**UPDATED REVIEW OF SOLAR MODELS AND SOLAR
NEUTRINO EXPERIMENTS**

Douglas R.O. Morrison
C E R N
Geneva, Switzerland.

Abstract

The Conventional Wisdom that there is a Solar Neutrino Problem and that New Physics is required, is examined. The various Solar Evolutionary Models, (or SSM), are described and in particular the four new 1992 papers. While the Evolutionary models are generally robust, there are important assumptions and uncertainties (screening, nuclear reaction rates etc) which mean that the errors cannot be small. Diffusion in the Sun is expected to be significant but so far there is no calculation which includes all types of diffusion, especially turbulent diffusion. The new and important helioseismological results are shown to be in agreement with some of the SSM calculations. The experimental results are beginning to be not inconsistent with the SSM calculations. Kamiokande is consistent with SSM calculations except for one with rather small errors. The new GALLEX result is in agreement with all SSM calculations within 1.3 to 2 standard deviations. The 1990 SAGE I experiment is shown to find no evidence of solar neutrinos and is inconsistent with all SSM calculations and with GALLEX. However the new 1991 SAGE II experiment finds neutrino rates not inconsistent with SSM calculations. The Chlorine experiment is significantly below SSM calculations and is inconsistent with Kamiokande. In particular the Chlorine claim that there is a variation of the solar neutrino flux with the inverse of the sunspot activity, which shows a correlation of 5 standard deviation significance, is in contradiction with the results of the Kamiokande experiment which finds no variation of the solar neutrino flux with time. The overall conclusion is that there is no compelling evidence for a Solar Neutrino Problem or need for New Physics. However the neutrinos could still have masses and further experiments with higher statistics are essential as they are one of the rare ways of studying this low mass region. Thus the Solar Neutrino Problem is becoming a Neutrino Mass Quest.

1. Introduction

The Conventional Wisdom [1] has been that the experimentally observed flux of solar neutrinos was less than that calculated by a Standard Solar Model, SSM. This was considered to be very significant and to require the introduction of New Physics. Further it was believed that the solar neutrino flux varied with time, in particular with the inverse of the sunspot activity, but this result from the Chlorine experiment was considered to be less significant being only five standard deviations [2].

Previous reviews [3a,b,c] of Solar Evolutionary Models and Solar Neutrino experiments led to the conclusion that some of the errors quoted by the models had been seriously underestimated and that extraction experiments were very difficult. It was concluded that the theory and experiment are not in significant disagreement and the need for New Physics is not compelling.

Since December 1991 when the latest paper of ref. [3] was written, there have been appreciable developments in Solar Evolutionary Models with four new papers and also important new experimental results. These are presented and discussed here.

This review is written by a particle physicist for particle physicists.

2. Evolutionary Models

For astrophysics it is necessary to have models of the evolution of the stars. Initially, progress was made with the Sun. In 1957 the first Evolutionary Model of the Sun was calculated by Schwarzschild et al. [4]. The basic idea is to follow the Sun from its beginning about 4.5 billion years ago, from a protostar (ie a large cloud of hydrogen and a mixture of other elements that are condensing into one or more clumps) to its present state. The Sun is divided into a large number of shells and the evolution of each of these shells is followed at a series of intervals of time.

The Sun is considered to have three zones; a Core where the nuclear reactions producing heat take place, a Radiation or Intermediate Zone from where this heat is transferred essentially by radiation to the outer Convection Zone where there is great turbulence. In 1958 Boehm-Vitense [5] introduced the Mixing Length Theory, MLT, in which a parameter, α , is used that is roughly the distance over which a convective element can be recognized. The Sun's helium abundance and the MLT parameter α are taken as the two parameters which are then adjusted to agree with the present-day values of the Sun's radius R_0 and luminosity L_0 – this was called the Standard Solar Model, SSM, from 1964 onwards [6].

There have been many, possibly hundreds, of calculations of the SSM type. Some are directed towards applications to other stars, more recently others have been directed towards helioseismology with many additional shells added [6] to have information on the surface where the pressure waves are reflected. Other SSM calculations have been directed to evaluating the solar neutrino flux and an interesting personal account of this is given by Bahcall and Davis in the appendix of ref. [1]. After building smaller detectors, Davis started work in 1964 on a large chlorine detector; he has encouraged by the first serious calculation by Bahcall et al. [7] of the solar neutrino flux of (40 ± 20) SNU.

In 1988 and 1989 two major and fairly independent SSM calculations were published by Turck-Chieze et al. [8] and Bahcall and Ulrich [9], which agreed well on many features such as the central temperature and density and on the neutrino flux for a gallium detector but not for a chlorine detector being (5.8 ± 1.3) SNU and (7.9 ± 0.87) SNU, ie with errors of 22% and 11% respectively. This difference in values, and even more importantly in errors, was critical for the evaluation of the Kamiokande experiment who expressed their result as $(\text{expt.})/\text{SSM} = (0.46 \pm 0.05 \pm 0.06)$ where $\text{SSM} = 1.00$ with zero error was taken as the Bahcall and Ulrich value of 7.9 SNU; this was generally taken as a significant difference from 1.00 and additional proof that there was a solar neutrino problem. However, if one compares with the Turck-Chieze et al. result of 5.8 SNU and includes the theoretical error of 22%, one finds [3a]

$$\text{SSM} - \text{expt.} = (1.00 \pm 0.22) - (0.70 \pm 0.12) = 0.30 \pm 0.25$$

which is just over one standard deviation and indicates no solar neutrino problem. Hence the existence or not of a solar neutrino problem depends critically on the details of the SSM calculation and even more critically on the errors assigned, which means that errors of 10% are crucial [3].

