Presented to the Conference on Solar Neutrinos and Neutrino Astronomy at Lead, SD, Aug. 23-25, 1984. To be published in the Am. Inst. of Physics Conference Proceedings

THE CHLORINE SOLAR NEUTRINO EXPERIMENT

BNL--35728

DE85 005208

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ABSTRACT

The chlorine solar neutrino experiment in the Homestake Gold Mine is described and the results obtained with the chlorine detector over the last fourteen years are summarized and discussed. Background processes producing ^{37}Ar and the question of the constancy of the production rate of ^{37}Ar are given special emphasis.

INTRODUCTION

The first underground experiment in the Homestake Gold Mine was the chlorine solar neutrino experiment, which was initiated nearly 20 years ago. The so-called solar neutrino problem is the discrepancy between the results of this experiment and the result predicted by solar model calculations using the best available input physics, i.e., by the standard solar model. The neutrino capture rate in the chlorine detector calculated using the standard solar model has changed with time as new data have become available. However, since 1969, in spite of great effort producing many new and improved measurements of nuclear reaction cross-sections, new opacity calculations etc., the capture rate predicted by the standard solar model has not changed in a major way. The chlorine detector has been operating regularly since 1970 with 61 experimental runs completed at the present time. The purpose of this paper is to give a brief description of the chlorine solar neutrino experiment and to discuss at greater length the results of these experimental runs.

The standard solar model is based upon the set of nuclear reactions shown in Table I.

Table I The proton-proton reaction chains

	Reaction	Neutrino Energy in MeV
	$H + H \rightarrow D + e^{+} + \nu$ (99.75%)	0-0.42 spectrum
	or	
PPI	$H + H + e^{-} \rightarrow D + \nu$ (0.25%)	1.44 line
	$D + H \rightarrow {}^{3}He + \gamma$	
	${}^{3}He + {}^{3}He \rightarrow 2H + {}^{4}He$ (87%)	
	${}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$ (13%)	
PPII	${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu$	0.861 (90%) line 0.383 (10%) line
	${}^{7}Li + H \rightarrow \gamma + {}^{8}Be \rightarrow 2\,{}^{4}He$	
PPIII	${}^{7}Be + H \rightarrow {}^{8}B + \gamma$ (0.017%)	
	${}^{8}B \rightarrow {}^{8}Be^{*} + e^{+} + \nu$	0-14.1

In addition to these reactions the reactions of the CNO cycles make a small contribution to energy generation. If the sun operated solely on the CNO cycles, the predicted neutrino capture rate would be very high, 35 SNU, and readily calculated. Using the PP reaction chains shown in Table I and the CNO reaction cycles, a neutrino spectrum of the standard solar can be calculated. The fluxes of neutrinos from various sources in the sun as predicted recently[1,2] from standard solar calculations are listed in Table II together with the resulting ^{37}Ar production rates in the chlorine detector.

Table II Neutrino fluxes and ^{37}Ar production rates predicted by the standard solar model

Neutrino type	Flux at earth, 10^{10} cm^{-2} sec^{-1}*	Production rate of ^{37}Ar: In SNU	Production rate of ^{37}Ar: In atoms day^{-1} in chlorine detection
pp	6.1	0	0
pep	0.015	0.23	0.04
^{7}Be	0.42	1.0	0.19
^{8}B	0.00046	5.0	0.93
^{13}N	0.05	0.08	0.01
^{15}O	0.04	0.26	0.05
Total	6.63	6.6	1.22

1 SNU is defined as one capture per sec in 10^{36} target atoms.
* Fluxes and capture cross-sections are from references 1 and 2.

Because the energy threshold for the reaction: $^{37}Cl + \nu \rightarrow {}^{37}Ar + e^-$ is 0.814 MeV and because of the dominant contribution of the transition to the bound isobaric analog state of ^{37}Ar, the capture rate in the chlorine detector is very sensitive to the internal temperatures in the sun. Therefore, the calculated rate depends critically on the assumed reaction cross-sections, opacities, internal composition and dynamic processes in the sun. The fact that the chlorine experiment is very sensitive to these factors was a strong argument that was used to obtain support to build the experiment in 1965.

DESCRIPTION OF THE EXPERIMENT

Since a detailed description of the experimental facility and procedures has been given elsewhere,[3] we will only outline them here and mention recent improvements and tests.

Outline of Procedure. The neutrino target is 2.2×10^{30} atoms (133 tons) of $^{37}C\ell$ in the form of 3.8×10^5 liters of liquid erchoroethylene, $C_2C\ell_4$. The tank containing this material is located at the 4350 foot level underground in the Homestake Gold Mine. The ^{37}Ar produced in the tank is separated at intervals averaging about 80 days, purified, and counted. Experimental runs were carried out on a rather irregular schedule during the period 1969-1975. During 1976 an attempt was made to perform measurements more frequently, every 35 to 50 days. Since that time measurements have been made on a nearly regular basis of six runs per year. In 1982 the schedule was modified because of a strike at the mine. Occasional special runs have been performed to look for increased neutrino fluxes from various astronomical and solar flare events -- the Lande event in 1974 (Run 32), solar flares (Runs 27, 35 and 54), novae (Runs 38 and 46), and the recent large x-ray flare on May 25, 1984 (Runs 84 - still counting).

The steps in the experimental procedures are:

1. After the end of a run approximately 0.2 standard cc of either ^{36}Ar or ^{38}Ar is added (alternately) to serve as a carrier for the ensuing run.

2. The tank is exposed for the desired length of time.

3. After exposure, the argon in the tank is removed by circulating about 4×10^5 liters (1 tank volume) of He through the gas and liquid phases in the tank, then through a condensor at −32 °C and a molecular sieve at room temperature, and finally through a charcoal trap cooled to the temperature of liquid nitrogen where the argon is absorbed. Gas circulation is accomplished and the tank is stirred by two large pumps, each connected to an educator system. About 95 percent of the argon is removed (and retained on the charcoal trap) by circulating this volume of helium.

4. The argon is transferred from the heated large charcoal trap to a line where it is purified, its volume measured, and it is loaded into a small (0.3 - 0.5 cc) proportional counter along with tritium-free methane which serves as a counting gas. The counters containing experimental samples are calibrated approximately every two months.

