The Homestake Chlorine Solar Neutrino Detection Experiment in Three Parts
Prologue, Experiment, epilogue

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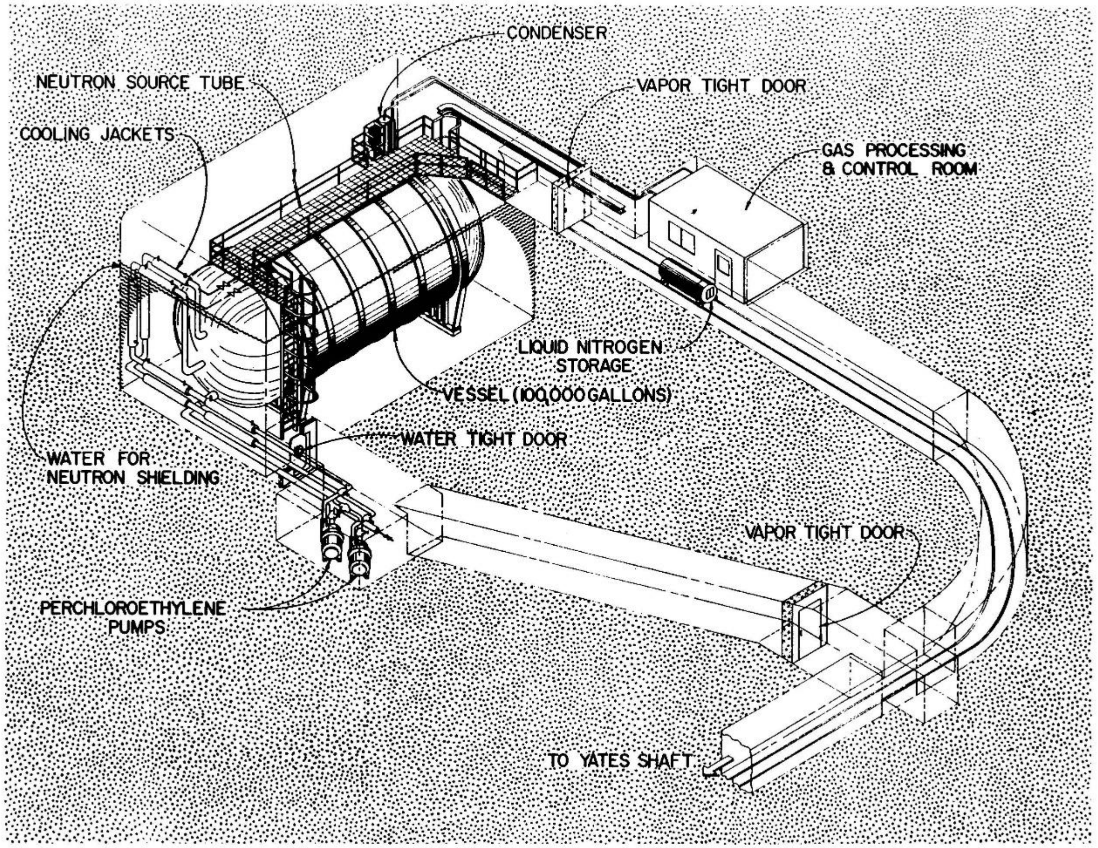

FIG. 1.—Homestake solar neutrino experiment. Arrangement of the detector elements in the rock cavity, 1478 m below the surface in the Homestake Gold Mine.

Selected Chronology

1) 1938 – Bethe describes both the Carbon & P-P fusion cycles in the Sun.

2) 1946 – Pontecorvo proposes neutrino detector using $\nu + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$
   [(p,n) reaction on halogen produces a non-interacting gas atom]

3) 1949- Alvarez describes details of the ${}^{37}Cl$ detector – size, extraction, etc

4) 1953 - Davis measures ${}^{37}Ar$ production rate in buried (25 mwe) C_2Cl_4 detector

5) 1958 – Holmgren & Johnston - $\sigma({}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma)$ is large!

6) 1963- Ben Mottelson points out that the transition from (g.s) of ${}^{37}Cl$ to 5.1 MeV state of ${}^{37}Ar$ is super allowed. This specific transition dominates the cross section for ${}^{8}B\ \nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$ and the signal rate of the Chlorine solar neutrino detector.

MARCH 1, 1939 PHYSICAL REVIEW VOLUME 55

Energy Production in Stars*

H. A. BETHE
Cornell University, Ithaca, New York

(Received September 7, 1938)

§1. INTRODUCTION

THE progress of nuclear physics in the last few years makes it possible to decide rather definitely which processes can and which cannot occur in the interior of stars. Such decisions will be attempted in the present paper, the discussion being restricted primarily to main sequence stars. The results will be at variance with some current hypotheses.

The first main result is that, under present conditions, no elements heavier than helium can be built up to any appreciable extent. Therefore we must assume that the heavier elements were built up *before* the stars reached their present state of temperature and density. No attempt will be made at speculations about this previous state of stellar matter.