3. Major Problems of Evolutionary Models

Evolutionary Models are very lengthy and complex. They require input from many different branches of physics and often consider states of matter which are unknown on Earth. As Bahcall truly writes [1], ‘No one person or small group of persons, can be expert in all the fields that are involved in the theoretical calculations’. A large amount of experimental data is needed as input and many simplifying assumptions are made. An excellent introduction to the subject is given by Bahcall in ref. [1] though considerable care is needed with errors, subsequent conclusions, and comments on other peoples’ models. For a more advanced description of Evolutionary Models, the Yale paper of ref. [6] is strongly recommended for its clear and mature style. Some major problems of Evolutionary Models are next considered.

3.1 Abundance of Elements

It is necessary to know accurately the abundance of all the isotopes of all the elements which were present in the Sun when it was created from a protostar 4.5 billion years ago. Today’s values for most can be measured on the surface, eg by spectroscopy, and an Evolutionary Model is used to extrapolate back to 4.5 billion years ago. To check that these values are correct, meteorites are studied to find some that are believed to have the same composition as the Sun 4.5 billion years ago. Excellent agreement has been found by Anders and Grevesse [10], also reproduced in fig. 3 of ref. 3a, except for ${}^7\text{Li}$ and ${}^9\text{Be}$ which are factors of 200 and 2 resp. lower than the surface value expected and, most importantly, for iron where the surface value is significantly higher than the meteorite value. Courtaud et al. [11] have shown that by taking the lower value for iron, the neutrino flux for the Chlorine experiment would be reduced by 20%.

3.2 Equations of State

It has been pointed out at this colloquium by W. Daeppen [12], that there are several equations of state describing the pressure and density. The basic problem is that the composition of solar matter is complex and a simple description, eg ‘fully ionised and ... reasonably close to a perfect gas’ [13] is inappropriate as the degree of ionization changes with radius. At the centre of the Sun the light elements are fully ionized while heavier ions such as iron retain some electrons; as the radius increases, more and more elements are partially ionized. This is very important as the heat is transported from the core almost entirely by radiation and the interaction of radiation is greatly increased if the ion is partially ionized. Coulomb interactions in the plasma (Debye-Huckel corrections) are often neglected but, as pointed out by Turck-Chieze [14] and at this colloquium by Bloecker and Stolzmann [15], they are important.

Daeppen [12] points out that there are two basic approaches to the Equation of State, EOS. In the ‘chemical picture’, the notion of atoms, molecules, ions, electrons and nuclei is used rather than a global plasma concept, and the ionization and dissociation reactions are considered (the Saha equation). In the ‘physical picture’, only electrons and nuclei are considered in the plasma.

The basic problem is that the behaviour of plasmas containing a wide range of elements at the temperatures and pressures occurring inside the Sun cannot be studied on Earth and appreciable theoretical extrapolations are needed. In particular, screening effects are poorly known in plasmas and this gives uncertainties in the areas of nuclear reactions, opacity coefficients and equations of state.

3.3 Opacity

The transmission of heat from the Core to the surface of the Sun is described by a parameter, the opacity.

In 1982 there were a number of problems with pulsating stars and this led N. Stone [16] to write a paper entitled ‘A plea for re-examining heavy element opacities in stars’ where he suggested that if the opacities in the convection zone were increased, this would solve the problems. This led two large groups to start re-evaluating opacities to replace the Los Alamos Opacity Library, LAOL. The international Opacity Project, OP was described at this colloquium by M.J. Seaton [17] and uses the ‘chemical picture’ – it is less suitable for neutrino studies. The LLNL group of Iglesias and Rogers and others have derived the OPAL code using a ‘physical picture’ where they use parameters for the atomic data and fit the parameters to the available data; OPAL is useful for neutrino studies. They find [18, 19] that the opacity is enhanced as proposed by Simon – there is a bump in the opacity near a temperature of 0.3×10^6 K of 2 to 3 times the LAOL value which is mainly due to improved atomic physics of partially filled M-shell ions. Several other changes occur due to improved atomic data, EOS, treatment of the hydrogen Lyman-alpha line wing, and degeneracy in the photon scattering from free electrons.

There was a persistent disagreement between SSM predictions and the frequencies observed by helioseismology of the p-modes and it had been proposed to remove the discrepancy by increasing the LAOL opacities by 30% in the Convection Zone. Now the Yale group of Guenther et al. [6] have shown that using the OPAL opacities solves this problem.

There is an unfortunate discontinuity in the use of opacity tables. The OPAL and LAOL codes are useful at higher temperatures but at lower temperatures other opacities are needed such as Cox [20] below 10^5 K and Kurucz [21] below 10^4 K.

3.4 Rotation, Overshoot and Turbulence

At present the surface of the Sun is seen to rotate slowly, 25 days at the equator and 35 days near the poles. However, when it was formed from the cloud of the protostar, it was probably like a T Tauri with a disk so that it accreted from the disk and was a fast rotator. It would lose angular momentum by having a strong solar wind. It is considered now to have very little or no rotation in the Core and Radiation Zones. In SSM models rotation is not considered and probably is not important for neutrino fluxes today.

At this colloquium J-P Zahn [22] reviewed turbulence. It is strong in the Convection Zone and powerful intermittent downdrafts (plumes, vortices) are calculated to carry appreciable energy flux. These downdrafts will penetrate into the Radiation Zone giving overshoots, ie the boundary between the Convective and Radiation Zones is not smooth and there will be appreciable differential rotation – this region is believed to be the seat of the dynamo responsible for the Sun’s strongly fluctuating magnetic fields.

3.5 Particle Transport Processes

Generally in SSM calculations, transport of particles is ignored except that in the Convection Zone a single MLT parameter, α , is taken to describe convection. At this colloquium, G. Michaud and C.R. Proffitt [23] described the various papers on diffusion by gravitational settling and radiation driving. Several formalisms systematically underestimate the effect of diffusion when compared with results from best estimates of the transport coefficients. They discuss the Bahcall and Loeb [24] terms which can differ by up to a factor of two. There is little discussion of turbulence and of meridional diffusion though, as discussed in section 3.4, they could be important.