5. The sample is counted for approximately 8 months and often longer.

6. The carrier yield is determined by mass spectroscopy.

In order to show that ^{37}Ar, produced in the form of a recoiling ion by the low energy neutrino capture process becomes a neutral Ar atom, a special test was performed.[4,5] Tetrachloroethylene labelled with $^{36}C\ell$ decays by beta-minus emission to ^{36}Ar:

$$C_2C\ell_3{}^{36}C\ell \rightarrow C_2C\ell_3{}^{+}(\text{fragments}) + {}^{36}Ar^{+} + e^{-} + \bar{\nu},$$

the dynamics of this process are nearly equivalent to the inverse beta process $^{37}C\ell(\nu,e^{-})^{37}Ar$. The Ar^{+} ion produced is believed to become a neutral atom[6,7] which should be recovered with the carrier ^{38}Ar. After standing a definite length of time the quantity of neutral ^{36}Ar produced was determined by activation analysis after separation using a helium purge. In this experiment (performed by Evans, Vera Ruiz, and Davis) the ^{36}Ar was recovered with 100 ± 3% yield. A similar experiment was performed in the Soviet Union with the same result.[8]

The ultimate test that the ^{37}Ar is quantitatively recovered would be to place a neutrino source of known neutrino intensity and neutrino energy in or adjacent to the chlorine detector. A 1.0 megacurie source of ^{65}Zn would be required to obtain an ^{37}Ar production rate of 4 ^{37}Ar atoms day^{-1}, a rate ten times higher that presently observed in the detector (presumably from solar neutrinos). In 1981–1982 a trial irradiation was performed in the HFIR reactor at Oak Ridge to measure the ^{65}Zn production in zinc (^{64}Zn is the 48.6% abundant). This test irradiation indicated that only 0.5 megacurie could be prepared at HFIR and further tests at HFIR were abandoned. A measurement of the neutrino capture cross-section using the spectrum of neutrinos from μ^+ decay could test the cross-section calculations to all excited states.[2] An experiment was proposed[9] to carry out this measurement at the Los Alamos Meson Physics Facility and the fast neutron background at the experimental site was measured. This experimental test is now entirely feasible and we believe this is the best way to verify the calculations of the neutrino capture cross-sections for $^{37}C\ell$.

Counting. The pulses in a proportional counter originating from the low-energy Auger electrons resulting from decay of ^{37}Ar differ from most electrons from β decay by having a short pulse rise-time. Consequently, both energy and pulse rise-time can be used profitably to characterize ^{37}Ar decays. Figure 1 shows a plot of pulse rise

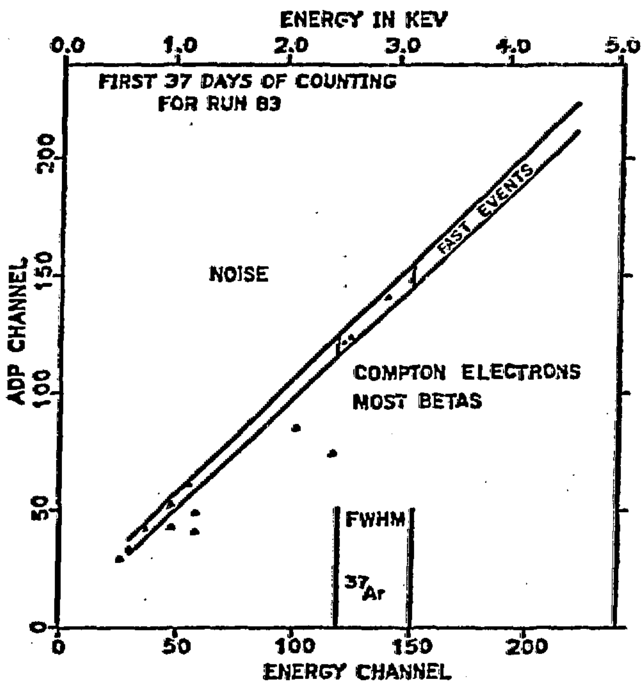

Figure 1. Plot of pulse rise-time versus energy for the first counting period of Run 83.

time (called ADP for amplitude of the differentiated pulse) versus pulse height for the first counting period of a very recent run (Run 83). The areas where pulses with different origins appear are labelled in this figure. An area within which 68% of ^{37}Ar decay pulses are located is defined by a calibration procedure with an ^{55}Fe source. This area is shown in the figure as the box containing four events. Although the counter background is greatly reduced by defining this area, some of the contained counts are background counts.

Over the course of this experiment many improvements in the counting have been made. Reductions in background have been achieved by using low radioactivity material in the counters and other counting components, by using a large well-type sodium iodide crystal as an anti-coincidence shield, and by moving the counting apparatus to the underground laboratory at Homestake.

Analysis of the Counting Data. The counts obtained in a given run within the proper pulse-height range and the proper ADP range are analyzed by the method of maximum likelihood.[3,10] For each run the counts are assumed to arise from a constant background and a constant production rate yielding a single decaying component. Except when it is desired to determine the half-life of the decaying component, this half-life is assumed to be equal to 35 days, that of ^{37}Ar. From the recorded times of all counts with the proper pulse-height and proper pulse rise-time a likelihood function is calculated. This likelihood function includes fluctuations in ^{37}Ar production, fluctuations during extraction and processing, and fluctuations during counting. The most likely values of the production rate and of the background rate are those that maximize the likelihood function. Results from many runs are combined by multiplying individual likelihood functions to give a combined likelihood function.

This method for treating the data has been used since 1977. It has been extensively tested by Monte Carlo simulations with varying input production rates and background counting rates. The results of these simulations show that the combined most likely values of the ^{37}Ar production rate and of the counter background state agree well with the input values.[10]

BACKGROUND PROCESSES

Once the total production rate of ^{37}Ar in the detector has been calculated using the maximum likelihood method, there remains the problem of subtracting any ^{37}Ar production from known non-solar sources. Four principal known background sources underground are known. These are: 1) cosmic ray muons and products of their interaction ($\pi^{\pm}$, energetic protons and neutrons, and evaporation protons), 2) fast neutrons from the rock wall by way of (α,n) reactions and from spontaneous fission of ^{238}U, 3) alpha particle interactions from uranium and thorium in the perchlorethylene, and 4) cosmic ray neutrinos. The background ^{37}Ar production rates from alpha particles[3] and from cosmic ray neutrinos[11,12] are both estimated to be quite small. We will discuss the other two background sources at greater length.

