REPORT ON THE HOMESTAKE CHLORINE SOLAR NEUTRINO EXPERIMENT

R. Davis, K. Lande, C.K. Lee
University of Pennsylvania, Phila., PA 19104

B.T. Cleveland
Los Alamos National Lab., Los Alamos, NM 87545

J. Ullman, Herbert Lehman Col., Bronx, NY 10468

ABSTRACT. A report on the results obtained from the chlorine radiochemical solar neutrino experiment in the Homestake mine, Lead, SD. Over the period 1970-1988 a neutrino capture rate of 2.3 ± 0.3 SNU was observed. This rate is discussed in relation to the theoretical standard solar model, the results from the Kamiokande II experiment, and variations in the solar neutrino flux.

1. INTRODUCTION

This report will be concerned with the latest experimental results from the Homestake chlorine experiment, a radiochemical neutrino detector based upon the neutrino capture reaction, ν_e + $^{37}Cl \rightleftarrows e^- + {}^{37}Ar$ (35 day half life). The detector contains 615 m tons of C_2Cl_4 , and the ^{37}Ar is removed by circulating helium through the liquid by a pump-eductor system (1). A measured volume of ^{36}Ar or ^{38}Ar carrier is used to measure the efficiency of argon recovery and finally the entire recovered argon sample is placed in a proportional counter to measure the radioactive ^{37}Ar produced. Argon-37 is identified by measuring the pulse amplitude (2.82 kev Auger electrons) and pulse rise-time (2). The experiment is located at a depth of 4100 ± 200 hectograms cm^2 standard rock, in the Homestake Gold Mine in Lead, South Dakota. The detector has operated continuously since 1970.3 except for a 1.4 year period from 1985.4 to 1986.8 when both liquid circulating pumps were out of commission. Except for this period, the observations were continuous and extractions of the ^{37}Ar activity were carried out at an average rate of 5 per year. Observations were extended over this long period for a number of

G. Berthomieu and M. Cribier (eds.), Inside the Sun, 171–177.

reasons: to obtain an improved result with reduced errors, search for short and long period variations in the ^{37}Ar production rate, measure the neutrino flux in the event of a supernova within 10 Kpc, and to insure that observations from the chlorine experiment overlapped those of new solar neutrino experiments. In this brief report we will compare our results with the standard solar model, and the recent observations from the Kamiokande II detector, and discuss the question of a variation in the observed ^{37}Ar production rate.

2. AVERAGE ^{37}Ar PRODUCTION RATE

The events observed in the proportional counter that had the correct energy (fwhm 2.82, 25% resolution) and pulse rise time were analysed by a maximum liklihood method into a decaying component with a 35 day half-life and a constant counter background (3). A growth factor for a 35 day radioactive product and the counting efficiency was applied to obtain the ^{37}Ar production rate. A plot of the individual measurements is shown in figure 1, and the average ^{37}Ar production rate is listed in table 1 for the entire observing period 1970.3 - 1988.3, and also for the period of overlap with the Kamiokande II observations, 1986.8 - 1988.3. Additional data up to the present time are being analysed and will be presented at a later date.

Table 1. Summary of ^{37}Ar Production Rates
(Atoms/day in 615 tons C_2Cl_4)

Period of Observation	1970.3-1988.3	1986.8-1988.3
Average ^{37}Ar production rate	0.518 ± 0.036	0.87 ± 0.13
Cosmic ray background	0.08 ± 0.03	0.08 ± 0.03
^{37}Ar above known backgrounds	0.438 ± 0.047	0.79 ± 0.13
^{37}Ar Production rate in SNU*	2.33 ± 0.25	4.2 ± 0.7

*Solar Neutrino Unit = 10^{-36} interactions sec^{-1} target $atom^{-1}$ or 5.31 ^{37}Ar atoms/day in the 615 tonne Homestake detector.

There is a cosmic ray muon background of 0.08 ± 0.03 ^{37}Ar atoms per day that must be subtracted to obtain the rate to be attributed to neutrinos. This background rate was derived from exposing smaller tanks of C_2Cl_4 at higher levels in the mine and deriving the rate for the full volume of C_2Cl_4 at the full depth of the experiment (4). An experiment is in progress that uses the photonuclear process ^{39}K ($\mu^{\pm}$, $\mu^{\pm}$ np) ^{37}Ar (5). The new results with the potassium experiment are similar to the ones used here, though somewhat lower, approximately 0.05 ^{37}Ar per day.