The energy production of stars is then due entirely to the combination of four protons and two electrons into an α-particle. This simplifies the discussion of stellar evolution inasmuch as the amount of heavy matter, and therefore the opacity, does not change with time.

The combination of four protons and two electrons can occur essentially only in two ways. The first mechanism starts with the combination of two protons to form a deuteron with positron emission, *viz.*

$$H+H=D+\epsilon^{+}. \quad (1)$$ ←

The deuteron is then transformed into He^4 by further capture of protons; these captures occur very rapidly compared with process (1). The second mechanism uses carbon and nitrogen as catalysts, according to the chain reaction

$$\begin{aligned} &C^{12}+H=N^{13}+\gamma, \qquad N^{13}=C^{13}+\epsilon^{+} \\ &C^{13}+H=N^{14}+\gamma, \\ &N^{14}+H=O^{15}+\gamma, \qquad O^{15}=N^{15}+\epsilon^{+} \\ &N^{15}+H=C^{12}+He^{4}. \end{aligned} \quad (2)$$ ← ←

The catalyst C^{12} is reproduced in all cases except about one in 10,000, therefore the abundance of carbon and nitrogen remains practically unchanged (in comparison with the change of the number of protons). The two reactions (1) and

* Awarded an A. Cressy Morrison Prize in 1938, by the New York Academy of Sciences.

This is the first page of Bethe's famous 1938 paper describing Hydrogen fusion into Helium in the solar core as source of the Sun's energy.

Notice that Bethe does not show neutrinos in the final states of reactions (1) and (2). When asked about this omission, he said that he omitted the neutrinos because they are not detectible. Given the low energies of these neutrinos he was almost correct.

(The article abstract is omitted for visual clarity.)

Inverse β Process

Bruno Pontecorvo

(National Research Council of Canada, Division of Atomic Energy. Chalk River, 1946, Report PD-205.

………

An Example

There are several elements which can be used for neutrino radiation in the suggested investigation. Chlorine and Bromine, for example, fulfil reasonably well the desired conditions. The reactions of interest would be:

$\nu + {}^{37}Cl \rightarrow \beta^- + {}^{37}Ar$	$\nu + {}^{79,81}Br \rightarrow \beta^- + {}^{79,81}Kr$
${}^{37}Ar \rightarrow {}^{37}Cl$	${}^{79,81}Kr \rightarrow {}^{79,81}Br$
(34 days; *K* capture)	(34 h; emission of positrons of 0.4 MeV)

The experiment with Chlorine, for example, would consist in irradiating with neutrinos a large volume of Chlorine or Carbon Tetra-Chloride, for a time of the order of one month, and extracting the radioactive ${}^{37}Ar$ from such volume by boiling. The radioactive argon would be introduced inside a small counter; the counting efficiency is close to 100%, because of the high Auger electron yield. Conditions 1, 2, 3, 4 are reasonably fulfilled in this example. It can be shown also that condition 5, implying a relatively low background, is fulfilled.

One short section of the five page 1946 paper by Bruno Pontecorvo - unpublished

UNIVERSITY OF CALIFORNIA

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A PROPOSED EXPERIMENTAL TEST OF THE NEUTRINO THEORY

Luis W. Alvarez

April 18, 1949

In 1949, Alvarez revisited the Pontecorvo ^{37}Cl neutrino Detector proposal with a detailed 58 page proposal – see adjacent cover page of report UCRL-328. His plan just like Pontecorvo's was to detect neutrinos from a reactor (then called a pile). There were several changes.

1) Alvarez used a smaller cross section, ~10^{-45} rather than 10^{-42}. this resulted in a larger detector volume – 25 m^3 rather than 1 m^3 that Pontecorvo used. The Davis detector was 390 m^3.

2) Pontecorvo had proposed boiling the detector to extract the ^{37}Ar. Alvarez planned to flush the detector with helium gas. Davis used a helium flush of the detector to extract the ^{37}Ar.

3) Alvarez developed a specific background evaluation that involved all the potential non-neutrino sources of ^{37}Ar production.

4) Both Pontecorvo and Alvarez discussed use of miniature proportional counters to observe the decay of ^{37}Ar. Davis constructed and used similar devices.

5) The distinction between interactions of neutrinos and anti-neutrinos did not enter into either of these proposals. This was a critical element in the Davis program.

$\sigma(^4He+^3He \rightarrow ^7Be+\gamma)$ is 2500 times larger than previously assumed.

