CONF-720651-1

Report on the Brookhaven Solar Neutrino Experiment*

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MASTER

(Abstract)

A solar neutrino experiment has been in progress since 1967 to observe neutrinos from the sun by the neutrino capture reaction $^{37}\text{Cl}(\nu, e^-)^{37}\text{Ar}$. 380,000 liters of perchloroethylene, C_2Cl_4 , are used as a neutrino capturing medium. The radioactive ^{37}Ar (35.1-day half-life) is removed from the liquid by purging with helium gas, purified, and counted in a small low-level proportional counter. Argon-37 decay events are characterized by the energy of the event, and the rise-time of the counter pulse. The results of six experiments performed during the last two years will be given. The ^{37}Ar production rate in the detector was 0.18 ± 0.10 per day, close to the production rate expected from cosmic ray muons. The experiment places an upper limit on the production of ^{37}Ar by solar neutrinos of $1 \times 10^{-36} \text{ sec}^{-1} (^{37}\text{Cl atom})^{-1}$. This limit can be compared to the currently predicted rate of $9 \times 10^{-36} \text{ sec}^{-1} (^{37}\text{Cl atom})^{-1}$ from solar model calculations of Bahcall and Ulrich, and Abraham and Iben.

A solar neutrino detector based upon the neutrino capture reaction $^{37}\text{Cl}(\nu, e^-)^{37}\text{Ar}$ was built in 1964-1967 and has been operating since early 1967. The initial experiments [1] showed that the total flux-cross section product was less than $3 \times 10^{-36} \text{ sec}^{-1} (^{37}\text{Cl atom})^{-1}$. This conclusion was

*Research performed under the auspices of the U.S. Atomic Energy Commission.

substantiated by additional experiments performed during the period 1968-1970, and reported in a series of reports [2]. In these experiments the ^{37}Ar decay events were characterized in the proportional counter by observing the energy of the Auger electrons emitted following the decay. The recent experiments that will be reported here, the ^{37}Ar decay event in the counter is characterized by the energy (pulse height) and rise-time of the pulse [3]. This added discrimination for ^{37}Ar events has lowered the counter background for ^{37}Ar -like events permitting a more sensitive search to be made for the neutrino radiation from the sun.

This report will present a brief summary of the critical experimental tests that have been performed to demonstrate the efficiency of recovering ^{37}Ar from 380,000 liters of perchloroethylene, the rise-time counting system, and the observations that have been made over the last two years. The detector was arranged so that it could be shielded with a water shield with an average thickness of about 2 meters to eliminate the effect of fast neutrons from the surrounding rock. Three experiments will be reported with this water shield in place.

The Detector

The detector consists of a 380,000 liter tank of perchloroethylene (C_2Cl_4), a pumping system for circulating the liquid and purging the liquid with helium gas, and a gas absorption system for removing argon from the circulating helium gas. The detector is located at a depth of 4400 hg/cm² in the Homestake Gold mine at Lead, South Dakota. The arrangement of the apparatus underground is shown in Fig. 1, and a schematic diagram of the extraction system is shown in Fig. 2.

Argon-37 produced in the liquid is removed by purging with helium gas. Two 1700 liter/min pumps circulate liquid from the tank through a series of

40 eductors that draw helium from the gas space at the top of the tank, and distribute it through the liquid in the form of small bubbles. The 20,000 liters of helium in the tank at 1.3 atmospheres pressure is circulated through the liquid every 2 minutes by the pumping system. Two eductors are used to draw the helium from the tank through a condenser at -35°C , a molecular sieve adsorption trap, a charcoal trap cooled to 77°K , and finally returning the helium to the tank. Helium flows through the extraction system at a rate of 310 liters/min. The helium flow rates depend upon the gas pumping rates of the eductors, and these rates have remained constant at the values given above.

The efficiency for extracting argon from the 380,000 liters of C_2Cl_4 was tested in several ways.