Underground muons, produced by cosmic rays in the upper atmosphere, penetrate deeply underground and produce cascades containing energetic pions, protons and neutrons together with evaporation protons which ultimately produce ^{37}Ar by the reaction ^{37}Cl (p,n) ^{37}Ar. The magnitude of this background process for the chlorine detector has been estimated[12,13] by exposing three 600 gallon tanks of perchloroethylene at higher levels in the mine, measuring the ^{37}Ar production rate at each of these levels and extrapolating these production rates to the depth of the chlorine detector. In making this extrapolation it is necessary to know the effective depth of each exposure site. Recently we have carefully calculated again the effective flat surface depth, in hg cm^{-2} of standard rock, of each location where these tanks were exposed and of the chamber containing the chlorine detector.

These calculations were performed in the following manner. We first read from topographic maps the surface elevations at evenly spaced points on the circumferences of concentric circles centered on a point directly above the site of interest. These readings were carried out to a horizontal distance from the center of the circles which was large enough that the largest circle included more than 90% of the total muons passing through the site of interest. Rock samples were collected at various levels near the vertical Yates shaft and their densities were measured. The average densities of the rocks in a given rock formation agreed well with those tabulated by the Homestake Mining Company. Weighted for rock formation thickness, the resulting overall average density above the neutrino chamber is 2.84 g cm^{-3}. Using the overall average rock density for each site together with the known elevations and zenith angles and the dependence on depth and zenith angle of the underground muon intensity, we performed a numerical integration to obtain the total muon flux at the site. Working backwards we could then obtain the equivalent flat-surface depth (in hg cm^{-2} of standard rock) of the site. For the neutrino chamber an additional correction was made for the average Z, $\overline{Z}$, of the overhead rocks. Based upon some determinations by the Homestake Mining Company of typical rock compositions in different rock formations, $\overline{Z}$ is equal to 10. Consequently, a multiplying correction factor[14] of 0.97 was used to correct for the fact that $\overline{Z}$ was not equal to 11, that of standard rock.

The resulting effective depth of the chlorine detector is $4.0 \times 10^{-3} \pm 200$ hg cm^{-2} of standard rock. The largest source of error is uncertainties in the rock densities. This uncertainty in effective depth translates into an uncertainty in the cosmic ray induced background of about 30%. However, since the vertical flux of muons in the chamber containing the chlorine detector has been measured (see later discussion), this is probably not the best way to estimate this error.

The results of all of the new effective depth estimations are shown in Table III along with the old depth estimations and the measured ^{37}Ar production rates in C_2Cl_4 scaled to the volume of the chlorine detector.

Table III Newly calculated depths of sites where cosmic ray induced ^{37}Ar production rates were measured

Mine level (location)	Depth in hg cm^{-2} of standard rock old	new	^{37}Ar production rate in 10^5 gallons of C_2Cl_4
300 foot (600 feet from Kirk portal)	290	254	320 ± 50
300 foot (1100 feet from Kirk portal)	405	327	178 ± 25
1100 foot (adjacent to Yates shaft)	1080	819	24 ± 13
4850 foot (neutrino chamber)	4400	4000	0.07 ± 0.03*

* extrapolated value

The result of the new extrapolation of the measurements at the other locations listed in Table IV to the depth of the neutrino chamber, 0.07 ± 0.3 ^{37}Ar atom day^{-1}, is essentially the same as the older estimate.

Another way to calculate the muon induced ^{37}Ar production rate is to utilize a measured value[15] of the vertical muon flux in the neutrino chamber (equal to 5×10^{-9} cm^{-2} sec^{-1} sterad^{-1}) to calculate the total muon flux which must then be multiplied by the calculated ^{37}Ar yield per muon appropriate to the average muon energy in the neutrino chamber. This average yield per muon may be estimated by interpolation from the results of calculations of Zatsepin, Kopylov, and Shirakova.[16] The final result of such a calculation is a muon induced background ^{37}Ar production rate equal to 0.09 day^{-1}, in good agreement with the value given in Table IV. We adopt the value, 0.08 ± 0.03 day^{-1} (0.4 ± 0.16 SNU) for this production rate.

A more extensive discussion of cosmic-ray induced background is presented in this volume in the paper by Fireman et al.

Fast Neutrons. Another background source of ^{37}Ar is fast neutrons which can produce ^{37}Ar by the reactions, $^{35}Cl(n,p)^{35}S$ followed by $^{37}Cl(p,n)^{37}Ar$. Since the threshold in neutron energy of this reaction sequence is about 1 MeV, the magnitude of this background process is made neglible by a water shield. In the absence of a water shield the magnitude of this background process for the chlorine detector has been estimated to be equal to 0.04 ^{37}Ar atoms/day by Davis[7] on the basis of measurements of the neutron flux in the chamber containing the chlorine detector combined with a yield of 7×10^{-7} ^{37}Ar per neutron absorbed. Barabanov et al.[17] used calculated (α,n) yields, a calculated neutron attentuation factor, and granitic rock composition to estimate a ^{37}Ar production rate from fast neutron in the chlorine detector equal to 0.08 atoms per day. Since 12 runs (Runs 18, 19,20, 38, 39, 76, 77, 78, 79. 80, 81, and 82) have been performed without a water shield and 49 runs with a water shield, it is interesting to compare the combined production rates of these two sets of runs. The results are:

49 runs with water shield	0.45 ± 0.05 ^{37}Ar day^{-1}
12 runs without water shield	0.51 ± 0.09 ^{37}Ar day^{-1}

Although the results without a water shield are about 12% higher than those with a water shield, the error in measurement is large enough that the difference cannot be considered statistically significant. We conclude that, since most of the runs were performed with a water shield, the effect of the runs without a water shield on the combined production rate of all runs is small and well within the quoted error. No correction for a fast neutron background has been applied to the ^{37}Ar production rates given in the following section.

