REVIEW OF SOLAR MODELS AND SOLAR NEUTRINO EXPERIMENTS

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Abstract

The conventional wisdom is that the measured flux of neutrinos from the sun is significantly less than that calculated from the Standard Solar Model (SSM) and that New Physics is required. Furthermore, it has been suggested that the neutrino flux varies with the inverse of the sunspot activity. The SSM follows the evolution of the sun from its formation 4.6 billion years ago, from a protostar, to the present. The model touches many aspects of physics and requires many assumptions, but despite the few constraints, it is robust. However, the input data needs improvements and the errors are too small. Results from the Kamiokande, Chlorine and Gallium Experiments, which are in apparent disagreement, are reviewed and found not to be significantly inconsistent. Studies of vibrations of the sun, helioseismology, give new information. It is concluded that, at present, the theory and the various experiments are not in significant disagreement and that there is no need for New Physics.

1. Introduction: conventional wisdom

For the last 15 years it has been the conventional wisdom that there is a serious solar neutrino problem: the experimentally observed flux was much less than that predicted by the theoretical SSM [1].

Over the last 20 years Davis et al. [2] have measured the production of ^{37}Ar from ^{37}Cl in 615 t of perchloroethylene by the reaction

$$\nu + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{Ar} \ , \tag{1}$$

and have found an average rate of solar neutrinos of 2.1 SNU to be compared with the theoretical prediction [1] from the SSM of 7.9 SNU, where SNU stands for Solar Neutrino Unit = $10^{-36}\ \mathrm{s}^{-1}$ (it is a product of the neutrino flux and the theoretical cross section).

Over the last three years the Kamiokande water Cherenkov detector has measured solar neutrinos and found [3] that the ratio

$$\text{Experiment/SSM theory} = 0.46 \ . \tag{2}$$

Both the above detectors only measure higher energy neutrinos, mainly from the decay of boron-8, but new detectors employing gallium with the reaction

$$\nu + {}^{71}\mathrm{Ga} \rightarrow e^- + {}^{71}\mathrm{Ge} \tag{3}$$

can detect most neutrinos including those from the basic pp reaction. The Soviet–American Gallium Experiment (SAGE) has presented results [4] giving a best fit of 20 SNU, a 68% upper limit of 47 SNU and a 90% upper limit of 72 SNU to be compared with the theoretical SSM value of 132 SNU.

It looks like a major disagreement between three experiments and theory! However, it is necessary to consider errors before making a judgement.

If a disagreement is one or two sigma (standard deviations) then that is considered not significant. If there is a three-standard deviation effect then that is generally considered adequate for confirming an expected physical result (a famous theorist once did an experiment: he took all the three-standard deviation results he could find and then checked that after some years only half of them still stood!).

It has become a convention among many particle physicists that to prove new and unexpected physics, one needs five standard deviations.

So the question is: what are the combined errors on the SSM value and on the experiments?

Take the case of the Kamiokande Experiment which is a cleaner experiment than the two radiochemical extraction experiments since there is an important check on the events: the direction is known and only the excess of events that are pointing towards the sun are taken. The ratio (eq. 2) is

$$\text{Experiment/SSM theory} = 0.46 \pm 0.05 \pm 0.06 \ , \tag{4}$$

where the first error is statistical and the second systematic. Combining these

$$\text{Experiment/SSM theory} = 0.46 \pm 0.08 \ . \tag{5}$$

But this is only the error from the experiment, if the error on the theory was zero then the difference between theory and experiment would be

$$1.00 - (0.46 \pm 0.08) = 0.54 \pm 0.08 \ , \tag{6}$$

and would be considered significant. In the past the SSM values have been taken from Bahcall et al. [1] with an 11% error so that the difference would then be

$$(1.00 \pm 0.11) - (0.46 \pm 0.08) = 0.54 \pm 0.14 \ . \tag{7}$$

But there are many SSM model calculations and the other outstanding one is by Turck-Chieze et al. [5] who predict for the

Particle World, Vol. 3, No. 1, p. 30–39, 1992.

Chlorine Experiment 5.8 SNU with a 22% error which would give for Kamiokande

$$(1.00 \pm 0.22) - (0.70 \pm 0.12) = 0.30 \pm 0.25 \ , \tag{8}$$

which is just over one standard deviation and not significant. Thus, whether or not there is a significant disagreement, depends on which SSM model is chosen. Hence we must consider effects with errors of the order of 10%. It will be shown that there are several effects with errors of 10% or more.

Earlier versions of this work were presented at the 1990 Rochester Conference [6] and at the 1991 Lepton–Photon Symposium and Europhysics Conference on High-Energy Physics [7]. This review is by a particle physicist and is intended for particle physicists.

2. Introduction to the evolutionary SSM

For the purpose of calculating neutrino fluxes, the most useful model is an evolutionary one. An initial composition of the sun is assumed at its moment of becoming a star, that is 4.6 billion years ago. It is divided up into a large number of cells and the evolution of each cell is followed taking into account all the boundary conditions (hydrostatic equilibrium, energy transport, etc.), i.e. there are a series of bins of time as well as of space. The model is required to fit "all known data" namely the present day luminosity $L_\odot$, mass $M_\odot$, radius $R_\odot$, surface composition and age.

The sun consists of ~ 70.5% hydrogen by mass, ~ 27.5% helium and the sum of all other elements, sometimes called "heavy elements" represent 2% of the total mass.

Fortunately our sun is a main sequence star which is relatively quietly burning mainly hydrogen, so many simplifying assumptions can be made such as spherical symmetry. The five main cycles of reactions are illustrated in fig. 1. The basic problem is how does the heat produced by nuclear reactions near the centre of the sun get transferred through the sun to the outer shell. It is assumed that, as illustrated in fig. 2, the sun can be divided into three zones:

- ***core***, where the nuclear energy is produced by fusion etc., it extends to 0.3 $R_\odot$;
- ***intermediate*** (***or radiation zone***), where heat is transferred by photons, it extends from 0.3 to 0.7$R_\odot$;
- ***convection zone***, where there is convection which is assumed to be the only method of heat transfer, it extends from 0.7 to 1.0 $R_\odot$.

