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Solar Neutrinos*

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INTRODUCTION

The prospect of studying the solar energy generation process directly by observing the solar neutrino radiation has been discussed for many years. The main difficulty with this approach is that the sun emits predominantly low energy neutrinos, and detectors for observing low fluxes of low energy neutrinos have not been developed. However, experimental techniques have been developed for observing neutrinos, and one can foresee that in the near future these techniques will be improved sufficiently in sensitivity to observe solar neutrinos. At present several experiments are being designed and hopefully will be operating in the next year or so. We will discuss an experiment based upon the neutrino capture reaction

$$\nu + Cl^{37} \longrightarrow Ar^{37} + e^- . \qquad (1)$$

This reaction is the inverse of the electron-capture radioactive decay of argon-37. The method depends upon exposing a large volume of a chlorine compound, removing the radioactive argon-37 and observing the characteristic decay in a small low-level counter. A high sensitivity for neutrino detection is achieved by using a large mass of chlorine and performing the counting measurements in a counter with a very low background. An experiment will be described that has been performed with 1000 gallons (6.1 tons) of perchloroethylene (C_2Cl_4) that served as a pilot experiment to test the method. A

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detector one hundred times larger is now being built that is designed to measure the presently calculated solar neutrino flux. The design and aims of this experiment will be described.

In planning a solar neutrino experiment one is guided by the present calculations of solar neutrino fluxes. These calculations have been developed in recent years, and one presently has confidence that the neutrino flux can be calculated within a factor of two. Sears[1] in particular has calculated the solar neutrino flux with his model using various values for the solar composition, age, luminosity, and nuclear parameters to test the errors introduced in the values of neutrino flux. Independent calculations have also been performed by Pochoda and Reeves,[2] and Cameron and Ezer,[3] and their results agree within a factor of two with those of Sears. It is generally agreed that the P-P chain of reactions is the dominant mechanism for the sun. In this chain, neutrinos are produced by three processes, the $H(H,e^+\nu)D$ reaction and the radioactive decays of Be^7 and B^8. The neutrino spectrum from these three sources may be combined to represent the gross neutrino spectrum from the sun. Figure 1 shows this spectrum and the fluxes of neutrinos at the earth as calculated by Sears. The neutrinos from the $H(H,e^+\nu)D$ reaction are below the threshold (0.816 MeV) for the capture reaction (1). However, the 0.861 MeV neutrino line from the Be^7 decay is above threshold for reaction (1), and contributes about ten percent of the expected capture rate in chlorine-37. The flux of energetic neutrinos from the B^8 decay (E_{max} = 14.2 MeV) is only 1.9×10^7 cm^{-2} sec^{-1} since the $Be^7(p,\gamma)B^8$ reaction plays only a minor role in the solar energy generation process. However, the cross section of reaction (1) is so large for these energetic neutrinos that the B^8 neutrinos would be expected to produce about 90 percent of the total signal in a detector based upon the $Cl^{37}(\nu,e^-)Ar^{37}$ reaction.

The reason that the cross section is high for these energetic neutrinos is that neutrinos above 6.0 MeV energy will be captured to produce an excited state in Ar^{37} at 5.2 MeV. Bahcall[4] has pointed out that this state is the analog state to the ground state in Cl^{37} and hence the neutrino capture to form this analog state is a superallowed transition and therefore has a high cross section. Bahcall's prediction has been recently verified by two separate experimental groups, at Brookhaven[5] and at McGill.[6] They observed the beta decay of Ca^{37} to reveal the 5.2-MeV level in the mirror nucleus K^{37}. The fact that the cross section for energetic neutrinos is large, had led us to believe we could observe the B^8 solar neutrinos by the Cl^{37}-Ar^{37} method.[4,7] It is interesting to note that the production of B^8 in the sun depends strongly on the central temperature, therefore a measurement of the B^8 neutrino flux allows one to deduce an accurate value for the central temperature of the sun.