RESULTS

In this section we report and discuss the results of 61 completed runs covering the period from 1970 to 1984. In these 61 runs the total counts having the correct energy and correct rise-time are 774. These counts were divided by the maximum likelihood procedure described earlier into about 435 background counts and 339 counts resulting from ^{37}Ar decay (these numbers depend on whether the runs are treated individually or are combined). Before discussing the production rate of ^{37}Ar, we will discuss counter backgrounds briefly.

Counter Background Rates derived from the maximum likelihood treatment have been variable. The average counter background rate over 61 runs in the two dimensionsal ^{37}Ar region is 0.033 day^{-1}. The range is from 0 to 0.137 day^{-1}. Over the last twelve runs the average background counting rate is 0.010 day^{-1}, i.e., 3.6 counts per year.

Table IV shows the results of the 61 experimental runs. Listed in the table for each run are the time at the start of exposure, the time at the end of exposure, and the mean time of exposure, defined as

$$t_{mean} = t_{start} + (1/\lambda)\ln[\frac{1}{2} + \frac{1}{2}\exp(\lambda\, t_{end} - \lambda\, t_{start})]$$

Table IV Exposure times and ^{37}Ar production rates from individual runs using the chlorine detector

Run Number	Exposure times, years Start	End	Mean	Atoms per day ^{37}Ar Production Rate	Upper Error Limit	Lower Error Limit
18	70.279	70.874	70.780	0.214	0.0	0.498
19	70.874	71.180	71.098	0.490	0.150	0.830
20	71.180	71.462	71.383	0.349	0.067	0.630
21	71.462	71.755	71.675	0.0	0.0	0.555
22	71.755	71.951	71.885	0.289	0.0	0.779
24	72.168	72.380	72.311	0.497	0.226	0.768
27	72.517	72.848	72.765	1.226	0.820	1.633
28	72.848	73.073	73.002	0.0	0.0	1.165
29	73.073	73.287	73.218	0.608	0.211	1.006
30	73.287	73.668	73.581	0.147	0.0	0.365
31	73.668	73.952	73.873	0.505	0.0	1.080
32	73.952	74.070	74.023	0.277	0.0	0.928
33	74.070	74.487	74.398	0.302	0.066	0.539
35	74.500	74.591	74.553	0.0	0.0	0.509
36	74.591	75.121	75.028	0.671	0.355	0.987
37	75.121	75.454	75.370	0.877	0.455	1.298
38	75.454	75.733	75.654	0.279	0.0	0.755
39	75.733	76.062	75.978	0.580	0.252	0.909
40	76.065	76.180	76.134	0.419	0.078	0.760
41	76.180	76.270	76.232	0.569	0.152	0.987
42	76.270	76.386	76.340	0.605	0.0	1.534
43	76.386	76.542	76.485	0.058	0.0	0.260
44	76.542	76.676	76.625	0.047	0.0	0.371
45	76.676	76.772	76.732	0.337	0.025	0.648
46	76.772	76.924	76.868	0.491	0.137	0.844
47	76.924	77.076	77.020	0.979	0.583	1.376
48	77.076	77.290	77.221	0.407	0.138	0.676
49	77.290	77.385	77.345	1.075	0.593	1.558
50	77.385	77.594	77.526	0.910	0.588	1.232
51	77.594	77.824	77.754	0.849	0.525	1.173
52	77.824	78.054	77.982	0.588	0.308	0.867
53	78.054	78.361	78.279	0.200	0.0	0.404
54	78.361	78.595	78.523	0.626	0.365	0.887
55	78.595	78.827	78.755	0.468	0.162	0.774
56	78.827	79.051	78.980	0.853	0.546	1.160
57	79.051	79.150	79.110	0.215	0.0	0.668

Table IV Exposure times and ^{37}Ar production rates from individual runs using the chlorine detector (continued)

Run Number	Exposure times, years: Start	End	Mean	Atoms per day: ^{37}Ar Production Rate	Upper Error Limit	Lower Error Limit
58	79.150	79.375	79.304	0.853	0.295	1.410
59	79.375	79.586	79.517	0.237	0.034	0.439
60	79.586	79.818	79.746	0.0	0.0	0.158
61	79.818	80.065	79.991	0.090	0.0	0.387
62	80.065	80.281	80,211	0.023	0.0	0.254
63	80.281	80.451	80.391	0.0	0.0	0.325
64	80.451	80.604	80.548	0.488	0.222	0.754
65	80.604	80.739	80.687	0.224	0.0	0.649
66	80.739	80.892	80.836	0.361	0.0	1.614
67	80.890	81.059	80.999	0.319	0.051	0.588
68	81.059	81.290	81.218	0.359	0.175	0.544
69	81.290	81.519	81.448	0.477	0.166	0.788
70	81.519	81.673	81.616	0.081	0.0	0.301
71	81.673	81.826	81.770	1.209	0.844	1.574
72	81.826	81.966	81.913	0.636	0.337	0.935
73	81.966	82.210	82.136	0.077	0.0	0.228
74	82.210	82.361	82.305	0.478	0.237	0.720
75	82.361	82.810	82.719	0.503	0.176	0.830
76	82.810	83.040	82.968	0.475	0.144	0.806
77	83.040	83.194	83.137	0.461	0.237	0.684
78	83.194	83.366	83.305	0.752	0.465	1.040
79	83.366	83.531	83.471	0.604	0.332	0.875
80	83.531	83.654	83.606	0.824	0.299	1.348
81	83.654	83.884	83.812	0.330	0.089	0.571
82	83.884	84.095	84.026	0.545	0.257	0.832
All sixty one runs combined				0.462	0.421	0.502

together with the production rate and the upper and lower 1 − σ error limits on this production rate derived by the maximum likelihood method from the time sequences of counts. We show in Figure 2 these same results along with the production rates resulting from combining the runs for each year. The vertical error bars show 1 − σ errors in both halves of the figure. The combined production rate of 61 runs show at the right of the upper part of the figure, is equal to 0.46 ± 0.04 ^{37}Ar atoms day^{-1}.