It is assumed that the heat is transferred in the core and radiation zones by radiation and this is controlled by a single parameter, the opacity. The opacity is a complex quantity; it is a function of the temperature and depends on the abundances of the elements at each radius.

In the convection zone it is assumed that the heat transferred can be described by a single mixing parameter.

The temperature at the present time is 15 million K at the centre, 8 at the core/radiation interface and 2 million K at the radiation/convection interface (~ 0.006 million K at the surface).

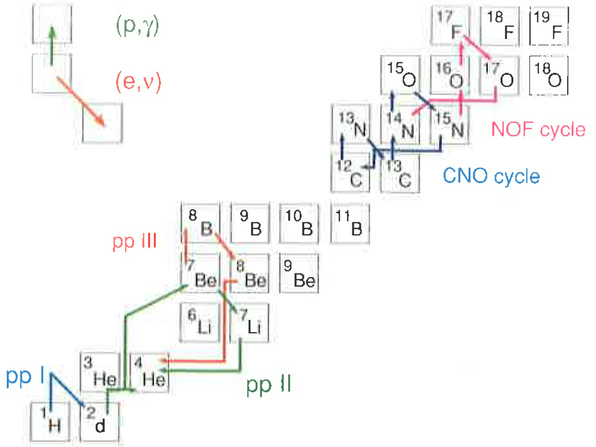

FIGURE 1

Illustration of the cycles of reactions, pp I, pp II, etc. involving the light isotopes. Upwarding going vertical lines are (p, γ) reactions and diagonally descending lines are electron capture reactions emitting neutrinos.

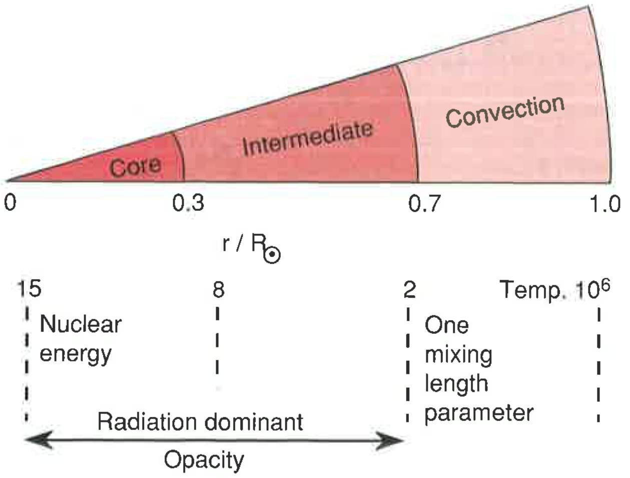

FIGURE 2

Slice of the sun showing the three zones, their characteristics, and the temperatures as a function of the fractional radius $r/R_\odot$.

3. Problems of the SSM

Evolutionary models are very complex and involve a surprisingly wide range of physics topics and necessitate input from many experiments. Here the most critical issues are evoked.

3.1 Opacity and abundance

The abundance of most elements is measured at or near the sun's surface. It is assumed that these are the same as the primordial composition of the protostar, with corrections to the lighter elements for subsequent nuclear reactions. This assumption that little has changed over the last 4.6 billion years, is checked by comparing with certain meteorites which are believed to have the composition of the solar system when it was formed. The subject is very complex and detailed [8] but finally, there is remarkably good agreement as shown in fig. 3, except in the case of iron (lithium and beryllium will be discussed later). Now iron is particularly important because in the core all the lighter elements are completely ionized but iron has kept some of its electrons; this increases the number of processes possible for heat transfer and therefore makes a considerable change to the opacity, in fact iron contributes ~ 20% to the opacity. Other heavy elements behave similarly but their abundance is much lower which is why iron is so important. The reason for the discrepancy may be that on the surface of the sun only neutral iron can be measured and this only represents ~ 5% of the total amount of iron whereas in meteorites all the iron is measured.

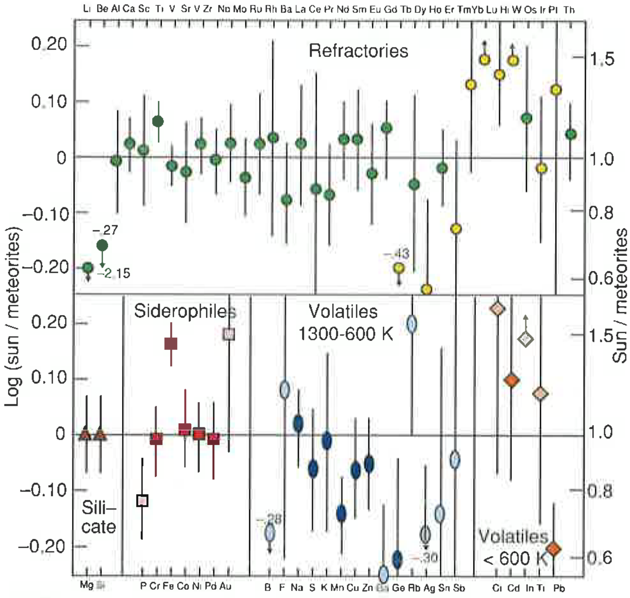

FIGURE 3

Log of the ratio of the abundance of elements as measured in the photosphere to the abundance as measured in Cl chondrite meteorites [8].

The values of the ratio of iron to hydrogen from measurements at the surface and from meteorites are $(4.68 \pm 0.33)\ 10^{-5}$ and $(3.25 \pm 0.075)\ 10^{-5}$ respectively a four-standard deviation difference. Courtaud et al. [9] have shown that by taking the value from meteorites instead of from the surface, the flux of neutrinos detectable by the Chlorine Experiment is reduced by 20%.

The neutrino flux is very sensitive to the opacity as a change in it causes the rate of heat transfer to change and hence the temperature in the core. The neutrino fluxes vary greatly with the temperature, the powers for the pp, ^{7}Be and ^{8}B neutrino sources being 4, 11.5 and 24.5 respectively [9]. However, the model has considerable stability as there is appreciable feedback. Thus, changes in the temperature are limited by the need to match the present-day luminosity of the sun.