- (1) In each experiment a measured volume (0.05 to 0.10 cm^3) of isotopically pure ^{36}Ar is introduced into the tank to serve as a carrier gas and to measure the argon recovery achieved in each experiment [1]. The ^{36}Ar carrier is introduced at the beginning of the period of irradiation and is recovered several months later by the helium purge. The ^{36}Ar content of the helium gas in the tank was analyzed, and from the relative volumes of the gas and liquid phases we calculate that approximately 95 percent of the ^{36}Ar introduced dissolves in the liquid. The recovery of ^{36}Ar as a function of the volume of helium circulated through the system was measured. The volume of argon remaining in the tank V_R decreases exponentially with the volume of helium circulated [1]. With the fixed flow rates, a 95 percent recovery can be obtained in a 22 hour period.
- (2) An analogous test was made with ^{37}Ar . A sample of ^{37}Ar activity in helium gas was prepared, introduced into the tank, recovered during 22 hours of operation extending over a 2 day period, and counted. The ^{37}Ar

activity introduced was 10.0 dis ^{37}Ar /day, and the recovered sample contained 11.0 ± 1.8 dis ^{37}Ar /day corrected to the time it was introduced. This experiment was performed May 19, 1972, and the counting of this sample and the analysis is not yet complete. However, this preliminary result does demonstrate the recovery of ^{37}Ar is consistent with recovery based on the ^{36}Ar carrier method.

- (3) The 380,000 liter tank is provided with a reentrant pipe that extends to the center of the tank. A Ra-Be neutron source was placed in this source tube to produce ^{37}Ar in the liquid by the successive nuclear reactions $^{35}\text{Cl}(n,p)^{35}\text{S}$ followed by $^{37}\text{Cl}(p,n)^{37}\text{Ar}$. The yield for this neutron source test was 7.4×10^{-7} ^{37}Ar atoms per neutron, and it was shown that the ^{37}Ar produced was removed in successive purges along with the ^{36}Ar carrier [1]. The yield of ^{37}Ar activity obtained in this experiment was compared to similar neutron irradiations of containers of perchloroethylene with smaller diameters. These yields (^{37}Ar atoms/neutron) and diameters were: 3.0×10^{-7} , 29 cm; 6.4×10^{-7} , 120 cm; 7.4×10^{-7} , 600 cm.

These experimental tests demonstrate that ^{37}Ar produced in the 380,000 liters of perchloroethylene is efficiently removed by the helium purge. This result is entirely reasonable based upon the chemical behavior of argon. The neutrino capture process forms an argon ion that recoils from its parent C_2Cl_4 molecule. The argon ion rapidly reaches thermal energy in the liquid, capturing an electron from adjacent C_2Cl_4 molecules becoming a neutral ^{37}Ar atom. This neutral ^{37}Ar atom is identical chemically with the dissolved ^{36}Ar carrier atoms present in the liquid at a concentration of 5×10^9 atoms/cm³. The recovery of ^{36}Ar from the liquid is therefore a valid measure of the ^{37}Ar recovery. Our colleagues at Brookhaven [4] have made a

search for the formation of complex argon- C_2Cl_4 ions in a high pressure mass spectrometer source. No evidence was obtained in these experiments for the formation of stable $C_mCl_nAr^+$ ions. Evidence was found for a charge transfer process that proceeds with a rate coefficient at least two orders of magnitude greater than an upper limit for the rate coefficient for the reactions producing $Ar-C_mCl_n^+$. This is evidence for rapid charge transfer in the gas phase and supports the assumptions made above concerning the charge transfer process in the liquid phase.

