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# The Lost Neutrinos of the Sun

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*Abstract*

For the past decade there has been a discrepancy between the number of solar electron neutrinos predicted and observed. This paper discusses the magnitude of this discrepancy and the various ways by which the problem might be resolved.

## Introduction

Since 1939 when Bethe first proposed the varying reactions of the stellar hydrogen and CNO cycles, physicists have felt that they have understood the heat generation processes taking place in the core of the Sun. Though the photosphere is only at a temperature of 6000 K, the temperature of the inner core is probably as high as $10^7$ K, and is maintained by fusion heating, with radiative and convective regions connecting the inside to the outside visible surface. Because the mean free path of the emitted photons is small compared with the solar radius, no direct radiation can be observed on Earth to give information about the state of the inner regions, and one has to rely on neutrinos as the only direct messengers from the core. The most likely reactions giving rise to this heating in our Sun are summarized in Table 1.

The fluxes listed in Table 1 represent the latest estimates (Bahcall 1980) using the most recent Los Alamos values for solar opacity (Huebner 1978). It can be seen from the table that the produced neutrinos fall roughly into two categories: (1) those of low energy with high flux, and (2) those of high energy with much lower flux. Every time this chain of reactions proceeds, four protons are effectively converted to an $\alpha$ particle, two positrons and two neutrinos with the release of about 25 MeV of energy. The energy spectra of these neutrinos are shown in Fig. 1.

The only experiment to actually run and take data in this field is the well-known experiment of Davis and his collaborators (Davis 1964, 1978) located in the Homestake gold mine in South Dakota (4400 m.w.e. underground). His experiment seeks to examine the amount of $^{37}$Ar produced in a tank of 610 tons ($\sim 6\cdot 2\times 10^5$ kg) of perchloroethylene ($C_2Cl_4$) when solar neutrinos instigate the inverse $\beta$ reaction

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^- .$$

The experiment is indirect in that the amount of argon present is determined after runs lasting some 30–100 days. The produced argon is flushed out and removed chemically; it is detected by observing the ensuing electron capture (half-life 32 days) with low background miniature proportional counters which observe the resulting Auger electrons and X rays.

**Table 1. Details of solar hydrogen cycle calculated from standard solar model**

| Solar reaction | Probability (%) | Maximum neutrino energy (MeV) | Flux at Earth's surface ($cm^{-2} s^{-1}$) |
|---|---|---|---|
| $p+p \rightarrow {}^2H+e^++\nu_e$ | 99·75 | 0·42 | $6{\cdot}1\times 10^{10}$ |
| $p+e^-+p \rightarrow {}^2H+\nu_e$ | 0·25 | 1·44 (line) | $1{\cdot}5\times 10^{8}$ |
| ${}^2H+p \rightarrow {}^3H+\gamma$ | — | — | — |
| ${}^3He+{}^3He \rightarrow {}^4He+2p$ | 86·00 | — | — |
| ${}^3He+{}^4He \rightarrow {}^7Be+\gamma$ | 14·00 | — | — |
| ${}^7Be+e^- \rightarrow {}^7Li+\nu_e$ | — | 0·86 (90%, line)<br>0·38 (10%, line) | $4{\cdot}1\times 10^{9}$ |
| ${}^7Li+p \rightarrow {}^4He+{}^4He$ | 99·98 | — | — |
| ${}^7Be+p \rightarrow {}^8B+\gamma$ | 0·02 | — | — |
| ${}^8B \rightarrow {}^8Be^*+e^++\nu_e$ | — | 14·06 | $5{\cdot}85\times 10^{6}$ |
| ${}^8Be^* \rightarrow {}^4He+{}^4He$ | — | — | — |

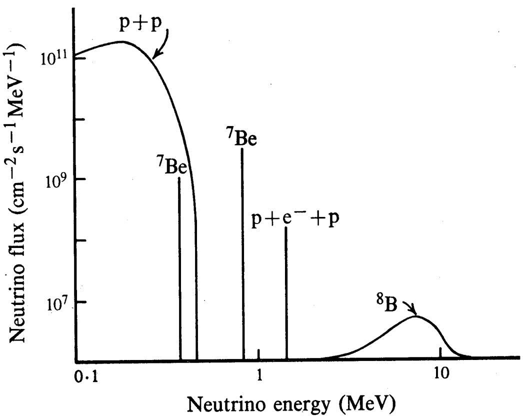


**Fig. 1.** Predicted energy spectra for electron neutrinos emitted by the Sun. The predictions are made using the latest standard model for the heating of the Sun's interior.

Table 2 shows the latest Davis results together with the predictions from the current standard model when applied to that particular experiment. As can be seen, there is a discrepancy of at least a factor of 3–4 between the predicted and observed values—this discrepancy constitutes the 'solar neutrino problem' which has stayed with us for at least a decade, and which has stubbornly refused to be resolved in spite of very careful measurements by Davis and his collaborators and increasingly precise calculations by the theorists. It is interesting to note that this dearth of neutrinos is the only area where the standard solar model does not work well. We now proceed to discuss various possibilities to explain this discrepancy.