It should be remarked that the calculations of opacity are very complex (for a start one must know all the energy levels of all isotopes) and historically these have changed significantly several times causing estimates of the neutrino flux to vary. At present large teams of people are performing these calculations again and it may well be that the opacity and hence the neutrino fluxes will vary again. Thus, Saio [10] in 1990 found the flux for chlorine to be 5.8 SNU instead of the value of 7.9 SNU given by Bahcall et al. [1,11]; he attributes the difference to using a slightly older set of opacity tables.

3.2 Nuclear-reaction cross sections

Most have been well measured but the most problematic one is

$$^7\text{Be} + p \rightarrow {}^8\text{B} + \gamma\ . \tag{9}$$

There are two problems. The first problem is that the experimental values measured are from 110 to 4000 keV while the region of astrophysical interest is below 20 keV, hence some extrapolation is necessary.

Bahcall and many other authors use the 1965 extrapolation of Tombrello et al. [12] who assumed only s state whereas it can be seen from the data shown in fig. 4(a), that a d state is also required [9] as the astrophysical S function S_{17} (E) rises steeply with energy. This extrapolation with s and d state has been made by Barker [13] and more recently by Kajino [14]. Turck-Chieze et al. [15] used this value and effectively showed that the value of 7.9 SNU of Bahcall et al. [11] should be reduced by 13% to 6.9 SNU from this cause alone.

The second major problem is that at the crucial lower energies, below 400 keV, there are only two series of experimental results and as shown in fig. 4(b), these two disagree violently, there being no overlap of the data points. Up to now, the convention has been to take the average assuming the experiments to be of equal worth. However, the 1983 experiment of Filippone is fully described in Physical Review C [16] and seems a carefully performed experiment with many corrections made, whereas the experiment of Kavanagh et al. [17] was performed much earlier in 1969 and is referred to in 12 lines of an abstract in the Bulletin of the American Physical Society so that it is difficult to judge the experiment. Now from compiling thousands of cross sections for CERN/HERA reports, we have found that, over a fourteen year period, experimental methods and corrections change appreciably so that, when there is a large discrepancy, it is normal that the later experiment has learnt from the much earlier one and in time will prove to be more accurate.

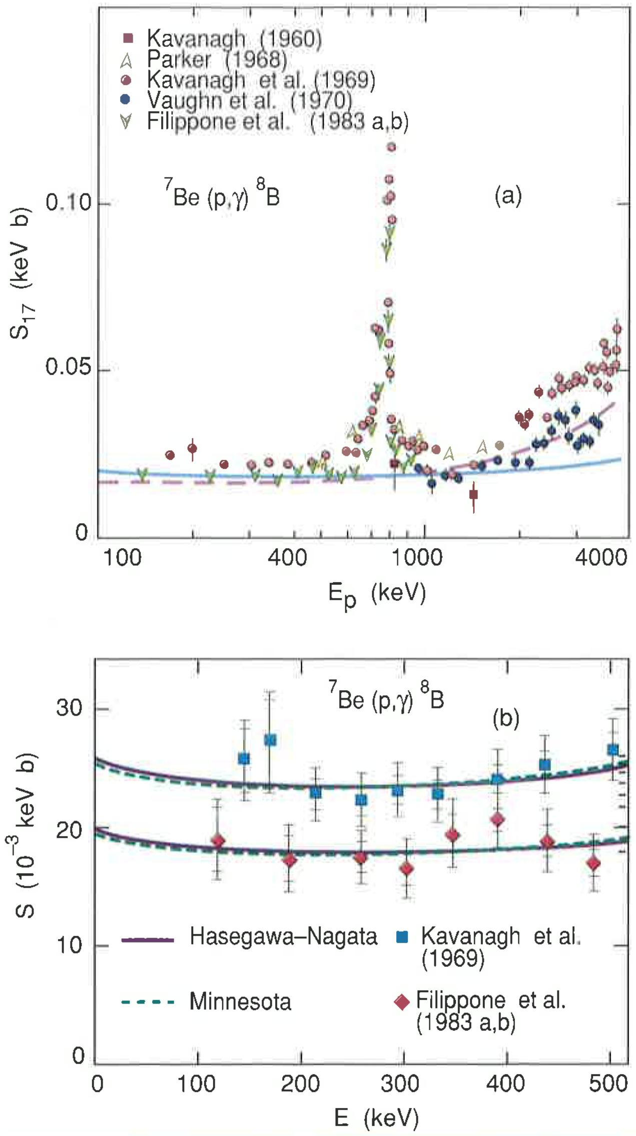

FIGURE 4(a,b)

For the reaction ^{7}Be (p, γ) ^{8}B: (a) astrophysical S factor (which is essentially the cross section with the barrier penetration factor removed) S_{17} with experimental points. The solid line is with s wave fit [12] and the dotted line is s and d waves fitted [13]; (b) S_{17} measurement below 450 keV, the Kavanagh et al. [17] and Filippone et al. [16] data are fitted separately by Johnson et al. [19] using s and d waves with two different assumptions.

Furthermore, the convention adopted in the Particle Data Group compilations [18] is to exclude data which are not reported in refereed journals. Hence only the Filippone values should be used, again lowering the cross section and hence the neutrino flux.

Recently, Johnson et al. [19] have studied "The Fate of ^{7}Be in the Sun". They conclude that it is necessary to extrapolate to $S_{17}(0)$ using s and d waves. They use other selection criteria to conclude that the Bahcall SSM neutrino flux should be reduced by 8%, whereas taking only the Filippone results and their extrapolation would lower the flux by 17% or 1.3 SNU to give 6.5 SNU. Taking two further factors into consideration (proton stopping power and ^{7}Li (d, p) ^{8}Li cross section), Barker and Spear [20] lowered the flux by 30% or 2.4 SNU to 5.5 SNU. As the 1982 Bahcall value [21] was 19% higher than his 1988 value, it may be seen that the uncertainty is large.

Thus, the situation is very unsatisfactory and it would be good if one or more experiments be performed to measure this important and controversial cross section.