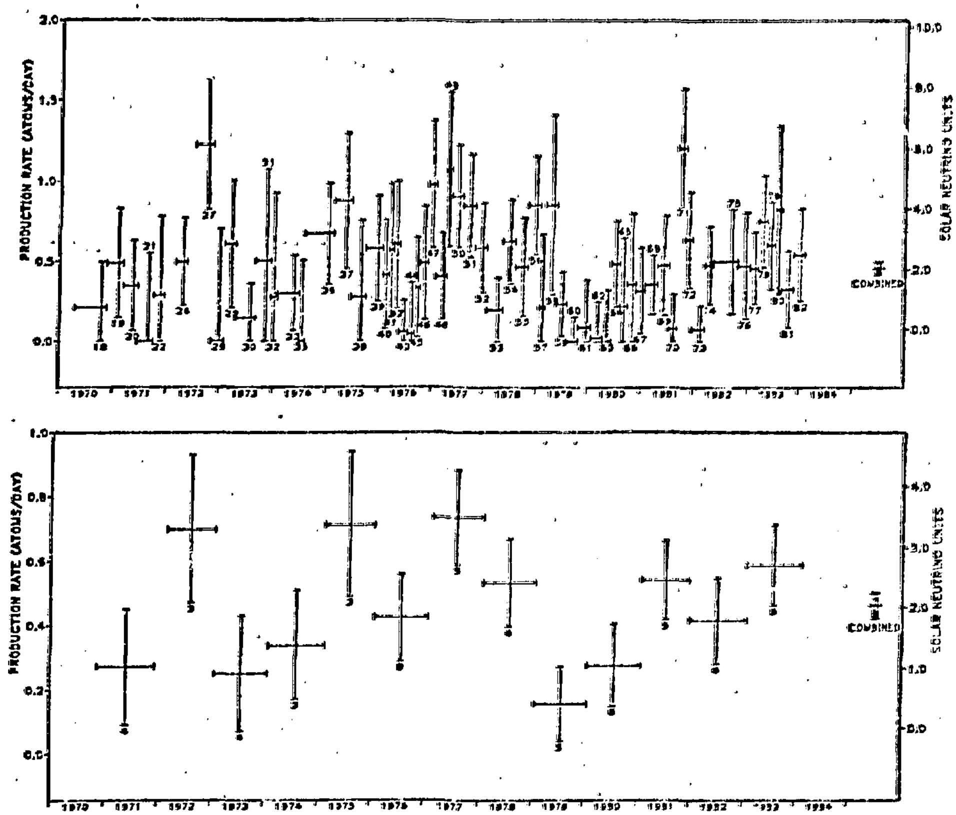

Figure 2. Experimental results from the chlorine solar neutrino experiment: upper — individual measurements; lower — yearly averages. The number beneath each point in the lower part shows the number of runs represented by that point.

In Figure 3 we present as a function of time the combined ^{37}Ar production rates. Each point represents a combined production rate for all runs starting with Run 18 and ending at the time where the point is plotted. Run 18 in 1970 was the first run for which pulse rise-time was used to characterize ^{37}Ar decay events. The 1 − σ error bars decrease with time as more runs are included in succeeding points until the present 10% error is reached. The pulse-rise time measurement has improved enormously the ability to distinguish ^{37}Ar decays from background.

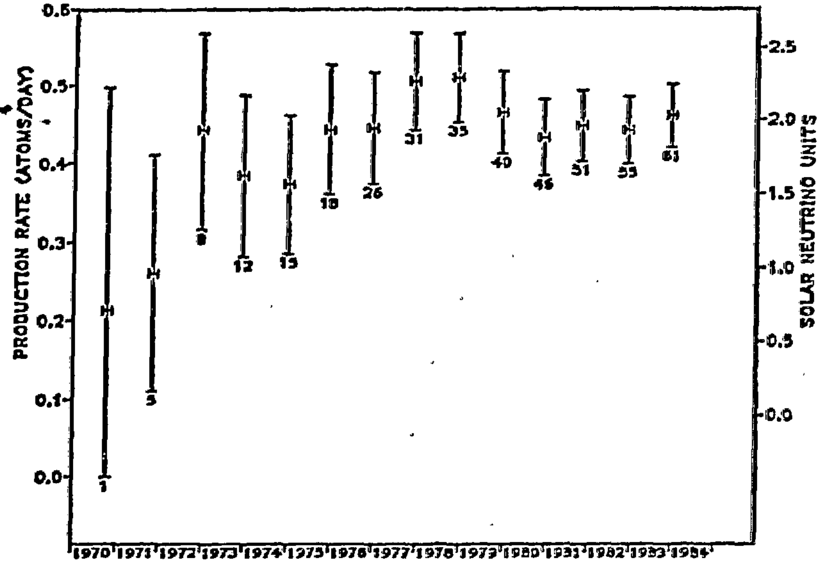

Figure 3. Experimental combined production rate beginning with Run 18 as a function of time. The number beneath each point shows the number of runs combined to give the production rate represented by that point.

In an independent maximum likelihood treatment of the counting data from all 61 runs, both the production rate and the half-life of the decaying component were assumed to be variables whose most likely values were to be derived from the treatment. The resulting values are a half-life of 37 ± 6 days and a production rate of 0.45 ± 0.05 ^{37}Ar atoms day^{-1}. That this half-life is in agreement with that of ^{37}Ar (35 days) offers convincing evidence that the decaying component is indeed ^{37}Ar.

If we subtract the cosmic ray induced background rate for ^{37}Ar from the combined production rate, we obtain:

Combined Production Rate = 0.46 ± 0.04 ^{37}Ar atom day^{-1}
Known Background Production Rate = 0.08 ± 0.03 ^{37}Ar atom day^{-1}

Net Production Rate = 0.38 ± 0.05 ^{37}Ar atom day^{-1}

This net production rate is clearly above that caused by known background processes. If we attribute this net production rate to solar neutrinos and translate it into SNU units (1 SNU ≡ 1 neutrino capture per second per 10^{36} target atoms), the result is: 2.0 ± 0.3 SNU, which may be compared with three values recently predicted using the standard solar model:

Bahcall (1984)[1]	6.6 SNU
Filippone et al. (1983)[18]	5.6 SNU
Fowler (1982)[19]	6.9 SNU

There is clearly a discrepancy between the experimentally derived number and all of the predicted values.