## Variations of Standard Solar Model

From Table 2 it can be seen that the Davis experiment is mostly sensitive to the high energy $^8B$ neutrinos. As the number of these high energy neutrinos varies roughly as $T^{13}$, one wonders whether in fact there is a discrepancy at all. The theoretical estimate could be reduced by the required factor of $3{\cdot}5$ by changing the temperature by as little as 10%. However, this poses considerable difficulties for any solar model in producing the mass and luminosity and the observed spectral composition of the surface, all quantities which are known to great accuracy.

Bahcall and Ulrich (1971) have developed a model in which the distribution of heavy element abundance is at least a factor of 10 less than the observed surface abundance (the radial dependence of this abundance is not known but is usually assumed to be constant at the surface value). This model gives them a result for the neutrino production rate of 1·5 SNU which they see as being the lowest possible value consistent with standard ideas of stellar evolution. Consequently, one possibility is that the inner core of the Sun has an abundance of heavy elements radically lower than assumed to date—surely an important conclusion if verified.

It should be noted that any admixture of the CNO cycle only increases the predicted number of high energy neutrinos (to 28 SNU if solely CNO); consequently it is normally neglected for any treatments of solar behaviour.

**Table 2. Comparison between expected and observed neutrino capture rates for Davis experiment**

1 solar neutrino unit (SNU) $\equiv 10^{-36}$ captures per target atom per second

| Theoretical | | Experimental | |
|---|---|---|---|
| Neutrino source | Neutrino capture rate (SNU) | Argon source | Argon production rate (atoms day$^{-1}$) |
| p+p | 0 | | |
| $^{8}$B | 6 | Measured | $0 \cdot 50 \pm 0 \cdot 06$ |
| p+e$^{-}$+p | 0·2 | | |
| $^{7}$Be | 1 | Background | $0 \cdot 18 \pm 0 \cdot 09$ |
| Other | 0·3 | | |
| Total predicted rate (SNU) | 7·5 | Total experimental rate (SNU) | $2 \cdot 2 \pm 0 \cdot 4$ |

## Davis Experiment

The second possibility is that, for some reason hitherto unsuspected, the Davis experiment is only partially efficient in the detection of the neutrinos. This seems most unlikely, however, in view of the considerable program of tests carried out by Davis and his collaborators:

(1) They have measured the background at various depths and extrapolated to their present operating position.

(2) They have checked their ability to retrieve produced argon atoms by injecting known amounts of $^{36}$Ar and $^{38}$Ar into the tank and then determining the final amount separated. With this technique, they find an efficiency of about 95%.

(3) They have observed carefully the chemistry of perchloroethylene molecules labelled with $^{36}$Cl (half-life 308 000 yr). They have studied the yield of $^{36}$Ar by neutron activation and found an efficiency of essentially 100% within errors. Thus it seems fairly clear that any argon atom produced in the molecule will eventually end up as a free neutral argon atom.

As a result of this most impressive procedure, it seems most likely that the Davis results are real and above background; though it is of paramount importance for other experiments using different techniques (direct and indirect), measuring high and low energy neutrinos, to verify the result.

## Neutrino Oscillations

There has been a considerable amount of speculation recently that neutrinos can oscillate between species in a manner somewhat similar to the $K^0$–$\bar{K}^0$ system. We know that there are at least the three types of neutrino $\nu_e$, $\nu_\mu$ and $\nu_\tau$, together with their antiparticles, and the possibility exists that these types are not forever separated. This speculation has been supported by recent results from both the U.S.A. and the Soviet Union. F. Reines and his collaborators reported in April to the Washington, D.C., meeting of the American Physical Society results suggesting that electron antineutrinos do not always remain as such. They compared the charged and neutral current reactions

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

The first reaction producing two neutrons is only possible for electron-type neutrinos ($\mu^+$ and $\tau^+$ being too heavy for production). However, the second neutral current channel producing only one neutron is open for neutrinos of all types. Measuring with a 268 kg detector of heavy water at 11·2 m from the Savannah River reactor, they find many fewer reactions of the first kind than expected, which suggests that some of the antineutrinos are changing from the electron type in transit. Their value of the ratio of experiment to conventional theory is $0 \cdot 43 \pm 0 \cdot 17$ or a 3·3 standard deviation effect. For this result to be convincing, however, one needs to take many such observations at different separations to actually observe the oscillations.

Further support for this possibility comes from V. Lyubimov and his team at the Moscow Institute of Theoretical and Experimental Physics, who claim to be able to assign a mass to the electron neutrino of a few tens of electron volts after a close inspection of the spectrum of tritium decay. The previous mass limit for electron neutrinos was around 60 eV. As at least one of the neutrino types is required to be massive to allow oscillations, this result is seen as consistent with the Reines experiment.