It should be noted that the measurements are not easy since as shown in fig. 4(c), the cross section falls very steeply with energy and is only 3 nb at the lowest energy reached of 117 keV.

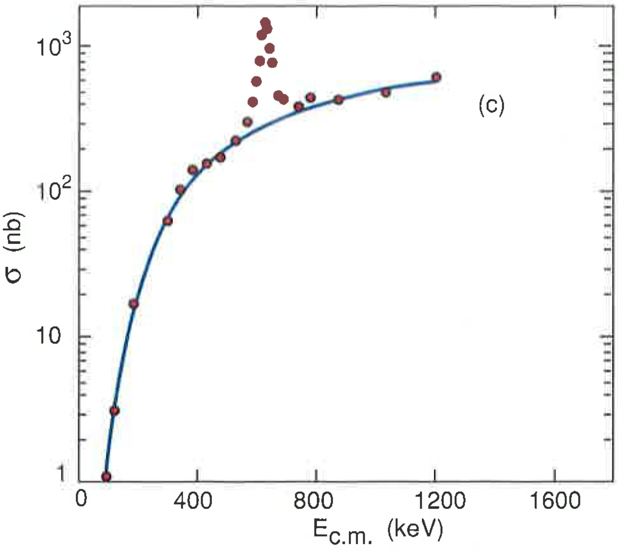

FIGURE 4(c)

Cross section for the reaction ^{7}Be (p, γ) ^{8}B.

A further point should be made: since the two experiments disagree substantially, the error taken on the average should be large enough to take this into account, but it seems "typical" errors, which are smaller than averaged errors, have sometimes been taken. To take an extreme example, if one value is 30 ± 1 and the other 10 ± 1 then taking a "typical" error would give 20 ± 1 while a more conventional averaging is closer to 20 ± 10 ± 1. This needs careful checking.

Thus, the theoretical neutrino flux should be appreciably reduced and the errors increased.

3.3 Other SSM experimental problems

It has been said that the SSM should fit ALL data. However, it may be pointed out that there are some other problems:

- the abundance of ^{7}Li at the surface is 1% of that calculated,
- the abundance of ^{9}Be at the surface is half of that calculated,
- the abundance of ^{3}He has a small excess over that calculated,
- a helioseismology result [22] is in 8 sigma disagreement with the calculation of Bahcall et al. [11].

It is interesting to note that ^{7}Li and ^{9}Be burn at temperatures of 2.5 and 3.5 million K which is just inside the radiation zone. Lebreton and Maeder [23] have suggested that there is appreciable diffusion in the convection zone and there is "overshooting" into the radiation zone; this would allow the ^{7}Li and ^{9}Be to burn and would also explain the small ^{3}He excess as it is produced in the radiation zone.

3.4 Assumptions in the SSM

Among the main assumptions are: no rotation, no magnetic field, no diffusion (neither turbulent or steady state), no overshooting, no hydrodynamic convection, but spherical symmetry.

- **Rotation:** the sun rotates in 25 days at the equator and 35 days near its poles. When the sun was born from the large cloud of the protostar, it was probably like a T Tauri with a disk; so it was then a fast rotator and would accrete from its disk. This would burn up ^{7}Li. It would slow down losing angular momentum with its solar wind (the solar wind is now very small, E^{-14} $M_{\odot}$ per year). Thus, there is some small amount of residual rotation whose proportion inside the sun is unknown though probably small.

- **Magnetic field:** there exists a magnetic field which is evidenced by the sunspots observed. The solar dynamo is complex and non-linear.

- **Diffusion:** as explained above, diffusion can explain the ^{7}Li and ^{9}Be disagreements with the SSM. The amount of diffusion in recent eons can be tested by studying ^{3}He; it is created in the radiation zone and burnt in the core zone so that it is expected to have a maximum at a radius of 0.3 $R_{\odot}$. If there were appreciable diffusion in the radiation zone then the amount of ^{3}He at the surface would be much bigger.

- **Overshooting:** in general boundaries between zones are not sharp as assumed, and evidence for this is given above.

- **Calculations in the convection zone:** due to the small number of pieces of input data used, the SSM can assume only one mixing parameter for the convection zone although there are many complex factors operating in the convection zone, such as the giant cells and small ones, the tubes of magnetic flux, etc.

4. Helioseismology

The sun is a resonant cavity with some ten million modes of which several hundred thousand have been measured. At present they are best observed as acoustic *p* waves, where *p* stands for pressure with a five minute period, which are measured to one part in ten thousand (later it is expected that the g waves, where g stands for gravity, will be very useful).

With these very accurate measurements [24], it is possible to do inversion calculations which allow the pressure and temperature to be established at different radii. These calculations give a lower central temperature than the SSM. This type of work is very recent and clearly will become more and more important as it gives a totally independent way of studying the sun. However, it is sometimes wise to wait until a field matures, so the helioseismology results have not been used in this comparison of theoretical calculations and experiment.

5. Many SSM calculations

There is a tendency in the particle physics community to consider that there is only one evolutionary model calculation and this is called the SSM calculation, but in fact there are many evolutionary model calculations. Of these two are outstanding:

(a) Bahcall and co-workers [1,11];
(b) the French–Belgian Collaboration of Turck-Chieze et al. [5].

Although these calculations were initially independent, they agree very well, e.g. some respective values are:

	Bahcall	Turck-Chieze	
Central temperature	1.56	1.55	E^{7} K
Central density	148	147.2	g cm^{-3}
Central pressure	2.29	2.27	E^{17} dynes s^{-1}
Gallium neutrino rate	132	125	SNU
But ^{37}Cl neutrino rate	7.9	5.8	SNU
with one sigma errors	0.87	1.3	SNU
or as percent	11%	22%	

From all the preceeding discussions, it is clear that the estimate of the neutrino flux for chlorine and its error, using an evolutionary model needs some reevaluation. After applying the modifications discussed above, it may be estimated that both of these SSM calculations give values that are close to 5 SNU and the errors on the ^{37}Cl rate are ~ 30% or more. However, it is important that a new full calculation be done to give a more precise estimate, though it is likely that the error will always be a guesstimate because of the many uncertainties and approximations. It will be noted that this value of 5 ± 1.5 SNU is less than one standard deviation from the Kamiokande value.