Holmgren & Johnston-Phys Rev 113, 1556 (1959) – 15 March 1959

- This measurement was critical to all future solar neutrino experiments. The resultant solar neutrino fluxes were:

Reaction	Flux	Neutrino Energy
1) $P+P \rightarrow {}^2H + e^+ + \nu_e$	$6 \times 10^{10}\ \nu_e\ /cm^2sec$	$E(\nu_e) < 0.42$ MeV
2) ${}^7Be + e^- \rightarrow {}^7Li + \nu_e$	$4.8 \times 10^9\ \nu_e\ /cm^2sec$	$E(\nu_e) = 0.86$ MeV
3) ${}^7Be + P \rightarrow {}^8B + \gamma$ ${}^8B \rightarrow {}^8Be + e^+ + \nu_e$	$6 \times 10^6\ \nu_e\ /cm^2sec$	$E(\nu_e) < 15$ MeV

Reaction 1 was the only one given in the Bethe paper and it was below the 0.81 MeV threshold for $^{37}Cl \rightarrow ^{37}Ar$. The significant fluxes for reactions 2 & 3, opened the possibility of looking for solar neutrinos with the C_2Cl_4 detector. Both Willy Fowler (CalTech) and A.G.W. Cameron (Atomic Energy-Canada) encouraged Davis to proceed with this search.

The Mottelson Question

- There remained one pressing question – what was the cross section $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$?

- One of the reasons for choosing this detection mode was the long ^{37}Ar lifetime – 35 days. A long product lifetime allowed a long time to collect Ar atoms, but it also meant that the matrix element is small and so, by detailed balance, the reaction cross section is small.

- In the summer of 1963, John Bahcall was giving a talk at the Neils Bohr Institute in Copenhagen describing this situation. Ben Mottelson, who was in the audience, asked John if he had considered transitions to excited states. Indeed, the 5.1 MeV excited state of ^{37}Ar was the analog of the ground state of ^{37}Cl and so neutrinos with E> 6 MeV had a super allowed transition to ^{37}Ar. Even with its extremely small flux, the large strength of this specific transition meant that the ν_e from ^{8}B would be the dominant source of ^{37}Ar in this detector.

- All that was now left to decide was (1) how deep, and (2) how large should the detector be. Of course that meant finding a mine that was willing to house this experiment. And, who would pay for all this?

Cross section for ^{37}Ar production vs Time & Experiment Results
Origins of the Solar Neutrino Problem

- With the Mottelson suggestion included, 90% of the ^{37}Ar production originates from the ^{8}B ν_e even though flux(^{8}B- ν_e) ≅ 2 x10^{-3} x flux (^{7}Be- ν_e) - This critical statement indicates the extreme sensitivity of the predicted signal to a very small flux fraction.

- 6Jan1964-PRL-Bahcall predicts ^{37}Ar production rate 40±20 SNU (10^{-36}/sec, ^{37}Cl atom)

- 6Jan1964- PRL- Davis reports ^{37}Ar production rate < 300 SNU in a 3900 liter C_2Cl_4 detector in the Barberton Mine – (1800 m.w.e.) – Measurement is cosmic ray bkgnd limited

- Davis concludes, in this paper, that detector volume must be increased to 390,000 liters and depth increased to at least 4000 mwe. – The parameters of the Homestake Detector are set.

- 11July1966 – Bahcall gives production rate as 30^{+30}_{-13} SNU – consistent with earlier rate

- 16April1968-PRL-Davis reports first results from the Homestake Detector < 3 SNU

- 16April1968 – PRL- Bahcall gives revised prediction of 7.5 ± 3.0 SNU

- **The Solar Neutrino Problem is born –observed signal ~ 1/3 of predicted**
    - (this observed to predicted ratio persists as precision improves)

What Could be Wrong?

- 1) In the Sun
- a) Is ^8B flux wrong – due to cross sections or temperature in center of Sun-
- note that the rate of $4P \rightarrow {}^4He + 2e^+ + 2\,\nu_e$ is determined by solar thermal
- emission rate – Much effort spent exploring this possibility
- 2) Between Sun and Earth
- a) ν_e decay (ruled out by SN87a) or ν_e convert into something else (next frame)
- 3) At the Detector
- a) Is $\sigma(\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-)$ wrong? Partially tested with LAMPF beam stop ν_e
- $\rightarrow$ b) Is there a problem with the extraction of ^{37}Ar from the tank?
- $\rightarrow$ c) Is there a problem with counting ^{37}Ar decays?
- (b) and (c) are related to the experiment – the others are theoretical

Neutrino Oscillations - 1968

Volume 28B, number 7 PHYSICS LETTERS 20 January 1969

NEUTRINO ASTRONOMY AND LEPTON CHARGE

V. GRIBOV * and B. PONTECORVO
Joint Institute for Nuclear Research, Dubna, USSR

Received 20 December 1968

It is shown that lepton nonconservation might lead to a decrease in the number of detectable solar neutrinos at the earth surface, because of $\nu_e \rightleftarrows \nu_\mu$ oscillations, similar to $K^o \rightleftarrows \tilde{K}^o$ oscillations. Equations are presented describing such oscillations for the case when there exist only four neutrino states.