MONTE CARLO SIMULATIONS

To form some feeling for the results shown in Figure 3 it is helpful to compare these results with those from a maximum likelihood treatment of Monte Carlo simulations assuming a constant production rate. The results of two such simulations are shown in Figures 4 and 5. Both of these simulations use the sequence of counter background rates that was observed, i.e., corresponding to the same actual run. The upper figure shows the results when a constant ^{37}Ar production rate of 7.6 SNU is assumed. The lower figure shows the results when a constant ^{37}Ar production rate of 1.8 SNU is assumed. Upon comparison with the real results in Figure 3 two conclusions are evident:

1. The results of the chlorine experiment are clearly different from the results of the simulation with a production rate 3 - 4 times higher.

2. The results of the chlorine experiment resemble closely the results of the simulation with a production rate of 1.8 SNU. The value of the standard deviation derived from the actual runs is equal to 0.32 day^{-1} and that derived from the simulated runs shown in Figure 5 is also equal to 0.32 day^{-1}. Note the occurrence of runs with a production rate of zero per day in both the actual runs (5 times in 61 runs) and the simulation (5 times in 47 runs). Note also the occurrence of high runs in both figures. Although a quick comparison of this kind indicates no reason to conclude that the real results are inconsistent with the constant production rate, this question will be considered in more detail in the last section of this paper.

The results of treatment by the method of maximum likelihood of other Monte Carlo simulations of the production, separation, processing and counting of ^{37}Ar can be summarized by the following expression for the fractional $1 - \sigma$ error in the production rate (in this treatment the half-life of ^{37}Ar was assumed to be a known parameter):

$$E^2 = \frac{0.027}{\eta\ \varepsilon SP}\left(1 + \frac{3.7\ B}{\varepsilon SP}\right)$$

where E is the fractional $1 - \sigma$ error in the production rate, η is the number of runs, P is the production rate in day^{-1}, B is the background counting rate in day^{-1}, ε is the fractional counting efficiency, S is the saturation factor defined as $1 - \exp(-\lambda t_e)$, λ is the decay constant for ^{37}Ar, and t_e is the exposure time. This expression is applicable for 300 days of counting time for each run and for an extraction efficiency of 95% for ^{37}Ar; these are both typical values. For two months exposure (t_e = 60 days), P = 0.47 day^{-1}, and ε = 0.40 the term 3.7 B/εSP may be evaluated for different values of B. When B = 0.01 day^{-1}, this term is equal to 0.28 and only 22% of the error comes from the term containing the

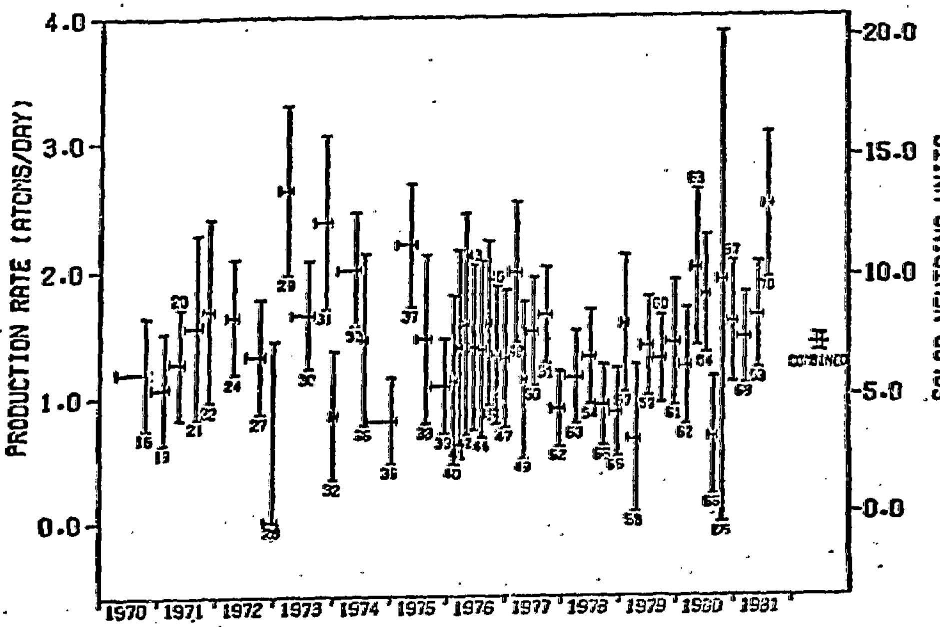

Figure 4. Results of maximum likelihood treatment of Monte Carlo simulations with constant production rate of 7.6 SNU.

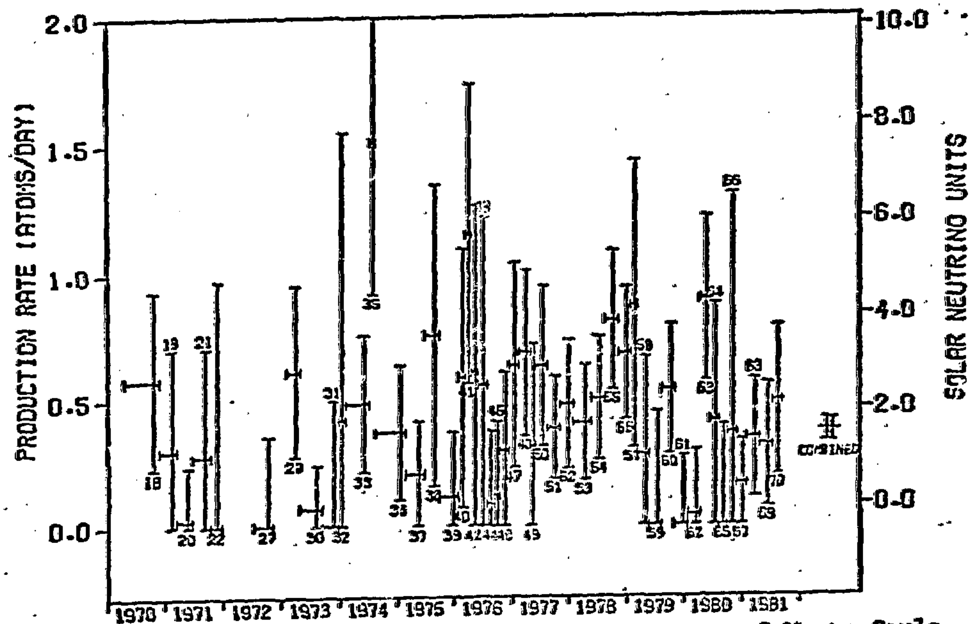

Figure 5. Results of maximum likelihood treatment of Monte Carlo simulations with constant production rate of 1.8 SNU.

background rate. From this viewpoint no large improvements in reducing the error can be achieved by further decreases in the counter background rate. If, however, both the production rate and the half-life are considered as free parameters to be derived from the counting data, there is still much to be gained by reducing counter background rates. In any case, it is a desirable goal to continue trying to reduce counter background rates.