3.6 The Solar Lithium Problem

A major problem of SSM is that the ^7Li abundance observed is only 0.5% of that predicted. One suggestion was that lithium was carried by overshooting from the Convection Zone into the

Radiation Zone where it would be burnt up (it burns at a temperature of 2.5 million K and the boundary is at 2 million K). This argument appeared to be supported by the fact that ^9Be , which burns at 3.5 million K, was also low though only by a factor of two. This was considered evidence in favour of overshooting or of a lower boundary that would give a higher temperature. However, Christensen-Dalsgaard et al. [25] have shown from p-mode helioseismology measurements that the boundary is at 0.713 ± 0.003 of the Sun's radius. Consideration of the dispersion of lithium abundances in other stars suggests that the explanation may lie in the early history of stars when accretion and rotation were important [26] – this is not included in standard models [6].

3.7 Nuclear Reaction Rates

There are many nuclear reactions in the Sun whose rates need to be inserted into a SSM calculation. Some of these are unmeasured such as the basic pp reaction, others are measured at different energies and need to be extrapolated to the Sun's value as with the $^7\text{Be}(p,\gamma)^8\text{B}$ reaction. This latter reaction has one of the biggest uncertainties in determining the neutrino flux for the Chlorine and Kamiokande experiments. The measurements are from 17 to 4000 keV and Bahcall et al. [9] use only a 1965 s-state extrapolation although it can be seen from the data (eg fig. 4 of ref. [3a] where there is a full discussion) that s- and d-states need to be included in the extrapolation. Turck-Chieze et al. [8] show that this decreases the ^8B neutrino flux by 13%. Of the experiments performed, only that by Filippone et al. [27] is fully satisfactory and it is recommended [3a] that the astrophysical S-value of 20.2 keV.b as calculated by Johnson et al. [28] for Filippone et al. should be taken. New experiments on this reaction rate are now beginning to be measured eg at Ryken in Japan involving Dr. Motobayashi and the Yale group of M. Gai.

3.8 Errors in SSM Calculations

The Standard Solar Model is surprisingly robust as when one value is varied there are strong feed-back mechanisms that tend to return other values back to near their original values. Previously astrophysical constraints were few, essentially the present-day mass, radius, luminosity, surface composition and age of the Sun. However, with the new data and inverse analysis of helioseismology results, new constraints can be imposed such as the average depth of the Convection–Radiation Zone boundary and p-wave frequencies. In addition, studies of data from all stars can impose constraints on our star.

For neutrinos from ^8B that are dominant for the Chlorine and Kamiokande experiments, the nuclear reaction rates are proportional to a high power of the central temperature, T, being T^{18} and T^8 for ^8B and ^7Be respectively. Also, there is no constraint on this ppIII chain from the luminosity as it contributes so little to the total luminosity.

S. Turck-Chieze [14] estimated the main errors to be approximately;

Opacity coefficients	10%
Some special cross-sections (eg $^3\text{He} - ^3\text{He}$)	5%
$^7\text{Be}(p,\gamma)^8\text{B}$ cross-section	15%
Screening effects	15%

Thus one would expect an uncertainty of at least 20% on water Cherenkov and on chlorine experiments, and about 15% on gallium experiments.

On the other hand, Bahcall [29] estimates errors to be 10%. This is largely explained in section 7.1 of ref. [1] which is delightfully entitled 'Logic' and explains that many theoreticians use a 'rule of thumb' where they 'ignore the formal errors quoted by their colleagues' and study the variation with time of some experiments. He applies this technique to the sum of all errors by studying the time dependence of the predicted neutrino flux for chlorine to justify the small error. In a more recent

paper [30] this rule of thumb is extended to theoretical questions, ‘Our policy is to estimate theoretical errors, in the absence of a specific error calculation, by comparing the differences with time of different state-of-the-art evaluations’. A worry could be that if one were to make a wrong assumption and keep on making it, then the error will get smaller and smaller with time as more and more identical results are produced. It is interesting to test this rule of thumb with one element – the $S(0)$ value (normalized cross-section) for the ${}^7\text{Be}(p,\gamma){}^8\text{B}$ reaction where, for the reasons given in ref. [3a], the only satisfactory modern experiment with a published and refereed paper below the inelastic threshold of 430 keV is that by Filippone et al. which is therefore taken as standard;

Experiment	$S(0)$ (keV.b)	Variation from standard
1983 Filippone et al. [27]	20.2	0.0 (std.)
1982 Bahcall et al. [31]	27	+ 34%
1988 Bahcall et al. [9]	24.3	+ 20%
1992 Bahcall et al. [30]	22.4	+ 11%
1988 Turck-Chieze et al. [8]	21	+ 4%
1986 Barker evaluation [32]	17	– 16%

It may be seen that if Bahcall’s rule of thumb were applied to this single component of the neutrino flux, then the error would be greater than his total error from all experiments and all assumptions of 10% [29].

Experimentalists and some theoreticians frequently express their errors in the form;

$$\text{value} \pm (\text{statistical error}) \pm (\text{systematic error})$$

In the future it would be good if errors on solar calculations could be expressed similarly, eg

$$\text{value} \pm (\text{error from experiments}) \pm (\text{error from assumptions})$$

since even if the error from assumptions were not well known, it would make it clear that they were not well known instead of concealing them.

4. Recent SSM Calculations

In 1992 new calculations have been presented by four groups; Bahcall and Pinsonneault [30], the Saclay group, S. Turck-Chieze et al. [14, 33], the Nice group of P. Morel et al. [34] and the Yale group of D.B. Guenther et al. [6]. All four groups make calculations varying the input assumptions and values. They all use the Anders and Grevesse [10] abundances.