A few months after Davis announced his low upper limit on the rate of ^{37}Ar production in the 390,000 liter C_2Cl_4 detector, Gribov & Pontecorvo suggested that this flux reduction might result from the conversion of some $\nu_e \rightarrow \nu_\mu$ during their flight from the Sun to the Earth, analogous to the oscillation of $K^o \rightarrow \bar{K}^o$. At the time this idea was dismissed since it only reduced the intensity by a factor of 2 rather than 3. Of course, the Gribov-Pontecorvo suggestion occurred a decade before the third neutrino was discovered. Had the ν_τ been discovered earlier, and this paper had subsequently explained why a factor of 3 reduction could occur, much of the subsequent developments might have been quite different.

The 1/e extraction time was about 7 hours. The extraction was run for three time constants or 20 hours for an extraction efficiency of ~ 95%.

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The flow rate through the external charcoal trap was 350 liters/min of He using 2 out of 40 eductors.

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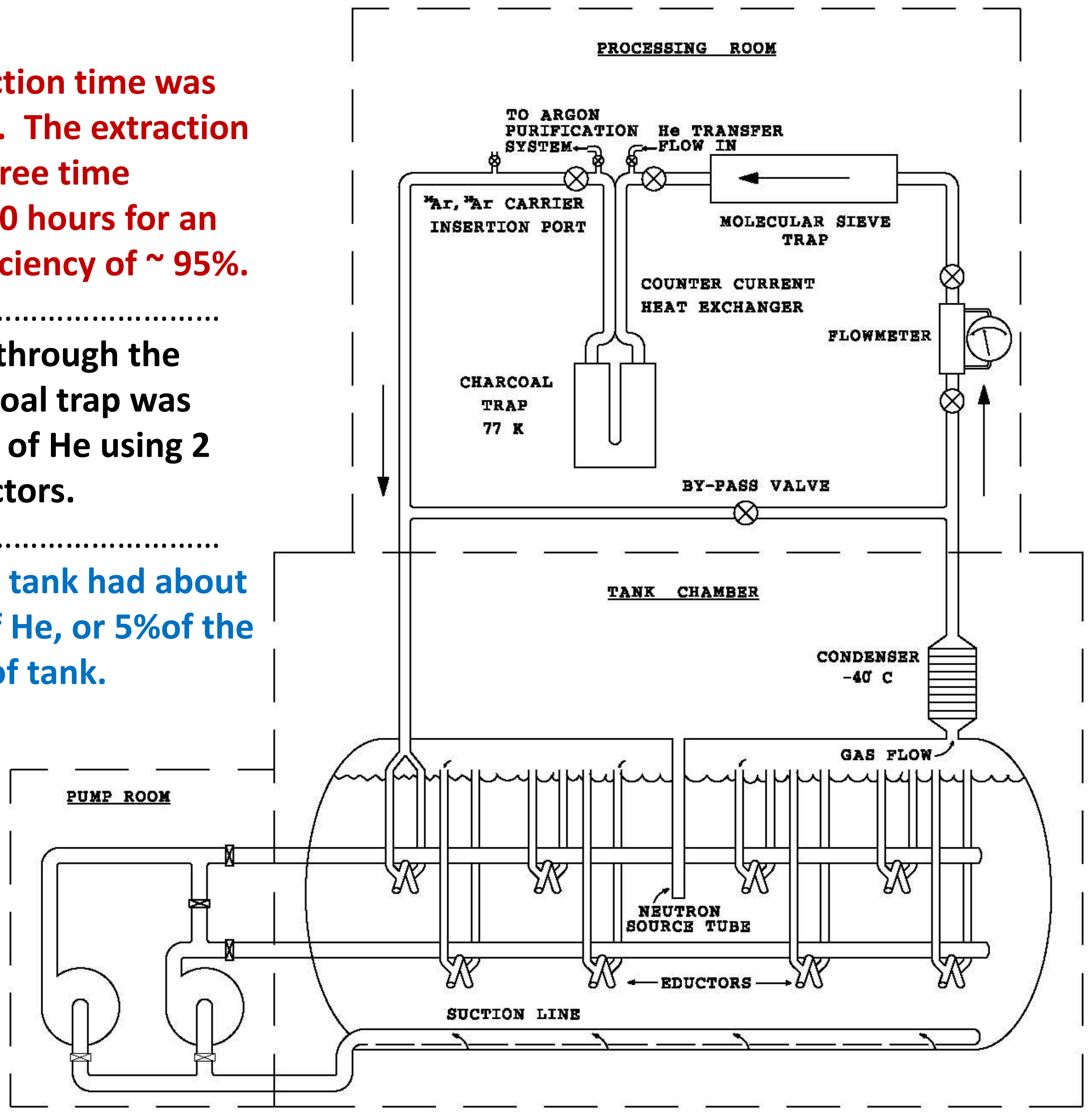
The top of the tank had about 20000 liters of He, or 5%of the total volume of tank.