3. COMPARISON WITH THE STANDARD SOLAR MODEL AND THE KAMIOKANDE II EXPERIMENT

The net rate from the chlorine experiment for the entire period 1970.3 to 1988.3 is 2.33 ± 0.25 SNU (1σ error). It is this value that can be compared to the standard solar model. The most recent calculations are those of Bahcall and Ulrich (6) who obtained 7.9 ± 2.6 (3σ error) SNU and Turck-Chieze et al (7) who obtained 5.8 ± 1.3 (1σ error) SNU. These calculations differ chiefly because the separate groups chose different parameters for the solar opacities and the cross-section of the Be (P,γ) ^{8}B reaction. It is well known that the chlorine experiment is primarily sensitive to the flux of the energetic neutrinos from ^{8}B decay, 0-15 Mev. Assuming the usual solar sources and fluxes, approximately 77 percent of the rate in ^{37}Cl should be produced by ^{8}B decay neutrinos.

Recently the Kamiokande II experiment has measured the flux of solar neutrinos above 9.3 Mev (8). This detector is an imaging water Cherenkov detector system that observes neutrinos by ν_e - e^- elastic scattering, a process that has a favorable angular distribution of the recoil electrons with respect to the neutrino direction of energetic neutrinos. They compare the rate of events from the direction of the Sun with those from all other angles to obtain the ^{8}B solar neutrino flux. The rate observed is 0.45±0.15 (1σ error) times the ^{8}B flux predicted by Bahcall and Ulrich using a Monte Carlo derived shape for angular distribution (6). The Kamiokande II results were obtained from January 1987 through May 1988 and correspond to the data period 1986.8 to 1988.3 when the chlorine experiment observed a rate of 4.2 ± 0.7 SNU, see table 1 and figure 1. These two very different solar neutrino detectors are considered to be in essential agreement assuming that both experiments are observing primarily the same solar neutrino source. The high rate observed recently by the chlorine experiment is probably the result of a variation in the measured solar neutrino flux. Both experiments at the present time observe rates close to those calculated by the standard solar model of Turck-Chieze et al (7).

A low signal rate in these experiments can be attributed to resonance mixing of neutrino flavors suggested by Mikheyev and Smirnov based upon matter

Figure 1. ^{37}Ar Production Rates in the Homestake C_2Cl_4 Solar Neutrino Detector.

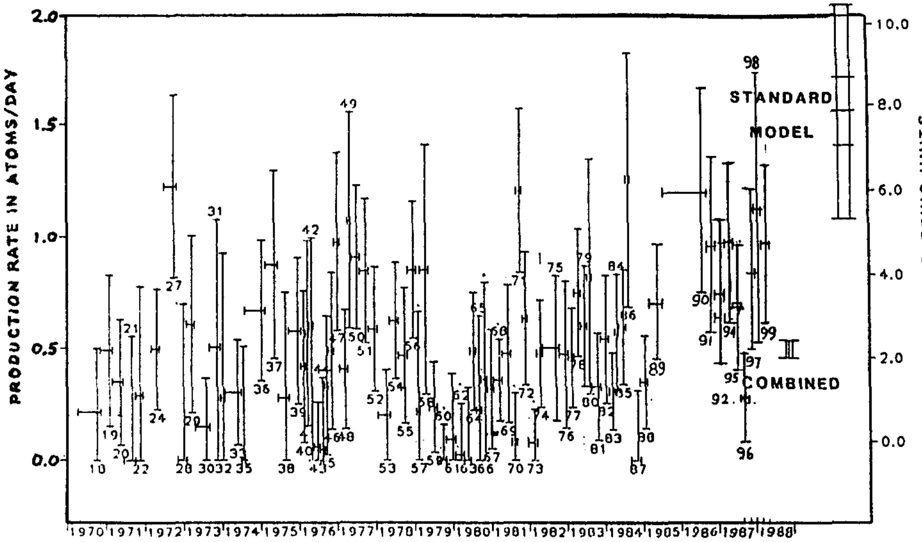
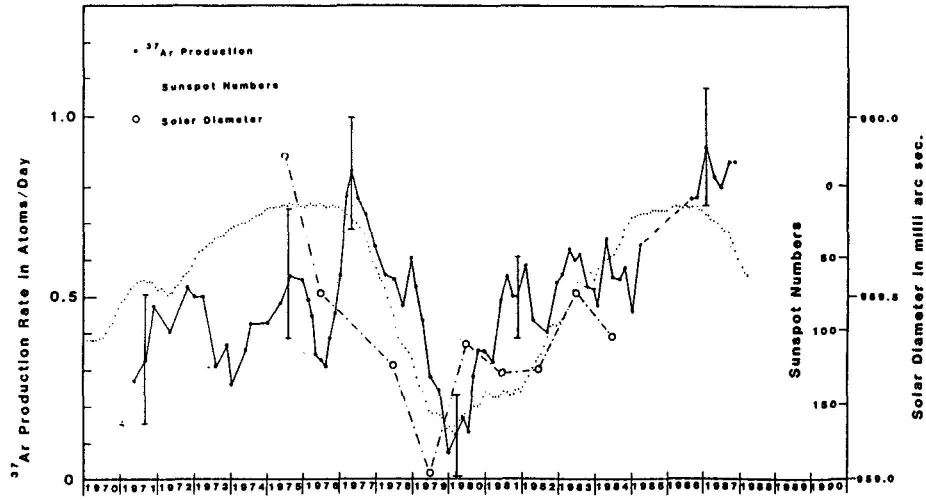