4.1 New Bahcall Paper

J.N. Bahcall has continued for some 30 years to update his Solar Evolutionary Model calculations, most recently [30] with Marc Pinsonneault of Yale. The Yale Rotating Stellar Evolutionary Code, YREC, [35] is used. A considerable number of changes have been made. They will be given in terms of the changes from the Bahcall and Ulrich [9] values, which they cause in the chlorine flux as given in ref. [30]. The most important, which decreases the flux by 17%, is that Bahcall has followed the Saclay suggestion [11] and now uses the lower iron abundance given by meteorites – this is now supported by recent spectroscopic measurements of FeI and FeII on the Sun’s surface. The change from the LAOL to the new OPAL opacities increases the flux by 13%. For the question of how to extrapolate the $S(0)$ values of ${}^7\text{Be}(p,\gamma){}^8\text{B}$ from the region of the measurements to the Sun’s range, Bahcall has changed from using only an s-wave and now, like the Saclay group, uses s- and d-waves following the theoretical paper of Johnson [28], this lowers the flux by 8%. Correction of an error in Bahcall and Ulrich increases the flux by 6%. Better estimates of

the ^{37}Ar energy levels from the CERN experiment of Garcia et al. [36] raise the flux by 3%. Combining these distinct major changes of -17% , -8% , $+13\%$, $+6\%$ and $+3\%$ overall reduces the chlorine flux by 3% from 7.9 to 7.7 SNU. In the paper [30] other changes are included and the final value is given as 7.2 SNU.

In the paper a major point is made of the introduction of the diffusion of hydrogen and helium. Three types of diffusion are mentioned – Gravitational Settling and Thermal Diffusion plus Radiative Levitation; the latter is considered to be unimportant for the Sun. This is found to increase the neutrino flux for chlorine by 11% from 7.2 to 8.0 SNU. However, no consideration is given to the more important Turbulent Diffusion, which could be expected to lower the flux more than the other three raise it. The diffusion calculation uses the Bahcall and Loeb [24] work which was commented on by Michaud and Proffitt [23]. Hence, in future work here, these diffusion changes will be excluded for safety.

As explained above and more fully in ref. 3, Filippone et al. [27] is the only experiment that can be used to determine the astrophysical S-factor for the $^7\text{Be}(p,\gamma)^8\text{B}$ reaction. If $S(0)$ is then changed from 0.0224 to 0.0202 keV.b, this lowers the chlorine neutrino rate from 7.2 to 6.6 SNU. In this work the age of the Earth was taken as 4.6 Gyr – if a more recent lower value had been taken [6], this would decrease the rate by a few per cent [37].

Bahcall and Pinsonneault find 127.5 SNU for the neutrino rate for gallium, or 132 SNU with their diffusion calculation.

The depth of the boundary between the Convective and Radiation Zones has been estimated to be $0.707 R_0$, in good agreement with the value obtained from helioseismology [25].

It is believed that initially a conductive core appeared in the Sun and then disappeared within 100 million years – the YREC includes this.

A large change has been made by Bahcall et al. [30] to the hep reaction ($3\text{He} + p \rightarrow 4\text{He} + e^+ + \text{neutrino}$) in that its rate has been reduced by a factor of six. Fortunately, the flux is so low that this does not seriously affect any experiment except for the highest-energy electrons from 15 to 18.8 MeV, which come only from this hep reaction – this might be of interest only to the Kamiokande experiment which can distinguish such electron energies.

4.2 *Saclay Paper*

A general review paper [33] on the Solar Interior has been written by S. Turck-Chieze, W. Daeppen, E. Fossat, J. Provost, E. Schatzman and D. Vignaud. Preliminary results from Saclay have been presented [14,38]. The effect of varying different parameters and assumptions is studied.

New values have been adopted for several reactions (pp, $^3\text{He} - ^3\text{He}$, and $^7\text{Be}(p,\gamma)^8\text{B}$). A low iron abundance has been taken and an age of 4.49 Gyr. Neutrino rates are given for two models with different screening corrections; the rates are 5.11 and 5.68 SNU for chlorine, and 116 and 118 SNU for gallium. However, these were made using the older LAOL opacities; if one corrects by 13% and 3% respectively, as given by Bahcall and Pinsonneault [30], then values of 5.8 and 6.4 SNU are obtained for chlorine and 119 and 121 SNU for gallium.

4.3 *Nice Group*

The Nice group of P. Morel, G. Berthomieu, J. Provost and Y. Lebreton [34] have developed a code, CESAM. They vary the input to see the effects on the predictions for neutrino production and for helioseismology and give extensive tables. Their model ST3 has the low iron value, uses OPAL opacities, and for the $^7\text{Be}(p,\gamma)^8\text{B}$ reaction takes $S(0)$ as 0.021 keV.b (as ref. [8]), age = 4.6 Gyr and then gives the chlorine rate as 6.5 SNU and the gallium rate as 125 SNU. Following Bahcall [37], the chlorine rate varies as the age to the power 1.28, so changing to an age of 4.5 Gyr gives a chlorine rate of 6.3 SNU.

4.4 *Yale Paper - Helioseismology*

The Yale paper of D.B. Guenther, P. Demarque, Y.-C. Kim and M.H. Pinsonneault [6] is directed more towards the helioseismological results, which seemed to be in disagreement with the Standard Solar Model. Since the p or pressure waves reflect at the surface of the Sun, the number of shells used was greatly increased from the normal few hundred to 1800 which were equally divided between the inner 95%, the outer 5%(by radius) and the atmosphere. There were 50 intervals in time – showing the effect of greater computing power.

A Reference Solar Evolutionary Model was given and many modifications were made to it. The current ‘best’ age of the Sun is (4.52 ± 0.4) Gyr, but, for reasons of ‘decimal prejudice’, 4.5 Gyr was used. It was found possible to get reasonable agreement with the radius of $0.713 \pm 0.003 R_0$ [25] for the Convection–Radiation Zone boundary when the OPAL opacities were used with a MHD equation of state and a Debye-Huckel correction to take into account Coulomb interactions in the plasma.