Inputs Required to Obtain the Measured

Solar ν_e Flux from the Chlorine Experiment

1) Flux of neutrinos from Sun as function of Energy – Theoretical contribution – common for all experiments

2) Cross section vs energy for $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$ - Theoretical contribution

3) Extraction efficiency of ^{37}Ar from the C_2Cl_4 fluid in the tank – Will be described

4) Counting efficiency of ^{37}Ar in proportional counters – Measured with ^{127}Xe – coming up

5) Background contribution to the total ^{37}Ar production rate – Estimation methods will be discussed

Extraction Rate of Air Argon dissolved in the C2Cl4 when the Cl detector was first filled

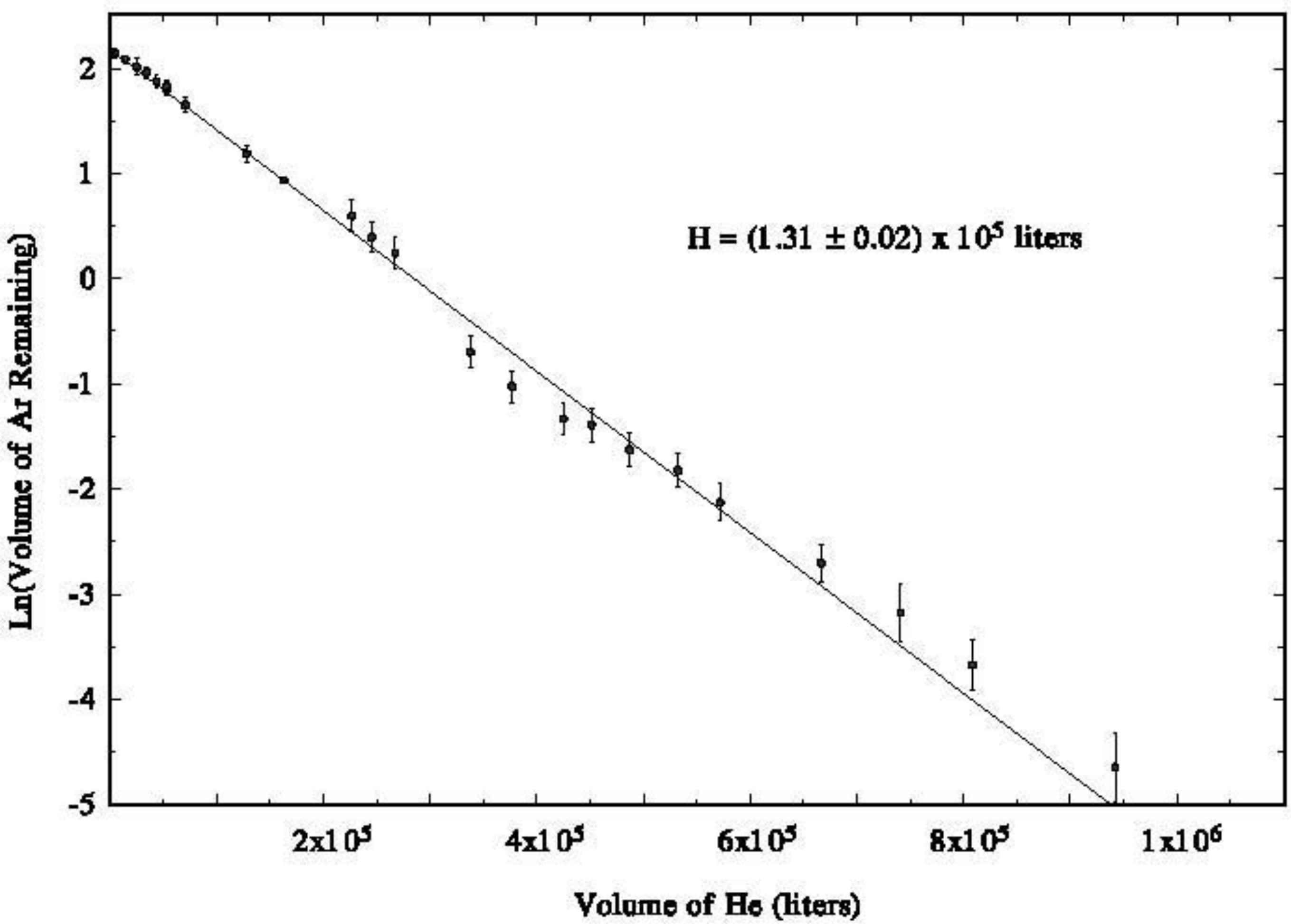


FIG. 6.—Removal of air argon. Amount of air argon remaining in the C_2Cl_4 tank as function of the volume of helium that flowed through the system during the initial purge. The response of the system does not deviate from an exponential for over 3 orders of magnitude.