6. Experiments

The experiments are of two types. Firstly, the observation of Cherenkov light by arrays of photomultipliers from electrons which are scattered forwards by neutrinos. Secondly, extraction or radiochemical experiments where neutrinos convert a few atoms of the target to another element and these atoms are extracted and their decays are counted.

6.1 Water Cherenkov detector — Kamiokande

The Kamiokande Experiment is run by a large powerful, well-funded group. They do many careful calibrations and their experiment and results are well and fully described.

The basic process is neutrino scattering of electrons which then give Cherenkov light which they detect.

The most important point about their experiment is that they measure TWO quantities at the same time; firstly a count and secondly the direction of the electron relative to the sun's direction. A clear peak can be seen in fig. 5 in the direction of the sun and the excess in that direction is then taken as coming from solar neutrinos. If they did not have that directional measurement, then their experiment would not be useful.

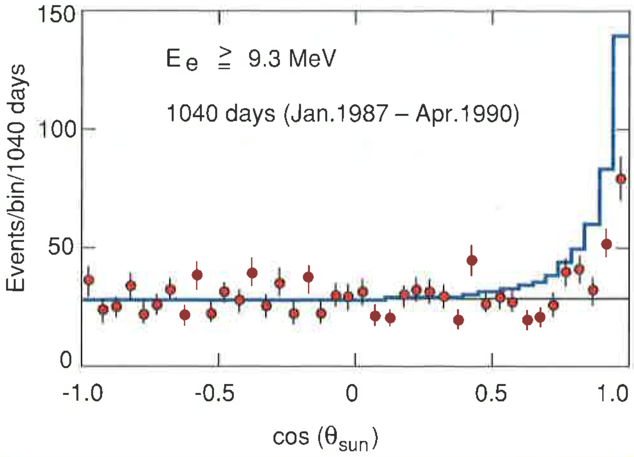

FIGURE 5

Counts of the Kamiokande detector plotted against the angle of the electron to the sun's direction [3].

Assuming the value of 5 ± 1.5 SNU, then their measurements are less than one standard deviation from the theoretical value.

It should be noted that in their 1040 days of operation as Kamiokande II, they counted an excess of ~ 100 events (with corrections this becomes about the 165 counts shown in the plots). This implies that they count about one event per 10 days or 35 events per year. It is intended to increase this counting rate by building the SuperKamiokande detector which will have a total mass of water of 32 000 t instead of the 3000 t now. Kamiokande III is now taking data and the cold fusion cells of Steve Jones et al. near the centre do not seriously affect the performance as the volume is so large.

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

Since 1967 Davis and co-workers performed a pioneering experiment by extracting ^{37}Ar from a tank of 615 t of tetrachloroethylene C_2Cl_4. This contains some 121 or 141 tons of ^{37}Cl quoted as 2.3×10^{30} atoms of ^{37}Cl.

The ^{37}Ar decays by electron capture. The hole in the K shell can give an Auger electron of 2.8 keV. The counter of 0.5 cm^3 volume is designed to measure this electron. The half-life of the decay is 35 days.

There are two crucial dates in this experiment begun in 1967:

(a) In 1970, it was decided to use the rise time of the pulse as it should be shorter for a decay which is localized in the counter, than for a traversing cosmic ray background particle. The data before 1970 were subsequently not used.

(b) For one and a half years in 1985–1986, the two pumps had broken down and measurements were stopped until new pumps could be installed.

A typical run lasts 50 days and after extraction the counting is continued for 260 days. For the period 1970 to 1984, the data were analyzed to give 339 counts of ^{37}Ar and 435 background counts [25], this gives an ^{37}Ar uncorrected counting rate of one per 15 days or 24 counts per year for this period, comparable with Kamiokande.

As this gives ~ 5 counts per run on average, ultra-low level statistical analysis is required and this is described by Cleveland [26] where Poisson statistics and maximum likelihood methods are required. It should, however, be observed that in the graphs published there seem to be an abnormal number of runs with zero or one count. It should be noted that in the method of analysis negative values are not allowed and since these could easily occur by statistical fluctuations, this could affect the result.

Now a major point made earlier was that counts alone are not convincing, it is better to have a second measurement. In the case of chlorine this could be the observation of a decay half-life of 35 days characteristic of ^{37}Ar.

When the Kamiokande II data were presented in five intervals of time, it can be seen in fig. 6 that there was excellent agreement with the Chlorine Experiment for four of the five intervals. If one takes the first two intervals, chlorine runs 92 to 100 (i.e. from 1987.0 to 1988.4), then the Chlorine Experiment found a rate of 3.6 SNU, in agreement with Kamiokande [25] and furthermore the time distribution of the decays [27] shown in fig. 7(a), gives a half-life of the order of 35 days. However, the low interval of the

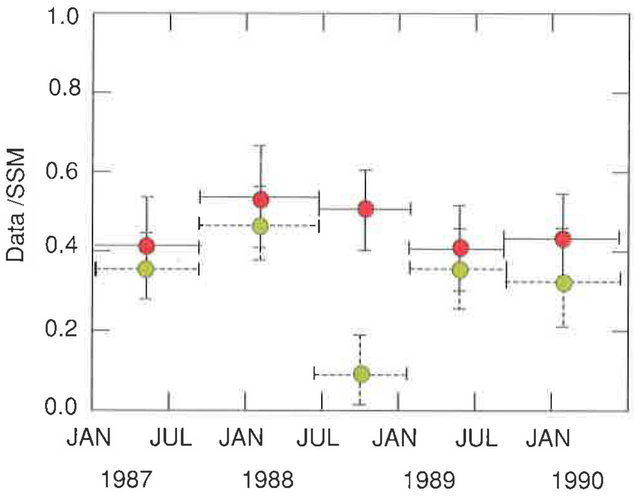

FIGURE 6

Time variation of the ratio of the neutrino counting rate to a SSM value [11] for Kamiokande II (red) and for the Chlorine Experiment (green) from ref. [31]

Chlorine Experiment is runs 101 to 104; the time distribution for these four runs is not available, but it is for the 5 runs 101 to 105 and as can be seen in fig. 7(b), this shows rather a longer half-life. This would seem to suggest that when a 35-day half-life is observed, a neutrino rate equal to that observed by Kamiokande is found, but when this important 35-day indicator is absent, a very low counting rate is observed.