Counting

The entire argon sample recovered from the tank was placed in a small proportional counter that has already been described [1]. In the experiments reported here the rise time of the pulse and the pulse height was measured for each pulse. The 2.8 keV Auger electron produced in the electron-capture decay of ^{37}Ar has a range in the counter gas of approximately 0.1 mm. The ion pairs produced in the gas are localized in a small volume of the counter, and therefore they reach the center wire nearly at the same time giving a fast rising pulse. Background events from more energetic Compton-electrons, betas or muons in passing through the counter gas, produce ion-pairs more widely spaced, and hence reach the center wire over longer periods of time giving a slower rising pulse. By measuring the rise-time of the pulse one can distinguish ^{37}Ar decay events, X-ray absorption events, and tritium decays from background events produced by gamma radiation, betas, and muons.

A fast charge-sensitive preamplifier with a 6 nsec pulse rise-time response feeds an Ortec model 410 timing filter amplifier that integrates (10 nsec) and differentiates (10 nsec) the charge pulse. The shaped pulse is then fed to a pulse-stretching amplifier for acceptance by an analog to digital converter. This digital information is plotted on a y-axis of a two

parameter plot and is designated the amplitude of the differentiated pulse (ADP). The pulse from the preamplifier is also separately routed to a conventional RC shaping spectroscopy amplifier and subsequently analyzed by a second analog to digital converter. This digital information is displayed on the X-axis as the energy. The arrangement is shown schematically in Fig. 3. Each time the counter functions the ADP and pulse height (energy) is written on a paper tape along with the clock time, and a sequence of test pulses for ADP and pulse height (energy). The system is automatically checked once every 1000 minutes with the test pulses, and at this time the anti-coincidence counter rate is recorded. The counting system is capable of recording events from four separate counters.

The counters are calibrated with an ^{55}Fe X-ray source. The location of region of fast-rising X-ray pulses is determined by recording on a separate pulse height analyzer the ADP pulses gated in coincidence with a narrow energy region selected by a single channel analyzer. This measurement is carried out at several different energies to define the region of X-ray pulses. The lines drawn on the two parameter plot define the X-ray region. The indicated region contains approximately 95 percent of the fast X-ray pulses. The location of the position of ^{37}Ar on the linear energy scale was determined from the ^{55}Fe X-ray peak position. The ^{37}Ar resolution (full width at half maximum, fwhm) was taken as 1.45 times the ^{55}Fe resolution.

The discrimination against pulses produced by gammas, was measured by placing a ^{60}Co source near the counter and recording the ADP pulse distribution corresponding to particular energies. The fraction of the area under the ADP spectrum exterior to the X ray region is a measure of the effective rejection of pulses arising from energetic betas, gammas, and muons. In the experiments reported here there was a variation in the rejection ratio that depended upon counter filling (argon pressure, percent CH_4) and the dimensions of the counter.

The lowest rejection ratio was 82 percent, and the highest achieved was 99 percent.

Results

Three experimental runs (Nos. 18, 19, and 20) were made with the unshielded tank, as in all previously reported experiments. The two-parameter plots for these three runs are shown in Figs. 4 and 5. The periods of counting are indicated on the plots, and correspond approximately to a half-life of ^{37}Ar (35.1 days). It may be observed that 5, 9, and 3 counts, respectively, were observed with the correct ADP and an energy within the half-width of the ^{37}Ar peak position. The samples were counted for additional periods to see if these ^{37}Ar -like events decayed away with the 35.1-day half-life period. The data are summarized in Table 1 where the number of fast counts observed in the energy intervals 1 to 2.4 keV, 2.4 to 3.2 keV (fwhm), and 3.2 to 7 keV are given. It may be seen that there was satisfactory decay in runs 18 and 19 to a background counting rate of ~ 2 and ~ 3 counts per 36 days, respectively, but little evidence for decay in run 20.