This plot is shows the rate of air argon extraction from the C_2Cl_4 when the tank was first filled. The dissolved argon concentration in the fluid was uniform throughout the tank volume. The fit to a single exponential indicates that there are no regions of the tank that have lower extraction efficiencies.

Also, the extraction coefficient here is consistent with that obtained for the carrier extraction rates for the individual solar neutrino runs.

Argon Isotope Carriers

Natural argon composition is 99.60% ^{40}Ar, 0.06% ^{38}Ar, 0.33% ^{36}Ar

At the end of each run, about 0.1 cm^3 of argon carrier gas was introduced into the tank. We alternated carrier gas between ^{36}Ar and ^{38}Ar.

So, for example, at the end of run N, we added 0.1 cm^3 of ^{36}Ar to the tank. In the tank there was 5% of the ^{38}Ar carrier from run N-1 that had not been extracted during the run N extraction.

Two months later, extraction N+1 was carried out. During this run, 95% of the 0.1 cm^3 of ^{36}Ar added two months earlier and 95% of the 0.005 cm^3 of ^{38}Ar remaining from run N-1 were extracted.

Of course, the procedure was to operate the extraction system for 20 hours and then measure the fraction of the inserted carrier that was recovered. The extraction efficiency was determined from the fraction of recovered carrier. This run by run measured extraction rate was essentially the same as that measured for the initial purge of the air argon from the tank.

There were no extraction anomalies.

Could the ^{37}Ar ion be Trapped in the C_2Cl_3 Molecule Remnant?

- It seemed highly unlikely that such an ionic trap could occur, but given the Solar Neutrino Problem concerns in the mid-1970's, Davis proceeded to devise a test of even this possibility.

- The procedure was to first produce C_2Cl_4 where one of the Cl atoms was ^{36}Cl (unstable with $\tau_{1/2} = 3 \times 10^5$ yrs) – total of 0.2 gms of ^{36}Cl. $^{36}Cl \rightarrow {}^{36}Ar + e^- + \bar{\nu}_e$ with a momentum transfer comparable to that involved in solar neutrino capture. Finally, the ^{36}Ar was exposed to neutron capture in the BNL reactor and converted to ^{37}Ar and then counted in the standard system. The yield was 100 ± 3%.

- There was no indication of ion trapping and

- all tests of the extraction procedure indicated that ^{37}Ar produced by solar neutrinos was

- efficiently extracted.

- All of these extraction tests were completed in the 1970-1984 time interval

The Problems of 1984-5.

- 1) In 1984 Ray Davis reached the mandatory Brookhaven retirement age of 70.
- 2) The Homestake Chlorine experiment reached a plateau, measurements inconsistent with theory.
- 3) And then, two major equipment failures – first one of the C_2Cl_4 circulation pumps failed and a few months later, the second one failed – the experiment was DEAD! Brookhaven notified the D.O.E. that it was prepared to terminate the experiment.
- Fortunately, the University of Pennsylvania intervened.
-
- 1)Davis was appointed a Research Professor at Penn,
- 2) the Dean of the University of Pennsylvania School of Arts and Science provided funds to purchase a replacement pump so that the experiment could resume and
- 3) the NSF took over support of the experiment.
- By mid-1986, the experiment was back in operation.

Homestake Chlorine Detector after 1986

- Personnel- over the next several years the group enlarged-in addition to Davis, Lande and Bruce Cleveland, who came to Penn after several years at Los Alamos, there were:

- Research scientist –C.K. Lee, Engineer – Tim Daily,
- Graduate students – Paul Wildenhain and Jim Distel

- Data taking – install a small computer based data taking system that permitted us to expand the energy and rise time range of the recorded proportional counter signals.

- Calibrate and recalibrate all the proportional counters both with ^{37}Ar and with ^{127}Xe. The former was produced at Penn by $^{40}Ca(n,\alpha)^{37}Ar$. We were extremely fortunate that Wick Haxton and Eric Adelberger were kind enough to produce ^{127}Xe for us.

- Carried out a cosmic ray sensitivity study at Fermilab with 200 GeV muons, and

- Carried out lower energy neutrino cross section measurement with neutrinos from the LAMPF beam stop.

- In addition, we embarked on a campaign to acquire as much data as possible so that we could reduce the statistical precision of our measurement to ± 5%.

Solar Neutrino Selected Chronology-continued

- 1985 – Mikhe'ev and Smirnov point out that resonant oscillations in the passage out of the Sun can drive $\nu_e \rightarrow \nu_\mu$ and/or ν_τ the MSW effect. Since the Chlorine detector is sensitive to only , a reduced detection rate is expected from this mechanism. Is this the resolution to the Solar Neutrino Problem?