This important consideration should be checked by grouping runs over one to two year periods to see if the 35 day half-life is observed. Similar analysis can be made using the 2.8 keV peak expected in the energy spectrum and this is clearly observed [27] for the combined runs 92 to 100 but very much less for the runs 101 to 105 (note run 105 has a high flux).

It is interesting to compare the Chlorine results for various time intervals with possible expected values:

Proposed SSM value	5 ± 1.5 SNU
Kamiokande value, approx. [25]	0.46 × 7.9 = 3.6 ± 0.6 SNU

Reported Chlorine results:

1972 upper limit [28]	< 1 SNU
1970–1984 [29]	2.05 ± 0.3
1986–1988.2 [30]	3.6 ± 0.7
1987.0–1990 [3]	4 high periods (~ 3.6 SNU) and one low

(note that if one takes the whole period 1970 to 1990, the average is only 2.3 ± 0.3 SNU and this conceals the possible step up at 1986 when the experiment was restarted).

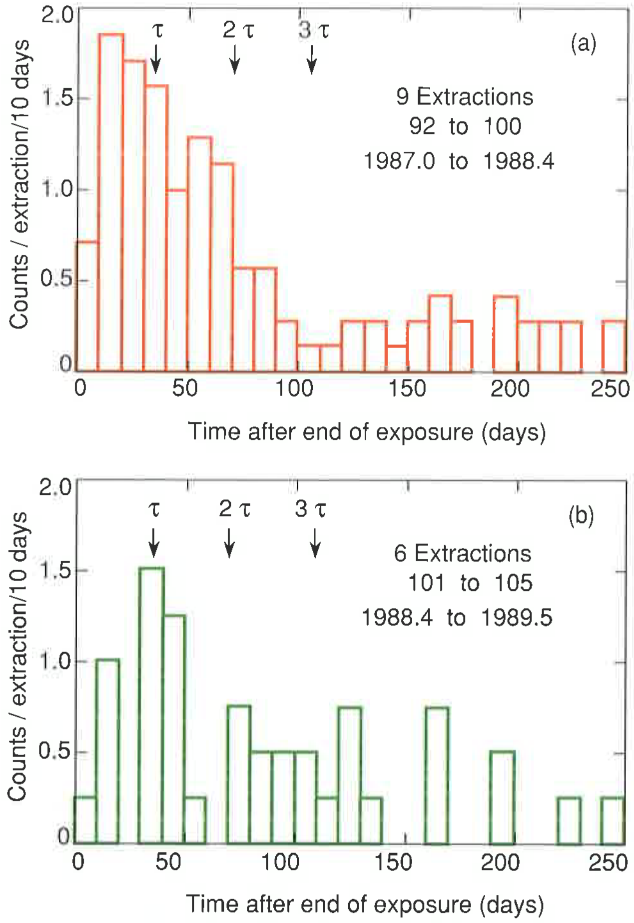

FIGURE 7

Counts in the Chlorine Experiment [27]: (a) for period 1987.0 to 1988.4; (b) for period 1988.4 to 1989.5.

Possible conclusions are:

(a) Until the pump failure, the rate was low, 2.05 SNU. After the restart, the rate was high (3.6 SNU) except when the 35 day half-life was not clearly observed. It would be interesting to know if during the 18-month wait until the new pumps were available, whether the physicists used the time to improve the counters or other parts of the experiment.

(b) It is suggested that results of counts should only be published when that set of counts shows clear evidence of a 35-day decay half-life.

6.3 Gallium Experiments

There is a tremendous advantage in using gallium as a target for the solar neutrinos in that low-energy neutrinos can also convert the ^{71}Ga to ^{71}Ge. With the Kamiokande and Chlorine

Experiments only the higher-energy neutrinos can be detected and they come from rare processes that are peripheral to the main pp fusion reaction that gives most of the solar neutrinos. Hence the argument is often used that by measuring with gallium the basic mechanism of the sun's burning is being tested and any disagreement with theory would be much more serious than a disagreement observed in a peripheral process. There are two large Gallium Collaborations: the SAGE, at Baksan, USSR and the Gallex Collaboration which is installed in the Gran Sasso tunnel, Italy. Both had 30 t of gallium; the SAGE Experiment has now started running with 60 t. The SAGE Collaboration uses the gallium as a metal while Gallex has it as a chloride $GaCl_3$; this implies different extraction procedures.

The ^{71}Ge decays by capture of an electron from an inner K, L, ... shell. The half-life is 11.4 days. The energy of the K shell is 10.37 keV which should be easy to measure, but it is much less for the L and M shells, being 1.3 and 0.16 keV respectively. However, of the 88% captures that go by the K shell, only 41.5% give an Auger electron while the other 46.5% go by emission of X-rays plus a low-energy (1.12 to 0.11 keV) Auger electron which are difficult to detect.

(a) The SAGE Experiment

The SAGE Experiment uses a 0.7 cm^3 proportional counter and a NaI detector in coincidence for the X-rays. However, they say that they can only measure the Auger electrons of 10.37 keV from the K shell; this means they are only measuring 41.5% of possible decays. Taking into account the extraction efficiency, counter efficiencies and ^{71}Ge atoms decaying before being extracted, the counting rate should be about one event per 10 days, that is about the same as for the Kamiokande and the Chlorine Experiments.

Runs lasted from 19 to 42 days and counting results have been shown for 26 to 96 days after. The five runs made in 1989 were rejected (the December run because a four-day half-life was observed corresponding to radon). Of the 1990 runs, five were accepted and three rejected.