SOLAR ACTIVITY AND THE CHLORINE SOLAR NEUTRINO EXPERIMENT

One of the major aims of continuing operation of the chlorine experiment during the last thirteen years has been to improve the statistical accuracy of the measurement of the ^{37}Ar production rate and to assure that ^{37}Ar is indeed being observed.[3] To achieve these goals we have continually improved counter backgrounds by using better electronic circuitry, a NaI anti-coincidence detector and a thick Pb-Hg-Boron-plastic shield and by carrying out the counting measurements underground. The present results of the chlorine experiment clearly demonstrate that ^{37}Ar is being produced in the detector, but that its production rate is inconsistent with that predicted by the standard solar model. Since the problem of explaining this discrepancy will be discussed by others at this conference, we will not discuss it here. Instead we would like to consider further the question of the constancy of the ^{37}Ar production rate.

We now have a long record of data that can be used to determine if the sun's neutrino output is constant during a period comparable to an eleven-year solar cycle and to search for pulses of neutrinos. We would like to discuss some interesting correlations that appear in the data that could be of great importance to our understanding of the sun and cosmic rays.

Because of the sun's slow response to changes, the neutrino luminosity of the core of the sun is generally believed to be constant for periods in the range of $10^4 - 10^6$ years. Processes that could perturb the rate of the thermal fusion reactions would not be expected to be observed over a period of a solar cycle.[20] However, in view of the fact that the interior of the sun is not very well understood it is important to look carefully at the results for changes in the ^{37}Ar production rate with time. One must bear in mind that observational neutrino astronomy is a new subject and there may be surprises. Because the chlorine detector is the only detector with a high neutrino (ν_e) sensitivity and a long observational record, a number of investigators have examined the results from the chlorine experiment for variations.

<u>Solar Cycle Variations</u>. In this report we will not review the literature on this subject, but will give some references and an indication of the analysis applied (see ref. 21). A number of investigators have pointed out that the ^{37}Ar production rate anticorrelates with solar activity as measured by sunspot cycles. This correlation is shown in Figure 6 in which the yearly average

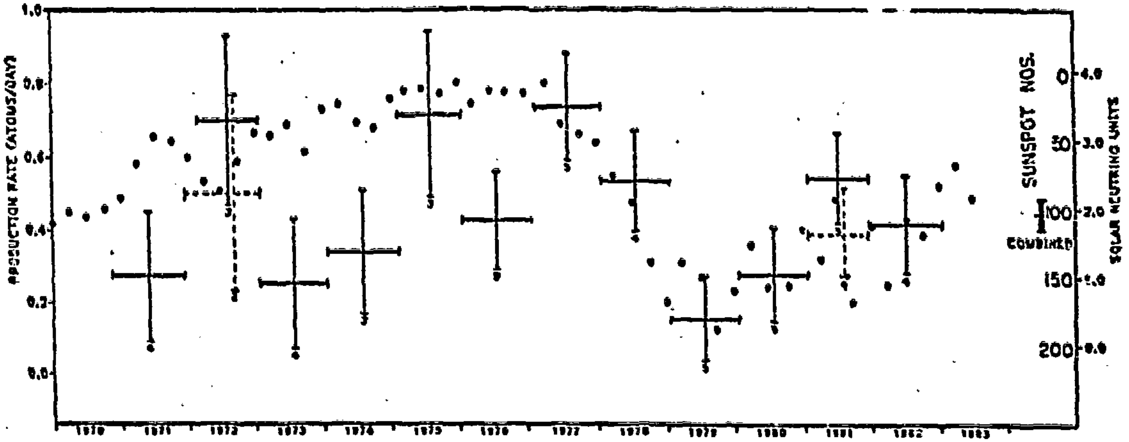

Fig. 6 (above). Yearly average results for the chlorine experiment superposed on monthly mean sunspot numbers (plotted inverted). The number of experimental runs included in the average is indicated for each year. The averages for 1972 and 1981 shown with dotted lines are without Runs 27 and 71, the runs that appear to correlate with the large solar flares of Aug. 4-8, 1971 and of Oct. 12, 1981.

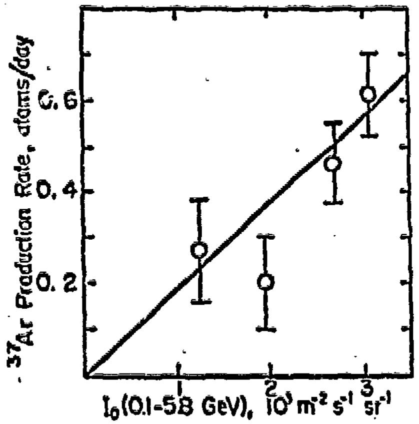

Fig. 7 (at right). The ^{37}Ar production rate divided into four bins according to the intensity of cosmic ray protons plotted against the intensity of cosmic ray protons in the energy range, 0.1-5.8 GeV, (from Bazilevskaya et al.[19]).