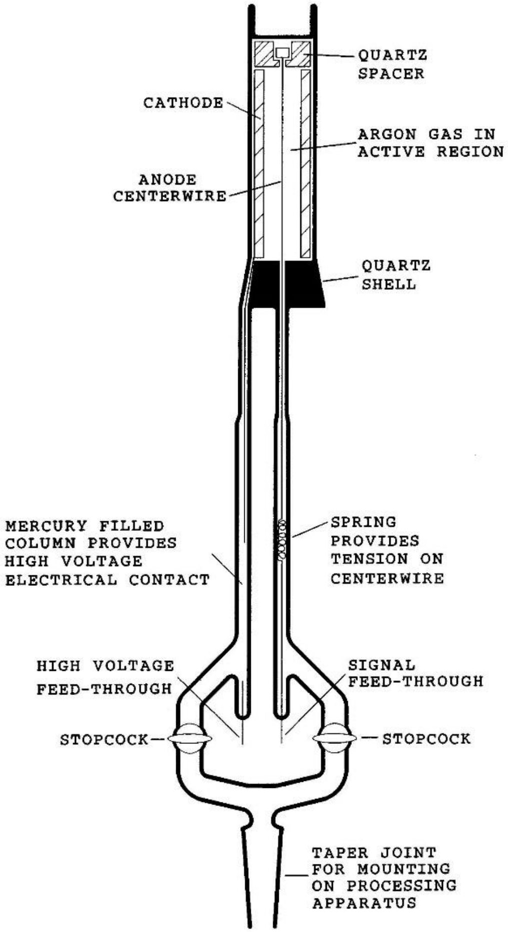
- 1989- PRL-Kamiokande publishes first results from ν –electron scattering in its water Cerenkov detector, the fraction of the 8B neutrino flux detected =0.46 ± 0.13(stat) ± 0.08(syst) and one year later these uncertainties are reduced to ± 0.05(stat) ± 0.06(syst) .

- The good news was that another, quite different detector has also observed a solar neutrino flux that is substantially lower than predicted. The confusing situation was that the Kamiokande measured signal was larger than the Chlorine measurement. Why?

- 1) Astronomy solution - The two measurements were just statistical fluctuations from the same neutrino signal AND the neutrino flux generated in the Sun was significantly smaller than predicted by the Solar Model.
- 2) Physics solution- The difference in the two measurements is due to neutrino physics, possibly the MSW effect, and the Solar Model is unaffected.
- THE SOLUTION –Reduce uncertainties of both measurements & see if the differences remain.

Proportional Counter

Active region is 30 mm long & 4.5 mm diameter



^{37}Ar decays by K shell orbital electron capture. This emits several gammas with a total energy of 2.82 keV. Since these gammas interact locally, the emitted pulse has a short rise time.

Background consists primarily of Compton scattered electrons which travel an appreciable distance and so have a longer rise time.

The significant diameter to length ratio of the active region results in an appreciable fringe field region where the amplitude of ^{37}Ar decays pulses are decreased resulting in a larger acceptance window and a higher background. Half of ^{127}Xe have similar K orbital Auger electrons in coincidence with two gamma rays. By specifying the decay location with the two gamma rays, it is possible to measure the Auger electron signal amplitude as a function of position in the active region. This improved the calibration and helped in the design of end disks for the active region that reduced the fringe field effect.