In fig. 8 are shown the graphs presented [4] for four of the five accepted months and a drawing of the other month where one count was observed on the first day and then no further counts were recorded. The number of SNU for each month is given (the total gives 20 SNU quoted in sect. 1), it is calculated on the assumption that 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 such a 11.4 day half-life; this is shown by the markers τ, 2τ and 3τ for 11.4, 22.8 and 34.2 days. If one adds the data for all five months together, there is no indication of an exponential decay, in fact the data have a small negative component.

The major worry is that the few atoms of germanium produced are lost in the long extraction process. If this were so, then one might expect by statistical fluctuations some positive and some negative SNU values, however, since the program considers negative values to be unphysical and these are put to zero SNU, what one should expect would be equal numbers of zero and positive values giving finally a small positive result and this is what is observed. An attempt has been made to test directly if germanium is lost or reaches the counter by bringing a 200 000 curies neutrino source to the gallium, but was unsuccessful. It is intended in the Fall of 1992 to take a stronger source, one million curies, whose neutrinos will irradiate the gallium and the resultant germanium will be extracted and counted. This is a crucial test and it is wiser to wait for this result before drawing conclusions.

(b) The Gallex Experiment

The Gallex Collaboration has now started to take data in the Gran Sasso tunnel. They say they will not announce any results until they have done all calibrations and tests.

(c) Possible conclusion

As for the Chlorine Experiment, it is suggested that results only be presented when sufficient statistics have been accumulated to confirm that the counts come from ^{71}Ge, for example by observing the 11.4 day half-life.

7. Solar cycles

The variability of the rates from runs of the Chlorine Experiment has been noted by several authors who suggest that there is a correlation with solar cycles.

The most complete investigation of this question has been that reported by Filippone and Vogel [31] who took all the data, not a selected sample, and analyzed them with Poisson statistics as befits low statistical data. They found the best fit was obtained with a cycle of 4.5 years. However, the most popular fit suggested is with the inverse of the sunspot activity. They found a probability of 3.9% for a constant flux while assuming there was also a correlation with $(\text{sunspot number})^{-1}$ increased the probability to only 8.3% which seems a small increase considering the extra free parameters.

When the chlorine results are taken for the period after the restart in 1987, no significant effect is seen if one excludes the one bin during which no 35-day half-life was observed.

It is suggested that no conclusion on any possible correlation be drawn until the runs have been grouped to show the 35-day half-life. The Kamiokande II Experiment does not show [4] any fluctuations during a period when the sunspot activity was varying sharply. Further dividing the data into night and day, or by seasons, as has been suggested, also does not show any significant variation. The new Kamiokande III data confirm the absence of any variation with sunspot activity and the results for the combined data is shown in fig. 9.

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

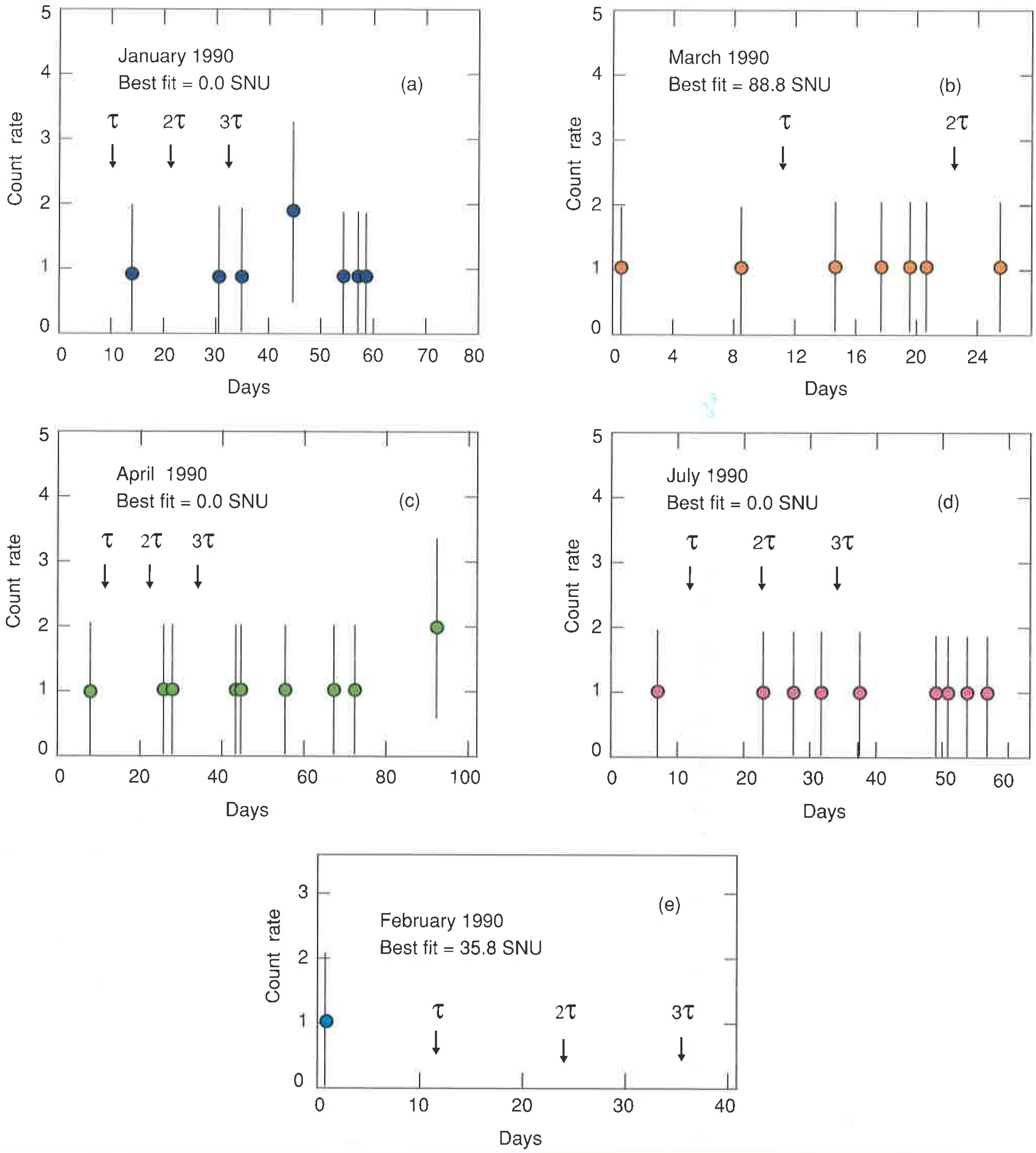

FIGURE 8

Counts recorded by the SAGE collaboration [4] during their five runs in 1990. The arrows correspond to one, two and three half-lifes τ.