What is remarkable is that agreement was obtained to $\pm 0.2\%$ with observed low l, p-mode frequencies. Previously, there was believed to be a discrepancy between the helioseismological results and the SSM, as was first pointed out by Ulrich and Rhodes [39] in 1983, and this was the Yale group’s belief still in 1991. This discrepancy was considered to indicate ‘a possibly serious flaw in our understanding of the Sun’s internal structure’. ‘It is worth noting that no single improvement in the physics, when taken individually, necessarily improves the degree of agreement’. Thus it was a large number of small improvements that removed this problem. It is possible that for the ‘Solar Neutrino Problem’ it will be the same, nothing too dramatic, just a series of improvements.

4.5 *Summary of Chlorine and Gallium Rates*

There are many calculations and many choices of parameters so that, in comparing the different models, it is not always sure that one is comparing exactly similar inputs. If one assumes low iron abundance, OPAL opacities, $S(0)$ for the ${}^7\text{Be}(p,\gamma){}^8\text{B}$ reaction of 0.020 keV.b, age of 4.5 Gyr, and no diffusion calculation, then the chlorine rate for the various models lies in the range 5.8 to 6.4 SNU. This shows that the codes are in good agreement, but for most people this does not give an error as there could still be major mistakes in the assumptions, for example in the use of screening corrections in the equation of state, in the determination of the opacity coefficients, and in the estimation of the nuclear reaction cross-sections. Still one could guesstimate the errors as about 30%, which would suggest a chlorine rate of about 6 ± 2 SNU, which is less than two standard deviations from the Chlorine experimental result. However using a higher $S(0)$ value, an age of 4.6 Gyr and a partial diffusion calculation, a value of 8.0 SNU is obtained [30].

The values found for gallium, with no diffusion calculation, lie in the range 119 to 128 SNU and extend to 132 SNU with a partial diffusion calculation [30]. The errors for gallium are less than for chlorine, probably in the range 12 to 15%, but better knowledge of the theory or entirely new experimental data is required before really meaningful errors can be quoted.

5. **The Kamiokande Water Cherenkov Experiment**

The Kamiokande experiment is run by a strong well-funded group. They do many careful calibrations and their experiment and results are fully described in refereed journals [40].

The basic process is neutrino scattering of electrons that then give a ring of Cherenkov light that is detected by arrays of photomultipliers on the walls.

In 1040 days of operation, Kamiokande II obtained some 100 events above background, ie one per 10 days. As discussed in section 2, this could be taken as being significantly below the SSM if the Bahcall and Ulrich [9] calculation with its small errors is taken, or consistent with the SSM if the Turck-Chieze et al. [8] calculation with larger errors is taken. After a long shutdown, an improved Kamiokande III has been running since January 1991 and the cold fusion cells of Steve Jones, which

initially used titanium or palladium in the centre, do not cause serious interference or loss as the detector is so large (3 000 tons of water), though this is less certain for the more recent cells using instead cement of uncertain radioactivity.

Taking SSM as the Bahcall and Ulrich [9] calculation, the Kamiokande II results for 1040 days were expressed as:

$$(\text{expt.})/(\text{SSM}) = 0.46 \pm 0.05 \pm 0.06$$

while the preliminary results [41] for 220 days of Kamiokande III are:

$$(\text{expt.})/(\text{SSM}) = 0.59 \pm 0.11 \pm 0.06.$$

This value is slightly higher than the previous result but not significantly. Further results are eagerly awaited. The SuperKamiokande detector with 32 000 tons, to be finished in about 1996, is even more eagerly awaited.

The Kamiokande data show no variation with time as has been suggested – not night/day, not time of the year, nor position in the solar cycle.

6. Extraction Experiments

6.1 Introduction

In Extraction or Radiochemical Experiments, neutrinos convert a few atoms of a large target into another element which can then be extracted chemically. The new element is radioactive and its decays can be counted in a small counter. Thus one starts with about 10^{30} atoms and has to extract a few atoms and count them in a small special counter. If the half-life of the decay is T , then the run is usually terminated for extraction after about $1.7 T$ since, after that time, the new atoms produced are comparable with the loss of atoms that have decayed before extraction.

A check that the neutrinos have interacted and the new element exists can be made in two ways – the measurement of the energy of the decay products, and the observation of the lifetime expected. Thus, for a chlorine experiment, the electron energy spectrum should show a peak at 2.82 keV and the decay spectrum should show a half-life of 35 days for ^{37}Ar above a steady background.

Extraction experiments are not easy but are sound if the decay energy and half-life are observed, and if the absolute value is calibrated by employing a powerful neutrino source.

6.2 Extraction of ^{37}Ar from Chlorine, Davis *et al.*

Since 1967 Davis and co-workers have performed a pioneering experiment by extracting ^{37}Ar atoms from a tank of 615 tons of tetrachloroethylene, C_2Cl_4 . This contains 121 or 141 tons of ^{37}Cl which is the target for the neutrinos and which is quoted as 2.3×10^{30} atoms of ^{37}Cl .

In 1970 it was appreciated that a ^{37}Ar atom decayed at a point and so gave a fast rise-time whereas a background cosmic ray track traversing the counter, gave an ionisation which was spread out producing a rise-time which was slower. The additional selection criterion of requiring a fast rise-time was so useful in reducing background that all the 1967 to 1970 data previously taken was discarded.

A typical run lasts 50 days and, after extraction, counting is done for 260 days. For the period 1970 to 1984, there were 61 runs and the data were analysed to give 339 counts of ^{37}Ar and 435 background counts [1]. This gives a raw counting rate of one count per 15 days. As the average number of raw counts is small, about 5.6 counts per run, ultra low-level statistical analysis is required and this is described by Cleveland [42] where Poisson statistics and maximum likelihood methods are required. It should be observed, however, that in the graphs published there seem to be an abnormal number of runs with zero or one count. It is important to note that, in the analysis, negative values are not allowed even though they could occur by statistical fluctuations – this could affect the result.