Figure 2. Comparison of Time Variation of 5 Extraction Running Averages of Measured Solar Neutrino Flux with Number of Sunspots and Solar Diameter.



oscillations of Wolfenstein (9). This process, called the MSW effect, arises from a difference in the scattering of electron neutrinos (ν_e) and muon or tauon neutrinos (ν_μ, ν_τ) with electrons. The process depends upon the difference in the masses between the neutrino types (or flavors), the mixing angle θ between the phases of neutrino eigenstates, and the electron density in the Sun. If leptons, $e^\pm$, $\mu^\pm$, $\tau^\pm$ and their neutrinos, are not conserved then electron neutrinos (ν_e) produced in the core of the Sun could be converted to ν_μ or ν_τ in passing through the Sun. The neutrino masses and mixing angles are unknown, but over a wide range of these parameters the flux of ν_e could be greatly reduced. These processes have not been observed in accelerator experiments, or cosmic ray studies. Perhaps the best opportunity for observing neutrino mixing is by solar neutrino studies.

4. IS THE SOLAR NEUTRINO FLUX CONSTANT?

The observed ^{37}Ar production rate exhibits an anti-correlation with the solar activity cycle. This matter has been pointed out in several earlier reports (10). Figure 2 shows a 5 point running average of 78 individual ^{37}Ar production rates measured over the last 18 years. The running average shows an anti-correlation with the solar activity cycle as measured by sunspot occurrences and correlates with the solar diameter measurements of Laclare (16). The rate was highest at solar minimum: in 1977 the average was 4.1 ± 0.9 SNU and in 1986.8 - 1988.3 the average was 4.2 ± 0.7 SNU. During solar maximum in 1979.5 to 1980.7 the rate was 0.4 ± 0.1 SNU. It is of course of great interest to see if the ^{37}Ar production rate is again low at solar maximum of cycle 22. Furthermore, it will be interesting to see if the Kamiokande II experiment observes a low rate in 1990-1991.

It is unlikely that the neutrinos from the core of the Sun would exhibit a large change in flux correlated with the solar activity cycle. There have been two suggestions. Voloshin, Vysotsky and Okun (11) suggested the spin of a left handed electron neutrino ν_e (L) could be rotated into a right handed sterile ν_e(R) in passing 10^{10}cm through transverse solar magnetic fields of a few thousand gauss, if the neutrino had a magnetic moment of 10^{-10} - 10^{-11} μ_B (Bohr magnetrons). This mechanism was considered unlikely by theorists when first suggested because a neutrino with a small mass would have a correspondingly small magnetic moment, ~ 10^{-17} μ_B. However, the magnitudes of the internal magnetic fields in the Sun are unknown. They could be very much larger at the base of the convective zone. Also a neutrino could have an acceptably larger transition magnetic moment (11,12). It was pointed out by Lim and Marciano (13) and Akhmedov (14) that the combined effect of matter and magnetic fields would produce a spin flavor transition, $\nu_e (L) \rightarrow \overline{\nu}_\mu (R)$, into non-detectable muonic anti-neutrinos. Calculations of these effects (15) show a large reduction in detectable neutrinos occurs in the convective zone of the Sun. It was pointed out by Voloshin, Vysotskii, and Okun (11) that an experimental test of these mechanisms could occur as a result of the fact that the Sun's axis of rotation is inclined 7 1/4 degrees with respect to the plane of the ecliptic. Twice a year the neutrinos reaching the earth come uneffected through the field-free solar equator (5 June, 5 December) and twice a year the neutrinos pass through the magnetic fields at higher latitudes (N or S, 5 March, 5 September) causing a greater loss of ν_e flux. The experimental data from 1979 - 1982 appears to show this effect (17).

