure 7 illustrates the tangent ray design principle: a ray at the chosen maximum angle to the axis θ_i is reflected tangentially to the curved photocathode surface. In two dimensions, figure 7 defines an ideal concentrator in the Liouville sense, all rays with $\theta \leqslant \theta_i$ are incident on the photocathode surface, and

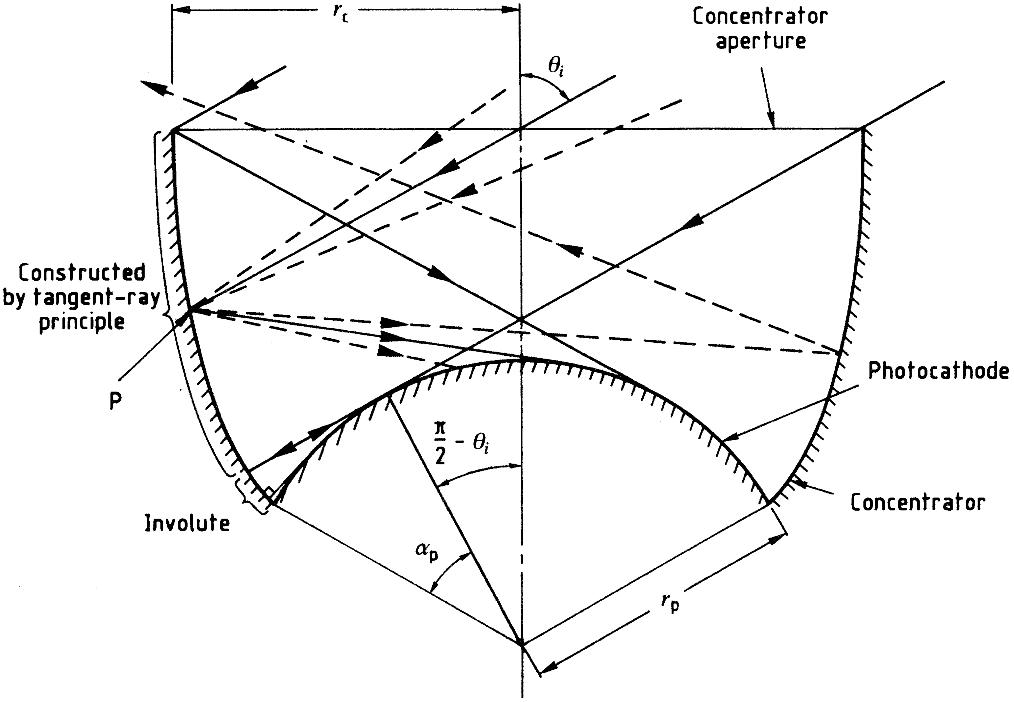

Figure 7. The geometry of the optics for the concentrator for a photomultiplier with a curved surface. All rays which enter the aperture at an angle to the axis $\theta < \theta_i$ reach the photocathode, and none for $\theta > \theta_i$. In two dimensions this is a perfect concentrator. The three-dimensional figure of revolution is not perfect but is a good approximation.

none with $\theta > \theta_i$. For the three-dimensional figure of rotation there are skew rays and the angular cut-off is less sharp, about 5° spread, partly because the conservation of the axial component of photon angular momentum is a more severe constraint than the Liouville theorem for non-planar photocathodes. The practical concentrators are designed for $\theta_i = 56°$ to include 1 m of H_2O outside the sensitive volume of figure 1 as an independent monitor via ν_e scattering. Apart from increasing the signal size at little cost the concentrators shield each photomultiplier from its neighbours and thereby effect a dramatic decrease in the background from β decays in the glass of the photomultipliers. Apparently light concentrators are all profit.

4. Ionization counters for solar neutrinos

These may well become the third generation of solar neutrino detectors. There are two systems under development, Icarus (Cline 1993) which is a liquid argon time projection chamber, and ^{3}He proportional counters for detecting the neutrons in the SNO Cherenkov counter.

Icarus would detect neutrinos via ν_e elastic scattering, and the reaction $\nu_e + A \rightarrow e^- + K$ which has a threshold of 5.85 MeV and is sensitive only to ^{8}B neutrinos. It would provide vastly better energy and angular resolution than any Cherenkov or scintillation counter can hope for, and is expected to be able to measure spectral distortions of the kind shown in figure 5. Nothing is known of the background prospects.

The ^{3}He proportional counters are being developed for neutron counting, as an alternative to the use of NaCl in the SNO Cherenkov counter, for the NC reaction $\nu d \to np\nu^+$ with the huge advantage that the NC signal would then be independent of and not additive to the CC signal from $\nu_e d \to ppe^+$. An equally spaced array of 100 proportional tubes distributed over the sensitive volume of the SNO counter is proposed. These tubes will impede about 20% of the Cherenkov light from the CC reaction, but should not add significantly to the background.