The neutrino rate found has always been substantially less than SSM calculations by Bahcall and co-workers which tended to be about 7.9 SNU. The main previously reported values are:

1972 upper limit [43]	<1 SNU
1970–1984 [44]	2.05 ± 0.3
1986–1988.2 [45]	3.6 ± 0.7
1986–1990 [46]	4 high periods (~ 3.6) and one low
1970–1990 [47]	2.2 ± 0.3

After the long shutdown in 1985/1986 due to pump failures, it appeared that higher results were being obtained in agreement with the Kamiokande value of about 3.6 SNU (see ref. 3a for a fuller discussion). However, the experimenters said that the long shutdown was not used to make improvements, and the long-term average over 89 runs had not changed substantially.

Recently they have added four more runs giving a total of 93 and obtained a value of:

$$1970\text{--}1991 [48] \quad 2.25 \pm 0.3 \text{ SNU.}$$

Thus, these results are in significant disagreement with the calculations of Bahcall et al. [9, 30] and with those of Turck-Chieze et al. [8, 33], but only two standard deviations from the guesstimate value of 6 ± 2 SNU proposed in section 4.5 with a 30% error. Apart from the period 1986 to 1990, they are in disagreement with the values reported by Kamiokande II and III.

If one compares, run by run, the rates given previously [47] with the new rates [48], it can be seen that the individual rates are almost all changed and are often substantially different! The number of runs with zero and one count, which was previously too high, is now reduced. Also the total number of raw counts given of 750 seemed different as it gave 8.1 raw counts per run for 93 runs to be compared with 5.6 raw counts per run for 61 runs [1]. The explanation [49] is that previously the counts were required to lie within an electron energy window of one full width at half-maximum about the centre of the electron energy peak at 2.82 keV and this gave 5.6 counts per run, while in the new analysis a much wider energy range was taken that is expected to increase the number of events by 50% (actually to 8.1 per run) – this after subtraction of background. Further, a weight was assigned to each event related to its energy relative to 2.82 keV. Clearly, it is an advantage to widen the capture range of events, but, if one widens the acceptance too much, the signal to noise ratio becomes unfavourable and one includes more background than signal. Thus it is not quite clear how one interprets statistically the number of 8.1 counts per run. While these are the main considerations in assessing the data, to obtain an absolute rate other factors such as the calibration and maintenance of the counter efficiency, exposure period, time to start of counting, cosmic ray produced background, etc. must also be considered.

The Chlorine experiment has an Achilles heel - the unusual variability of the SNU values of the runs, shown for example by the unusually high number of runs with zero SNU and also by the time variability said to be related to the inverse of the sunspot activity. It is the intention to start a new experiment using iodine which will give a substantially higher rate.

6.3 Extraction of ^{71}Ge from Gallium

The great advantage of using gallium as a target is that low-energy neutrinos can convert ^{71}Ga to ^{71}Ge and thus neutrinos from the basic pp reaction can be studied – they represent about 60% of the neutrinos reacting in gallium.

The half-life of ^{71}Ge is 11.4 days so that runs normally last about 20 days. The germanium decays by capture of an electron from an inner K, L, M, ... shell. The energy of the K shell is 10.37

keV which should be easier to measure than the 2.82 keV electrons from ^{37}Ar , but the energy of electrons from the L and M shells are 1.3 and 0.16 keV respectively. However, of the 88% of K shell captures, only 41.5% give an Auger electron of 10.37 keV while the other 46.5% go by emission of X-rays plus a low-energy electron (1.15 to 0.11 keV), which are difficult to measure.

There are two experiments using gallium. The Soviet American Gallium Experiment, SAGE, has used almost 30 tons of gallium but now uses 57 tons. The GALLEX experiment uses 30.3 tons. The gallium is present as gallium metal in SAGE, and GALLEX used a 8.13 molar aqueous solution of gallium chloride, GaCl_3 (101 tons) – the difference in the way gallium is held might be important. The SAGE experiment is in a tunnel in Baksan in Southern Russia. The GALLEX experiment is in the Gran Sasso underground laboratory shielded by 3300 metre water equivalent of rock.

6.4 *The SAGE Experiment*

The SAGE experiment had 5 acceptable runs in early 1990 whose results have been published [50]. They used a 0.7 cm^3 proportional counter for the electrons in coincidence with a NaI detector for the X-rays. However, they found that they could measure the Auger electrons from only the K shell of 10.37 keV; this means measuring only 41.5% of the decays. Taking into account all the efficiencies, they could expect to have about one event per ten days, that is about the same as Kamiokande and the Chlorine experiment. Runs lasted from 19 to 42 days and counting results have been shown for from 26 to 96 days afterwards.

The SAGE Collaboration state [50] that their best fit is 20 SNU, and the 68% and 90% confidence limits are quoted as 47 and 72 SNU respectively. They conclude that there is a major disagreement with Solar Standard Models.

In fig. 1 are shown the graphs presented [3a] for four of the five accepted runs plus a drawing of the fifth month (February) where one count was observed on the first day and no further counts were observed for the subsequent 61 days. The rate in SNU is shown for each month – it is calculated assuming there is a constant background and an exponential decay with a half-life, τ , of 11.4 days. It may be noted that there is no indication of an 11.4-day half-life; this is shown by the markers τ , 2τ , 3τ , corresponding to 11.4, 22.8 and 34.2 days respectively. The five rates are 88.8, 35.8, 0.0, 0.0, and 0.0. SNU. The analysis is basically similar to that of Cleveland [42] and in particular it appears that negative values of the rate are put to zero, thus the fact that three of the five runs are said to have 0.0 SNU indicates that these three runs have given negative rates – this would be statistical fluctuations. If one adds together the data for all five runs [3a], there is no indication of an exponential decay, in fact the data have a small negative component.