ACKNOWLEDGEMENT. This work was supported by the National Science Foundation and grants from the University of Pennsylvania Research Foundation and from the CUNY Research Foundation of the City College of New York.

5. REFERENCES

1. Davis, R., Harmer, D.S., and Hoffman, K.C. (1968), Phys. Rev. Lett. 14, 20.

2. Davis, R. (1978), 'The Status and Future of Solar Neutrino Research' 1, 1, in G. Friedlander (ed.), Brookhaven National Laboratory Report BNL 50879; Rowley, J.K., Cleveland, B.T. and Davis, R. (1985), in M.L. Cherry, W.A. Fowler, and K. Lande (eds.), American Inst. Phys. Conf. Proc. No. 126, p.1; Bahcall, J.N. and Davis, R. (1976), Science 191, 264.

3. Cleveland, B.T. (1983), Nucl. Inst. and Methods 214, 451.

4. Wolfendale, A.W., Young, E.C.M. and Davis, R. (1972), Nature, Phys. Sciences 238, 1301; Cassiday, G.L. (1973), Proc. 13th Inst. Cosmic Ray Conf. 13, 1958; see calc. Zatselim, G.T. et al (1981), Soviet J. Nucl. Phys. 33, 200.

5. Fireman, E., Cleveland, B.T., Davis, R. and Rowley, J.K. (1985), in M.L. Cherry, W.A. Fowler and K. Lande (eds.) American Inst. Phys. Conf. Proc. No 126, p.22.

6. Bahcall, J.N. and Ulrich, R.K. (1988), Rev. Modern Phys. 60, 297; report Inside the Sun Conference.

7. Turck-Chieze, S., Cahen, S., Casse, M. and Doom, C. (1988), Astrophys. J. 335, 415; report Inside the Sun Conference.

8. Hirata, K.S. et al (Kamiokande group) (1988), Phys. Rev. Lett. 63, 16 (see also Phys. Rev. D38, 448); report Inside the Sun Conference.

9. Mikheyev, S.P. and Smirnov, A. Yu. (1985), Soviet J. Nucl. Phys. 42, 913 (see the excellent review in Soviet Phys. Uspkhi 30, 759 (1987) summarizing calculations by many authors); Wolfenstein, L. (1978), Phys. Rev. D17, 2369.

10. Rowley, J.K. et al ref (2); Davis, R., 7th Workshop on Grand Unification/ICOBAN-86, Toyama, Japan, p.237, J. Arafune (ed.); Davis, R., Cleveland, B.T. and Rowley, J.K., 20th Int. Cosmic Ray Conference, Aug. 2-15, 1987 Moscow, 4, 328; Neutrino 88 Conference, Boston, MA, 5-11 June 1988, J. Schneps (ed.).

11. Voloshin, M.B., Vysotskii, M.I. and Okun, L.B. (1986), Soviet J. Nucl. Phys. 44, 440; (1986) Soviet Phys. 64, 446.

12. Fukugita, M. and Yanagida, T. (1987), Phys. Rev. Lett. 58, 1807; Babu, K.S. and Mohapatra, R.N. (1989), Phys. Rev. Lett. 63, 228.

13. Lim, C.-S. and Marciano, W. (1988), Phys. Rev. D37, 1368.

14. Akhmedov, E. Kh. (1988), Soviet Nucl. Phys. 48, 382; (1988) Phys. Lett B213, 64.

15. Minakata, H. and Nunokawa, H. (1989), Phys. Rev. Lett. 63, 121 and Akhmedov, E. Kh., (1989), Zh. Eksp. Teor. Fiz. 95, 1195; and 95, 442.

16. Delache, P., Laclare, F. and Sadsaoud, H. (1985), Nature 317, 426; report Inside the Sun Conference.

17. Veselov, A.I., Vysotskii, M.I. and Yurov, V.P. (1987), Soviet J. Nucl. Phys. 45, 865.