Following these experiments the tank chamber was flooded with water to provide a neutron shield. Fast neutrons above 1 MeV energy can produce ^{37}Ar in the liquid by the successive reactions mentioned earlier. A small flux of fast neutrons arises from spontaneous fission of ^{238}U and (α, n) reactions from alpha decays of the uranium and thorium and their daughters present in the rock. The fast neutron flux was measured by a sensitive radiochemical technique based upon the $^{40}\text{Ca}(n, \alpha)^{37}\text{Ar}$ reaction. These measurements indicated that the ^{37}Ar production in the 380,000 liter tank was about 0.04 ^{37}Ar atom per day, too small to be observed. However, the water shield should completely eliminate any possible fast neutron background from the rock wall.

The number of fast counts observed in the indicated energy intervals for three experiments with the water shield in place, nos. 21, 22, and 23, are listed in Table 2. It is clear from these results that the number of counts that could be attributed to ^{37}Ar is low, less than or equal to 1 per experiment. In Run 23 a large counter (5 cm^3) with a correspondingly high background was used. However, this particular counter had an exceedingly high rejection ratio, and thus a low background for fast counts. The three fast counts observed in the ^{37}Ar peak position correspond approximately to the expected background of this counter.

A detailed statistical analysis of the data has not been made, though it is evident that the counting rates are indistinguishable from counter background for experiment nos. 20 (without water shield), 21, 22, and 23 (incomplete decay information), and an indication of a positive amount of ^{37}Ar in the two runs nos. 18 and 19 without the water shield. The data can be used to derive an upper limit to the solar neutrino flux. We have taken the experiments with the water shield in place and the observed number of fast counts in the energy region 2.4 to 3.2 keV as ^{37}Ar decays. Accepting all of these counts as ^{37}Ar without allowing for counter background should be a safe procedure for setting upper limits. Correcting for growth factor, decay factor, counter efficiency, and recovery yield we derive an ^{37}Ar production rate in 380,000 liters of C_2Cl_4 of 0.18 ± 0.10 per day.

Background Effects

Cosmic ray muons and cosmic ray produced muon-neutrinos can produce ^{37}Ar in the liquid. The ^{37}Ar production from muons was evaluated by exposing 6800 liters of C_2Cl_4 arranged in 3 tank cars at various levels in the mine from 285 to 1080 hg/cm^2 depth. An analysis of this data is given in another paper presented at this Conference [5]. It is concluded that the ^{37}Ar

production rate from muons in 380,000 liters of C_2Cl_4 at a depth of 4400 hg/cm² is approximately 0.12 ± 0.04 per day. Argon-37 can also be produced by cosmic ray produced muon-neutrinos, ν_μ , by the reaction $^{37}Cl(\nu_\mu, \mu^-)^{37}Ar$. The production rate from this process was estimated to be 0.024 per day [5].

Some attention was devoted to the possibility that there is ^{37}Ar in the earth's atmosphere. In the processing of the 380,000 liters of C_2Cl_4 an excess of ^{40}Ar is found in each experiment, and this is attributed to the inleakage of atmospheric argon. Quantities of ^{37}Ar have been found in the atmosphere that are two orders of magnitude higher than the amount produced by cosmic ray interactions [6]. The level was high during the period corresponding to our run no. 19, however the specific activity was a factor of ten below that observed in the run 19 argon. The air in the Homestake mine was monitored during the period March (1971) to March (1972) but the ^{37}Ar content was in general low, <0.15 dis/min liter of argon.

Conclusions

The cosmic ray muon background must be subtracted from the ^{37}Ar production rate limit of 0.18 ± 0.10 given above. The resulting rate that could be attributed to solar neutrinos is then 0.06 ± 0.11 ^{37}Ar atoms per day. We then conclude that the solar neutrino production rate is less than 0.2 ^{37}Ar atoms/day. The corresponding flux-cross section product limit is then,

$$\Sigma\phi\sigma < 1 \times 10^{-36} \text{ sec}^{-1} (^{37}\text{Cl atom})^{-1}$$

This limit can be compared to the currently calculated flux-product from standard solar models of

$$\Sigma\phi\sigma \text{ (theoretical)} = 9.1 \times 10^{-36} \text{ sec}^{-1} (^{37}\text{Cl atom})^{-1}$$

The significance of this discrepancy between observations will be discussed by Dr. J. N. Bahcall in a paper presented at this conference.