It is concluded that there is no evidence for any germanium having been observed in the SAGE counters. The question is whether this is some subtle new physics of neutrinos, or whether there is a problem in the extraction of the germanium from the gallium or in the extraction processing.

The best test of whether germanium in a charged state can be extracted by the method SAGE uses is to irradiate the gallium with a neutrino source. An attempt has been made with a 200 000 curie source but some problems and statistics did not allow a conclusion to be drawn. In the Autumn of 1993 it is planned to use a million-curie source.

Until such a test has been performed, it may be wise to reserve judgement.

In June 1992 new preliminary results from runs in 1991, called SAGE II, were presented [51]. They are all positive results, the best fit values for July, August, September, November and December being 27, 300, 48, 75 and 93 SNU respectively. It is tempting to add these values all together and derive an average of over 100 SNU, but the authors insist that one should not do so as the statistics are small so that Poisson-type analysis is required, however one can expect the full 1991 results to be available soon. These preliminary results are clearly not in contradiction with SSM predictions

Figure 1: Counts recorded in Sage I counters for the five good runs of 1990. The arrows correspond to one, two, and three half-lives, τ , of 11.4 days [3a].

Normally the SAGE Collaboration use a selection requiring a fast rise-time for the pulse in the counter (as in the Chlorine experiment), but they give a value for June 1991 separately as it was not possible to make a rise-time cut due to unstable electronics - the value found was 8 SNU. They also report that in the SAGE I experiment, in the run of May 1990, a similar situation arose and a best fit value of 79 SNU was found but with no rise-time selection. It will be recalled that the Chlorine experiment excluded all their data from 1967 to 1970 because they had no rise-time selection.

The complete set of results for 1990 and 1991 is shown in fig. 2 - this includes the May 1990 and June 1991 runs where there was no rise-time selection. The authors point out that the data are preliminary and different criteria have been used for different runs, hence they do not wish to combine data. However the overall trend is clear - in 1990 three of the five or six good runs gave 0.0 SNU, ie were negative, while in 1991 no runs gave zero SNU, so that overall the solar neutrino flux measured by SAGE appears to be increasing with time. The SAGE II results which have been presented at conferences, may be considered as being in agreement with GALLEX and with SSM values.

Figure 2: Solar Neutrino rates in SNU for the SAGE I and II experiments as a function of time. It should be noted that the runs of 1990.4 and 1991.4 should be treated with circumspection as they did not have a rise-time selection - their exclusion would make the SAGE I average lower and the SAGE II average higher [51]. After June 1991 the runs used 57 tons of gallium instead of almost 30 tons.

6.5 The Gallex Experiment

The GALLEX Collaboration started to take data in the Spring of 1991. They stated that they would not present any results until they had done all the calibrations and tests. In early June 1992 they announced [52] that they had made 14 runs in just under a year. After corrections they found the solar neutrino rate to be:

$$83 \pm 19 \pm 8 \text{ SNU.}$$

This value of roughly 83 ± 21 SNU is consistent within less than two standard deviations with most Standard Solar Models if we take them as lying between 119 and 128 SNU with errors of 10% to 15%. If one takes the highest theoretical estimate, which is that of Bahcall and Pinssoneault [30], including their diffusion calculation, and which is $132 + 21/-17$ SNU, the difference is just under two standard deviations, – certainly not enough to justify New Physics. It should be recalled that this calculation includes those types of diffusion that increase the SNU rate, but does not include Turbulent Diffusion, which may be a bigger effect, and which would reduce the SNU rate. On the other hand, if one takes the lowest value of Turck-Chieze et al. of 116 SNU, then this is 1.3 standard deviations away from the experimental value of GALLEX. Again hardly a justification to call for New Physics.

This result means that GALLEX have evidence for the first time of neutrinos from the pp reaction.

As a check on their absolute rate, the GALLEX Collaboration are intending to calibrate using a million curie neutrino source perhaps in the Autumn of 1993.

6.6 Details of the GALLEX Experiment

A reading of the GALLEX papers [52] shows that very great care has been taken with many aspects of the experiment and this great care is needed as it is a very low counting rate experiment, of the order of one real count per 5 calendar days similar to the Kamiokande, Chlorine and SAGE experiments. Some interesting points are:

- a) Counting rates – the 30.3 tons of gallium contain 12 tons of ^{71}Ga . Taking the highest SSM rate of 132 SNU would yield 1.18 atoms of ^{71}Ge per day and for a typical run of 21 days, would give 14 atoms of ^{71}Ge (allowing for decays during these 21 days). However there are many reduction factors. The K peak gives a 10.37 keV Auger electron 41.5% of the time, and the L peak gives an Auger electron of 1.2 keV in only 10.3% of the decays. The statistical error is 19 SNU for 83 SNU total which would indicate a total of 20 raw counts if there were no background. However there is background, as shown in fig. 3, where the counts are given as a function of the energy for three different decay intervals, (0 to one tau), (one to two tau) and (two to four tau) where the tau used here is the mean life of 16.49 days rather than the half-life of 11.4 days used in fig. 1. In fig. 3 the individual counts can be easily recognized. Guided by the background shape (not defined), there are about 30 to 40 raw counts of ^{71}Ge with rather more in the L peak than in the K peak. This indicates that two to three atoms of ^{71}Ge are counted per run. It is clear that one is dealing with very low statistics and fluctuations are important so that it is not wise to analyse in too much detail.
- b) The analysis is similar to that of Cleveland [42] which has the special feature that negative values of ^{71}Ge rates are put to zero. In the 14 GALLEX runs there are two zero values which is reasonable for an average of two or three counts per run.*
- c) The analysis assumes a constant background only in the initial analysis, but then adds a time-dependent background. This is to account for the problem of contamination by ^{68}Ge which has a half-life of 288 days. Before the runs began there were estimated to be some 17 million atoms of ^{68}Ge produced by cosmic rays on the surface. Long and extensive cleaning removed most but some seem to have been picked up by some trace impurity which releases the germanium slowly. The decay of ^{68}Ge can be recognized by the positrons emitted from the 68-min daughter ^{68}Ga . In six runs, eight atoms of ^{69}Ge were identified during the many months of counting after the exposure.
- d) Radon, ^{222}Ra , with a half-life of 3.8 days, is always a problem and extensive controls are used. In a typical run about three atoms of ^{222}Ra are introduced which give about one count in the ^{71}Ge acceptance "windows" in the plot of rise-time against energy. Since the radon decay chain gives three alpha and two beta decays within three hours, these can be recognized and excluded.
- e) Five blank runs (very short exposures) have been performed and a low rate obtained (actually $8 \pm 16/-8$ SNU).
- f) Some 22 counters are used and great care has been taken to make them similar.
- g) The counting of the samples is not yet finished for many runs and hence the Collaboration says that the results should be considered preliminary.
- h) In view of the low counting rate, the GALLEX Collaboration intend to continue for at least three more years which will reduce their statistical error to about 10 SNU
- i) The GALLEX Collaboration generously acknowledge the discussions with and hospitality from the SAGE Collaboration.