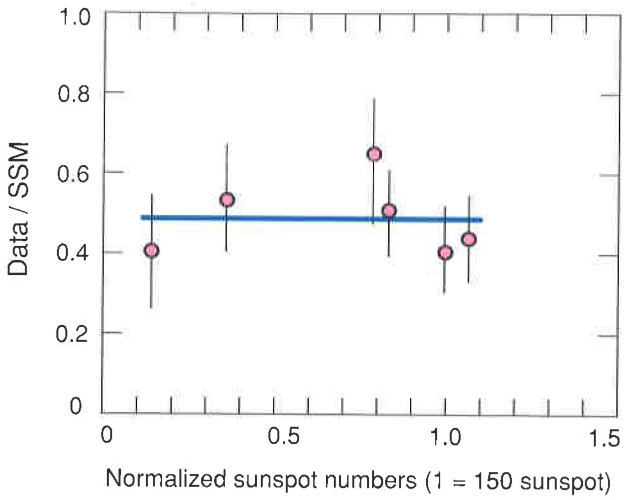

FIGURE 9

Ratio of the Kamiokande data to the SSM calculation of Bahcall and Ulrich [11] plotted against the sunspot number normalized to give 150 sunspots = 1.00.

8. Conclusions

The evolutionary (SSM) makes a number of assumptions, has many input values which have and should change appreciably giving lower SNU values; however, the model is robust and broadly satisfactory. The overall conclusions are that solar neutrinos have been measured and that the rate for higher-energy neutrinos is in agreement with evolutionary model calculations. Definitive results for lower-energy neutrinos are awaited. There is no significant evidence that could, at the present time, be interpreted as requiring New Physics.

The sun is the only star near us and it is a tremendous laboratory that is vital for understanding stellar evolution. It is important that a wide variety of experiments be performed to study the sun.

References

[1] J.N. Bahcall, Review talk to Neutrino '90 Conf., CERN (June 1990);
J.N. Bahcall, Scientific American (1990) 26–33.
[2] R. Davis, Workshop on Neutrino Telescopes, ed. M. Baldo-Ceolin, Palazzo Loredan, Venice (1990) 1–13.
[3] M. Mori, Workshop on Neutrino Telescopes, ed. M. Baldo-Ceolin, Palazzo Loredan, Venice (1991) 61–72;
K.S. Hirata, KEK preprint 90–43 (1990).
[4] V.N. Gavrin, Int. Conf. on High-Energy Phys., Singapore (Aug. 1990);
V.N. Gavrin, Workshop on Neutrino Telescopes, ed. M. Baldo-Ceolin, Palazzo Loredan, Venice (1991) 1–10.
[5] S. Turck-Chieze et al., Astrophys. J. 335 (1988) 415–424.
[6] D.R.O. Morrison, Int. Conf. on High-Energy Phys., Singapore, eds K.K. Phua and Y. Yamaguchi (1990) 676–680.
[7] D.R.O. Morrison, CERN/PPE 91–104 (1991).
[8] E. Anders and N. Grevesse, Geochim. Cosmochim. Acta 53 (1989) 197.
[9] D. Courtaud et al., Solar Phys. 128 (1990) 49–60.
[10] H. Saio, 4th Workshop on Elementary Particle Picture of the Universe, Tateyama, Japan (1989).
[11] J.N. Bahcall and R.K. Ulrich, Rev. Mod. Phys. 60 (1989) 297–372.
[12] T.A. Tombrello et al., Nucl. Phys. 71 (1965) 459–464.
[13] F.C. Barker, Aust. J. of Phys. 33 (1980) 177;
F.C. Barker, Phys. Rev. 28 (1983) 1400.
[14] T. Kajino et al., to be publ. in Supl. J. Phys. Soc., Japan (1990).
[15] S. Turck-Chieze, Inside the Sun, eds G. Berthomieu and M. Cribier, Kluwer Acad. Publ., Dordrecht (1989) 125–132.
[16] B.W. Filippone et al., Phys. Rev. Lett. 50 (1983) 412;
B.W. Filippone et al., Phys. Rev. C28 (1983) 2222.
[17] R.W. Kavanagh et al., Bull. Am. Phys. Soc. 14 (1969) 1209.
[18] Particle Data Group, Phys. Lett. B239 (1990) 1–516.
[19] C.W. Johnson et al., Caltech Report MAP–140 (Nov. 1991) submitted to Astrophys. J.
[20] F.C. Barker and R.H. Spear, Astrophys. J. 307 (1986) 847.
[21] J.N. Bahcall et al., Rev. Mod. Phys. 54 (1982) 767.
[22] Y. Elsworth et al., Nature 345 (1990) 536.
[23] Y. Lebreton and A. Maeder, Astron. Astrophys. 175 (1987) 99.
[24] K.G. Libbrecht and M.F. Woodward, Nature 345 (1990) 779.
[25] J.N. Bahcall, Neutrino Astrophysics, CUP, Cambridge (1989).
[26] B.T. Cleveland, Nucl. Inst. and Meth. 214 (1983) 451.
[27] K. Landy, talk given at Neutrino '90 Conference (1990).
[28] J.N. Bahcall, Comments on particle physics (1972) 59;
R. Davis Jr, A progress report on the Brookhaven solar neutrino experiment, abstract of an invited paper for the Washington Meeting of the APS (1972).
[29] Same as ref. [25] p. 319.
[30] Same as ref. [25] p. 338.
[31] B.W. Filippone and P. Vogel, Phys. Lett. B246 (1990) 546;
P. Vogel, Workshop on Neutrino Telescopes, ed. M. Baldo-Ceolin, Palazzo Loredan, Venice (1991) 23–32.

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Received on December 1991.