Our conclusions may be summarized as follows:

- (1) The total flux-cross section product for solar neutrino capture in ^{37}Cl is a factor of 9 below the total (B^8 , Be^7 , and PeP) rate predicted by standard solar model calculations, and below the rate predicted from ^7Be decay and PeP reaction neutrinos
- (2) The flux of ^8B solar neutrinos is less than $10^6 \text{ cm}^{-2} \text{ sec}^{-1}$
- (3) The sun produces less than 3 percent of its energy by the CNO cycle.

Acknowledgement

The authors would like to acknowledge the skillful technical assistance of Mr. John Galvin during the entire period of these investigations.

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Table 1

Summary of Results

Without Water Shield

Run No.	Exposure Period	Counting Period	Fast Counts		
			1.0-2.4 keV	Ar ³⁷ FWHM 2.4-3.2 keV	3.2-7 keV
18	Apr 12 to Nov 14 (1970)	I 39 days	10	5	5
		II 35 "	9	5	9
		III 34 "	12	3	6
		IV 36 "	6	1	9
		V 39 "	11	2	11
19	Nov 14 (1970) to Mar 6 (1971)	I 36 days	6	9	3
		II 39 "	5	5	13
		III 37 "	7	5	12
		IV 41 "	20	4	8
		V 37 "	20	3	8
		VI 36 "	7	3	5
		VII 34 "	5	4	8
20	Mar 6 to June 17 (1971)	I 40 days	3	3	2
		II 30 "	7	1	2
		III 37 "	15	3	7
		IV 38 "	8	0	3
		V 51 "	13	1	6
		VI 36 "	7	3	3

Table 2

Summary of Results

With Water Shield

Run No.	Exposure Period	Counting Period	Fast Counts		
			1.0-2.4 keV	Ar ³⁷ FWHM 2.4-3.2 keV	3.2-7 keV
21	Jan 17 to Oct 2 (1971)	I 39 days	5	0	7
		II 34 "	8	1	8
22	Oct 2 to Dec 13 (1971)	I 35 days	6	2	3
		II 36 "	9	2	5
		III 40 "	9	3	6
23	Dec 13 (1971) to Mar 2 (1972)	I 40 days	4	3	5

COUNTER

TEST
PULSE

-HV

$\tau = 100 \mu \text{ sec}$

10 n sec

X-RAYS

γ 's

FAST
SHAPING

FAST
STRETCHING

X-RAYS
 γ 's

ADP
ADC

ENERGY
ADC

IMPULSE
NOISE

NORMAL
PULSE

SLOW
SHAPING

2 $\mu \text{ sec}$

PEAK TIME

AMPL. DIFF. PULSE

ENERGY

X-RAY

γ 's

CRITERIA FOR ACCEPTING PULSE

ANTI-COINCIDENCE WITH RING PULSE SHAPE
(REJECTION OF NOISE) AMPLITUDE DISCRIMINATION

SYSTEM TESTS

PULSE TEST WITH EACH EVENT AND EVERY 1000 MIN.

RECORDING

EVENTS, ADP AND ENERGY

Figure 3

CRITERIA FOR ACCEPTING PULSE

ANTI-COINCIDENCE WITH RING PULSE SHAPE
(REJECTION OF NOISE) AMPLITUDE DISCRIMINATION

SYSTEM TESTS

PULSE TEST WITH EACH EVENT AND EVERY 1000 MIN.

RECORDING

EVENTS: ADP AND ENERGY
PULSER TEST: ADP AND ENERGY, TWO LEVELS
TIME
ANTI-COINCIDENCE RING COUNTS
DEAD TIME

CROSS SECTIONS
CHANNELS 121-125

CHANNELS 58-62