5. Supernovae

The solar neutrino counters would all detect the burst a few seconds long of *ca.* 30 MeV neutrinos from a supernova in our own galaxy, whether or not it was observed optically. Apart from the Magellanic Clouds, all other galaxies are too far away. Neutrino emission carries away *ca.* 99% of the energy of a supernova outburst, and it may not be easy to secure a soundly based understanding of the processes involved in a supernova without observing the neutrinos. The problem is that the frequency of galactic supernovae is estimated at about one every 50 years, which would require the maintenance of a neutrino supernova-watch over many decades.

For the SNO Cherenkov counter filled with 1000 t of D_2O + NaCl and a supernova event at the centre of our galaxy (10 kpc) the following events are expected, assuming 100% detection efficiency:

reaction	$\nu_e d \to ppe^-$	$\nu e \to \nu e$	$\nu d \to np\nu$	$\bar{\nu}_e d \to nne^+$
first 10 ms	10	1	6	0
next 10 s	33	16	760	10

In addition about 60 events would be observed in the H_2O near the sensitive volume from the reaction $\bar{\nu}_e p \to ne^+$ during the 'next 10 s'. The dominance of the NC interaction is notable and would prescribe that any supernova-watch counter would have to have that sensitivity.

6. Summary and comments

Disregarding errors and uncertainties there is a deficiency of solar neutrinos, namely: Homestake (77% ^{8}B, 14% ^{7}Be), 26% of SSM; Kamiokande (100% ^{8}B), 50% of SSM; Sage and Gallex (54% pp, 26% ^{7}Be, 11% ^{8}B), 54% of SSM, and it is impossible to account for the discrepancies by any conceivable adjustment to the SSM. By default we are left with MSW enhanced oscillations as the candidate explanation, i.e. particle physics.

If the Sage and Gallex result, with improved statistical accuracy and the confidence provided by the ^{51}Cr calibration, stays close to the present 54% of SSM it will be very difficult to avoid a particle physics explanation. The dominant pp neutrino flux from the Sun is fixed by the energy output to about 5%.

However, the definitive proof of neutrino oscillations/MSW effect must await the next generation of detectors which are expected to produce positive evidence of muon or tau neutrinos, ν_μ or ν_τ, from the sun as well as ν_e. The most convincing evidence is likely to come from the energy spectra from SNO shown in figure 4 for successive fillings with H_2O, D_2O + boron, and D_2O + NaCl, which respectively measure background (plus the recognizable $\nu e^- \to \nu e^-$), $\nu_e d \to ppe^-$, and $\nu d \to pn\nu$ for all ν. It will be very important to have a good understanding (based on the radium analysis of the water) of the background which for $D_2O + NaCl$ contributes a deuterium photo-disintegration background to $\nu d \rightarrow pn\nu$.

In principle detection of neutrino–electron scattering can also provide evidence of ν_μ or ν_τ as the scattering cross sections for these neutrinos are about 15% of that for ν_e. However, scattering can be observed only for ^8B neutrinos for which the SSM is uncertain by 14%, and a comparison of scattering (Superkamiokande) with the ^8B ν_e flux determined by the reaction $\nu_e d \rightarrow ppe^-$ (SNO) is subject to a 10% uncertainty of the reaction cross section and errors associated with the sensitivity to the energy calibration of the scattering measurement. It may be difficult to make a convincing case for ν_μ or ν_τ from the scattering data.

The distortion of the ^8B ν_e spectrum as measured by the reaction $\nu_e d \rightarrow ppe^-$ in SNO could be very illuminating with regard to the parameters of the MSW effect, but it will be a difficult measurement for the unfavourable but possibly realistic example shown in figure 3. A comparison with figure 4 suggests that it would be necessary to measure the background with H_2O and otherwise establish that the D_2O background would be the same.

It is likely that the definitive particle physics evidence will have to come from the NC reaction $\nu d \rightarrow np\nu$ in SNO, and it is therefore disconcerting that there is no other NC measurement in prospect. Practically all other possible NC counters depend on nuclear excitation revealed by a γ-ray of a few MeV which is subject to the ubiquitous ^{208}Tl and ^{214}Bi backgrounds.

Supernovae neutrinos are expected to be mostly ν_μ and ν_τ and also require NC detection, but as the energies are higher and they arrive in a highly recognizable bunch the background problem is much less significant. However, a supernova-watch counter would have to be designed for a century of service, not a decade, and would require hundreds of tonnes of D_2O.

I am indebted to my colleagues in Oxford and the SNO collaboration generally for supplying, usually unconsciously, the information included in this review. The errors, however, are my private property.

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