Proportional Counter Calibrations

Pulse amplitude-Energy

Slope of Pulse Front Edge-inverse rise time

^{37}Ar fill

Solar data-first 3 $\tau_{1/2}$

Solar data-late

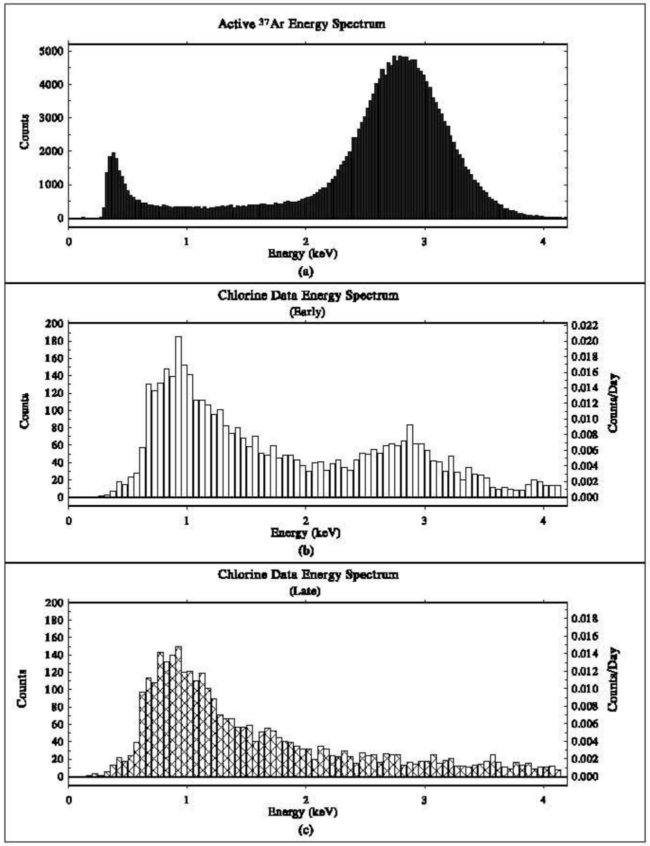


FIG. 9.—(*a*) Energy spectrum from a counter filled with active ^{37}Ar. (*b*) Cumulative energy spectrum from 93 solar neutrino observations (early counting data: 0–105 days following the end of an extraction). (*c*) Cumulative energy spectrum from 93 solar neutrino observations (late counting data: 175–350 days following the end of an extraction). Plots (*b*) and (*c*) are of events with normalized ADP between 0.85 and 1.02 (i.e., fast events).

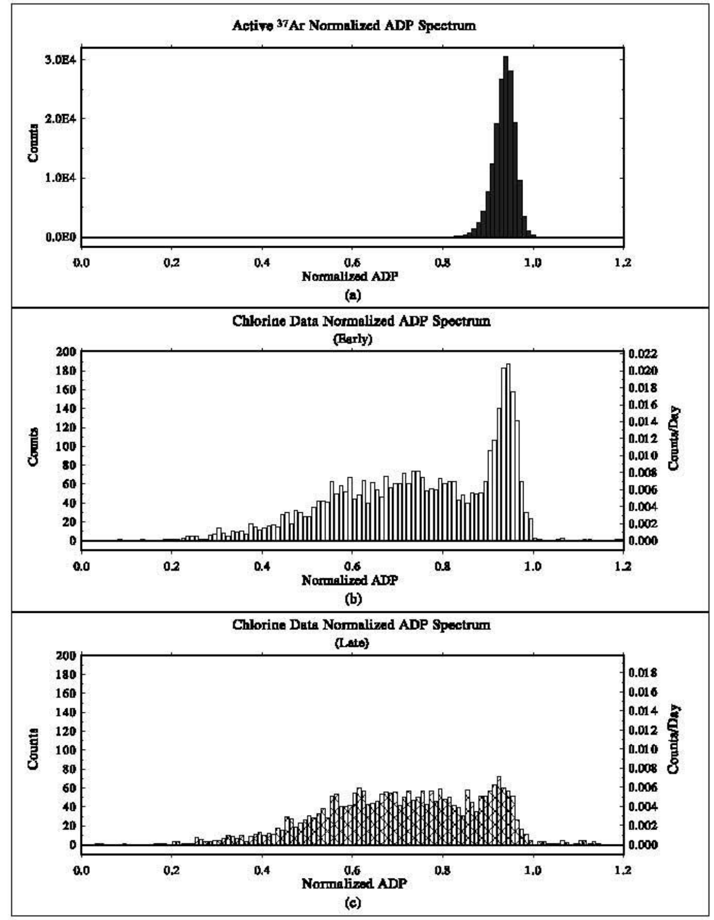
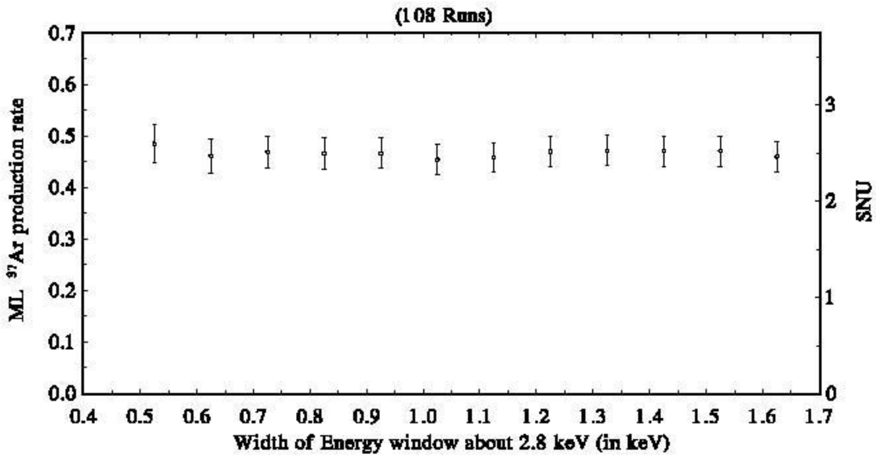


FIG. 10.—(*a*) ADP spectrum from a counter filled with active ^{37}Ar. (*b*) Cumulative ADP spectrum from 93 solar neutrino observations (early counting data: 0–105 days following the end of an extraction). (*c*) Cumulative ADP spectrum from 93 solar neutrino observations (late counting data: 175–350 days following the end of an extraction). Plots (*b*) and (*c*) are of events with energy between 2.0 and 3.6 keV.

Chlorine Experiment Results



The final result was the rate at which solar electron neutrinos interact is

2.56±0.16(stat)±0.16(syst) SNU