^{37}Ar production rate is compared to the sunspot numbers. In this plot the sequence of points appear to anticorrelate with sunspot numbers during the rise and fall of solar activity in cycle 21. It is well known, and understood, that the galactic cosmic ray intensities of protons and alpha particles with energies less than a few Gev also anticorrelates with solar activity. In Figure 7 we show, following the example of Bazilevskaya et. al.[22,23] a plot of the cosmic ray intensity in the energy range 0.1 to 5.8 Gev against the ^{37}Ar production rate. Although the errors in the ^{37}Ar production rates are large, there does appear to be a correlation of the rate with the cosmic ray intensity. This effect could not arise directly from low energy cosmic ray particles because they would not reach the neutrino detector at a depth of 4000 hg/cm^2 ($\overline{E}_\mu$ = 340 Gev). It is conceivable that neutrinos from μ^+ decay that are associated with low energy cosmic rays could be responsible for the signal observed. The $^{37}C\ell$ capture cross section for electron-type neutrinos from μ^+ decay is 1.1×10^{-40} cm^2, a value one-hundred times greater than the cross-section of neutrinos from ^8B decay. Present estimates of the flux of low energy neutrinos from cosmic ray interactions in the atmosphere are too low to account for a flux of low energy neutrinos (20 to 100 Mev) as high as 10^4 cm^2/sec, as explained by Stanev at this conference.[24] However, it has been reported that the Kamioka proton-decay experiment has observed neutrino-like events in the energy range of 35 to 100 Mev. Large scale water Cherenkov detectors in the future could achieve the required sensitivity to observe low energy neutrinos.[25]

Resolution of the question of the validity of this apparent correlation is of great importance to our present interpretation of the observations of the chlorine neutrino detector as a flux of neutrinos from the core of the sun. Although it is unlikely that the neutrino luminosity of the sun varies, this possibility should not be absolutely ruled out. The chlorine detector responds primarily to the ^8B and ^7Be neutrino fluxes and the production of these neutrino emitters is a very sensitive function of the temperatures in the solar interior (the ^8B neutrino flux is proportional to the twenty-fifth power of the central temperature of the sun). Therefore, the chlorine detector is the best of the radiochemical detectors to search for possible variations. A gallium detector would be far less responsive. The 3000-ton chlorine detector planned in the USSR[26] would, of course, be a great improvement over the Homestake detector.

Solar Flare Effects. It was pointed out ten years ago that run 27, the highest experimental run, corresponded in time with the great solar flare of August 4-7, 1972.[27] If this flare was responsible for the increase, we missed observing its full magnitude because the ^{37}Ar decayed by a factor of six before the sample was removed from the tank. At that time, and also at the present time, it is believed that measurable fluxes of neutrinos could not be produced in a solar flare[28] or by solar flare particles interacting in the earth's atmosphere.[29] Shortly after the time of occurrence of the large solar flare of October 7-12, 1981 and before any results of run 71 were known, Stozhkov predicted that this flare might be detected by the chlorine experiment.[22,23] Our second highest run resulted. Since that time, this Soviet group noted that there are, in all, two flares that occurred on the visible disc and one on the invisible disc of the sun that produced in the earth's atmosphre a large flux of protons with energy above 150 Mev and that a measurable increase in the ^{37}Ar production might be detected.[23] These events are listed below, in Table V, along with the decay period before collecting the sample and the ^{37}Ar production rate (calculated in the usual way assuming a uniform flux).

Table V Solar flares with large observed proton fluxes and the measured ^{37}Ar production rates for the same periods

Run No.	Flare Date	Solar Coordinates	Proton Intensity (> 150 Mw) cm^{-2} sec^{-1} Sr^{-1}	Decay Period in Days Before Counting	Observed ^{37}Ar Production Atoms/Day
27	8/ 4/72	14N; 8E	~ 90	94	1.23 ± 0.41
	8/ 7/72	14N; 36W	~ 3	91	
51	9/24/77	10N; 120W	~ 3.5	35	0.85 ± 0.32
71	10/ 7/81	19S; 88E	~ 0.5	21	1.21 ± 0.37
	10/12/81	22S; 35E	~ 4	16	

If these three flare events were responsible for the increase in rate above the average rate (0.40 ± 0.04 atoms/day), the approximate numbers of ^{37}Ar atoms produced in the detector in runs 27, 51 and 71 were 250 ± 130, 20 ± 15, and 56 ± 30 respectively.

As mentioned earlier Monte Carlo simulations of our data indicate that experimental runs as high as these are expected, approximately 1 - 2 for 60 experiments. It is unlikely that high values would correlate in time with a solar flare event, but to be convinced one would like to observe a flare event as large as the 1972 event immediately after its occurrence. It is interesting to note that the great flare of 1956 was over one-hundred times larger than the 1972 flare.[30] A special run was performed in early May 1984 to see if the April 25, 1984 x-ray flare was observed (run 84). The Soviet group detected little or no increase in proton flux at the earth from this flare. There was not an enhanced ^{37}Ar production in run 84.

There is no ready explanation for a measurable neutrino flux to be developed by a solar flare, or by the interaction of flare protons with solar matter,[28] or with the earth's atmosphere.[29] However, a large water Cherenkov detector could observe neutrinos if their energies were over 30 Mev and the flux were as high as indicated by our measurements. Using the threshold and sensitivities given in reference 13 for the Kamioka detector, the production of one ^{37}Ar atom in the chlorine detector would correspond to 0.6 events in a Kamioka detector. On this basis neutrinos from a large solar flare should be readily measured if the chlorine detector observes another large flare.

THE FUTURE OF THE CHLORINE SOLAR NEUTRINO EXPERIMENT

The chlorine detector is the only neutrino detector with a well-known neutrino (ν_e) energy response, low threshold, and high sensitivity which has a long observational record. Because of its unique character and importance to astronomy, we believe observations using this detector should continue.

ACKNOWLEDGMENT

This research was carried out at Brookhaven National Laboratory under contract DE-AC02-76CH00016 with the U.S. Department of Energy and supported by its Office of High Energy and Nuclear Physics. This experiment has involved the help of many people. Co-workers are J. C. Evans, J. P. Galvin, D. Harmer, K. Hoffman, L. Rogers and V. Radeka. We would like to express our gratitude to many people from the Homestake Mining Company. Without their cooperation and vital help this experiment could not have been performed. We are especially grateful to A. Gilles and J. Dunn who have helped in so many ways at Homestake. We are also especially grateful for the continuous support and encouragement from W. A. Fowler and J. N. Bahcall.

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