6.7 Conclusions on Extraction Experiments

* The authors say that fig. 2 only contains the fastest of the fast-rise counts. The total number of raw ^{71}Ge counts is then about 65 which means one such count per five calendar days.

The two gallium experiments have been in significant contradiction with one another. The Chlorine experiment is in disagreement with the Kamiokande experiment. The first conclusion must be that Extraction Experiments are more difficult than was first thought.

While the Chlorine and SAGE I experiments are both in disagreement with all published Standard Solar Models, the GALLEX result is between 1.3 and 2 standard deviations from all Solar Model calculations and SAGE II is not inconsistent with predictions. In these circumstances no definitive conclusion can be drawn at present and it would be wiser to await further results, and, in particular, to see what is found when SAGE and GALLEX calibrate with a strong neutrino source.

Figure 3 : Energy spectrum of counts in the 14 GALLEX runs during different time intervals, a) 0 to 1 tau, b) 1 to 2 tau, c) 2 to 4 tau where tau is the mean-life of 16.5 days. To facilitate comparisons a similar curve has been drawn in each figure - this curve and its use are not explained and may represent the shape (though not absolute value) of the background. d) measurements of calibration sample - the background is not the same [52].

7. Variation with Solar Cycle

The extreme variability of the results of the runs of the Chlorine experiment has led many people to suggest that there is a cyclic behaviour and that this is the inverse of the 11-year sunspot cycle. In 1987 Davis reported [2] that the correlation was a five-standard-deviation effect. This is surprising for astrophysicists as the neutrinos are produced in the Central Zone while the sunspots are generated in the Convection Zone and the time for photon information to travel across the Intermediate Zone is many orders of magnitude greater than the 11-year period of the sunspots. However, many theories have been presented involving new properties of neutrinos.

The most complete analysis has been done by Filippone and Vogel [53] who took all the data and analysed them with Poisson statistics. A best fit was obtained with a cycle of 4.5 years. They found a probability of 3.9% for a constant neutrino flux, whereas assuming an anti-correlation with the sunspot number increased the probability to only 8.3% which seems a small increase considering the extra free parameters.

The Kamiokande II and III experiments [41] do not show any variation with time and in particular not with the inverse of the sunspot number. Thus the Chlorine experiment, with its claimed five-standard-deviation variation, is in complete disagreement with the Kamiokande experiment. However, recently K. Lande [54] has said that the correlation is only about two standard deviations.

The overall conclusion is that there is no significant evidence of any variation of the solar neutrino flux with any solar cycle.

8. Future

While the Solar Neutrino Problem is quickly disappearing, it has not gone yet and more experiments with higher statistics are needed to resolve the residual issues. However a much more important issue is the question of whether the neutrinos have masses. There are many reasons for expecting neutrinos to have masses, eg to wholly or partially solve the Dark Matter mystery. Theories such as the MSW approach, are attractive though it should be appreciated that these beautiful plots of $(\delta m)^2$ versus $\sin^2 2\theta$, are only for the case of two neutrinos having a mass - if all three neutrinos had masses, this nice plot is not applicable and the analysis is very complicated. Solar neutrinos are almost the only way of studying low mass differences and major experiments are justified to search for them.

9. Conclusions

The four new Evolutionary Solar Models are in broad agreement and show that the model is robust. The SSM model is continually being improved and it is now possible, with the introduction of many more shells in the calculation, to obtain reasonable agreement with the results from helioseismology for the depth of the convective layer and for the structure of the low l, p-wave frequencies. However, there are still major uncertainties for example in some of the nuclear cross-sections, in particular for the reaction ${}^7\text{Be}(p,\gamma){}^8\text{B}$, and in the question of screening, for it must be remembered that the plasma being studied does not exist on earth so that control experiments cannot be easily performed. There are variations in the neutrino flux predicted and it is probable that the errors given on the model calculations are underestimated.

The earlier experimental results are in contradiction with later ones for the gallium experiments, SAGE I is significantly different from GALLEX and SAGE II. The Kamiokande and Chlorine experiments disagree in absolute rate and even more strongly in their variation with time.

The neutrino rates for the Chlorine and SAGE I experiments are significantly different from published SSM rates, but the SNU rate from GALLEX is in agreement with all model calculations within 1.3 to 2 standard deviations and SAGE II results are not inconsistent with SSM rates. The Kamiokande rate is consistent with some SSM calculations but not with others with surprisingly small errors.

The overall conclusion is that there is no compelling evidence for a solar neutrino problem nor for a need for New Physics.

The history of Science is full of incidents where a first pioneering experimental result was controversial and it took time for later experiments to correct.

The major question of whether neutrinos have masses can best be tackled using solar neutrinos - further major experiments are essential

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