The oscillation length $l$ (m) for neutrinos of energy $E$ (MeV) changing between species $j$ and $k$ is given by (Primakoff 1978)

$$l_{kj} = 2 \cdot 5(\mathrm{m}) \times E(\mathrm{MeV}) / \left( \{ m_{\nu_k}^2 - m_{\nu_j}^2 \} (\mathrm{eV})^2 \right),$$

and is thus strongly dependent upon the neutrino masses. Bahcall *et al.* (1980) have recently considered neutrino oscillations as a possible solution to the solar problem. Assuming the Reines result to be correct, they estimate a factor of 2 reduction in solar neutrino flux when properly averaged over the energy spectrum of the Sun. Even if the Reines result proves to be the effect of some other cause, neutrino oscillations could still be an important factor in modifying the flux during the journey from Sun to Earth whilst being undetectable over the smaller separations possible with reactor-based experiments.

## Conclusions

It becomes increasingly apparent that the solar neutrino field will be extremely fruitful and enlightening for at least the next decade. By the end of this period, we should have a much more clearly defined picture of what is transpiring in the core of our Sun and, as a consequence, a better understanding of stars in general.

It is also apparent that new data are essential, and to this end many new experiments have been proposed with a variety of targets and techniques. Prominent among these second generation experiments is one to be conducted by a consortium of institutions including the Max Planck Institute (Germany), the Weizmann Institute (Israel), the Brookhaven National Laboratory, the Princeton Institute of Advanced Study and the University of Pennsylvania. This consortium has begun construction of an experiment utilizing gallium as a target. A small amount of gallium (1·4 tons) is currently being used to test for background contamination. The final experiment will need about 50 tons and will indeed be a major undertaking. Gallium has the low threshold of 0·24 MeV and will be of paramount importance in determining the flux of low energy solar neutrinos (which is hardly dependent at all upon any solar model).

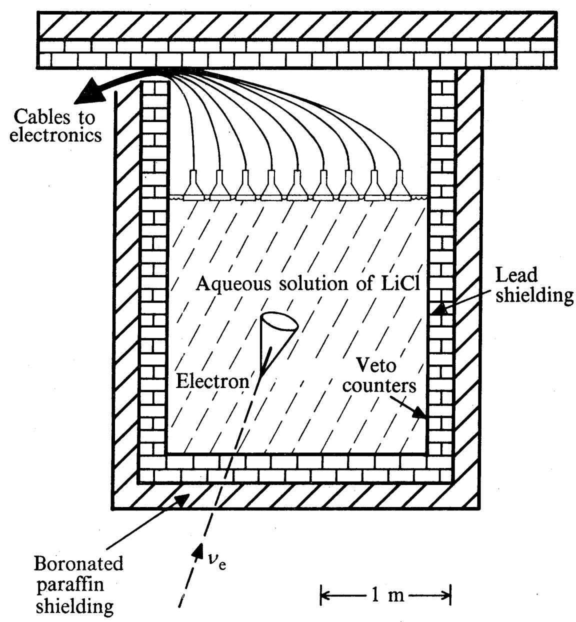


**Fig. 2.** Schematic drawing of the proposed neutrino detector of the Sydney University School of Physics. The tank has side dimensions of a few metres, and is shown together with the veto system and shielding.

This consortium seems to be the most advanced of the second generation experiments, though it is not clear how far a major radiochemical device, using chlorine or gallium, has progressed in the Baksan Underground Laboratory, Caucasus, U.S.S.R. (Alekseyev *et al.* 1979).

Fig. 2 shows a neutrino detector proposed by the University of Sydney. We feel that Australia can make a contribution in this field, for a modest cost outlay, if lithium is used as a target. Lithium chloride is fairly cheap and extremely soluble thus enabling an aqueous solution to combine both target and detector. The aim is to observe the Cherenkov radiation from the electron emitted in the reaction

$$\nu_e + {}^7\mathrm{Li} \rightarrow {}^7\mathrm{Be} + \mathrm{e}^-,$$

thus detecting the neutrinos *directly*. Because lithium has one of the highest neutron capture cross sections for neutrinos, the side dimensions need only to be a few metres to detect between 30 and 50 events per year. Background will be reduced by clean shielding, having a long veto pulse, and by locating the tank in a deep mine (more than 1000 m underground). Imposing a high threshold (6–7·5 MeV) on the electrons accepted will also be instrumental in rejecting most of the signals from radioactive decay and uranium fission.

Active testing of a small prototype version has been in progress since the beginning of 1980, and will continue until the end of 1981 when construction of the main device should begin. As this experiment will only measure the flux of high energy neutrinos, even a rough result for the flux will result in a knowledge of the temperature of the Sun's inner core to high accuracy. It is quite likely that this experiment will do no more than confirm the results of the Davis experiment; nevertheless, it will be a confirmation using an entirely different method and will thus render the result far more credible.

In summary, it appears as if neutrino oscillations and/or a slight variation in the standard model of the Sun are the most likely causes for the lack of experimentally observed high energy neutrinos. It would seem that a whole range of both accelerator and astrophysical experiments will be needed to completely clarify the issue.

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