Using the calculated solar-neutrino fluxes from Be^7 and B^8 and the values of the cross section for the $Cl^{37}(\nu, e^-)Ar^{37}$ reaction one deduces the value of the

$$\sum \phi\sigma = 3 \pm 2 \times 10^{-35} \text{ sec}^{-1} .$$

The error indicated reflects the uncertainties in the solar model calculation. The error in the cross section values are small, around 10 percent. This sum of the products of the flux and the cross section would correspond to an expected capture rate of 5 ± 3 per day in 600 tons of perchloroethylene. Let us now describe the pilot experiment which uses 1000 gallons of perchloroethylene to illustrate how a neutrino detector based upon reaction (1) operates. The performance of this modest scale detector will also show how close we are to observing the presently calculated solar neutrino flux.

THE PILOT EXPERIMENT

Let me review briefly the history of the method. The advantages of the Cl^{37}-Ar^{37} method of detecting neutrinos was pointed out 18 years ago by Pontecorvo.[8] The experimental method was outlined and background effects were analyzed in detail by Alvarez[9] with the view of using the technique to observe neutrinos at a nuclear reactor. We developed a detector based upon these suggestions and performed experiments near a Savannah River reactor.[10] Since a nuclear reactor is a source of antineutrinos we found these antineutrinos would not drive the reaction. In terms of present concepts, these experiments served to test the principle of lepton conservation.

It was apparent that the Cl^{37}-Ar^{37} method with its inherent sensitivity to low-energy neutrinos would be useful to observe solar neutrinos.[7] The sensitivity of the apparatus was severely limited during the Savannah River experiments by a large background effect from cosmic ray muons. By placing the apparatus 2300 feet underground (1800 meters of water equivalent) the cosmic ray background effects were reduced to a negligibly small value. We used the limestone mine of the Pittsburgh Plate Glass Company at Barberton Ohio. Figure 2 is a photograph of the apparatus. It consisted of two 500 gallon tanks (total of 6.1 metric tons) of perchloroethylene, C_2Cl_4, equipped with agitators, and a helium purging system. Helium was passed through the tanks in series, through condensation traps and finally through a liquid nitrogen cooled charcoal trap. At the liquid nitrogen temperatures used, argon was adsorbed on the charcoal and helium passed through without adsorption. By this simple procedure any argon-37 produced in the tanks could be removed and transferred to a small charcoal trap with an efficiency of 90-95 percent. The efficiency of this process was measured by the isotope dilution method in each experiment by introducing 0.05 cm^3 of Ar^{36} carrier at the start of each exposure and performing a mass analysis of the recovered argon. The argon so isolated was removed from the charcoal, purified, and counted in a small low-level counter. Pulse height analysis was used to observe the 2.8 keV Auger electron from the electron-capture decay of argon-37. The counter was operated in anticoincidence with guard proportional and scintillation counters, a technique commonly used in low-level counting. The pulse height spectrum is shown in Fig. 3. The position of the argon-37 Auger electron peak was determined by calibrating the counter with Fe^{55} X-radiation. The position of the argon-37 peak is shown, and it can be seen that no distinguishable argon-37 peak was observed. A safe upper limit to the neutrino-capture rate may be deduced by taking all the events in the argon-37 region of the spectrum, and computing the limiting solar neutrino capture rate.

The rate so derived was found to be less than 0.3 neutrino captures per day in the 6.1 tons of C_2Cl_4. In terms of product of flux and cross section the limit may be given as

$$\sum \phi\sigma \leq 16 \times 10^{-35} \text{ sec}^{-1} .$$

This value may be compared to the calculated value for this product for solar neutrinos discussed earlier,

$$\sum_{\text{Solar}} \phi\sigma = 3 \pm 2 \times 10^{-35} \text{ sec}^{-1} .$$

It is apparent from a comparison of the experimental limit from this 1000-gallon detector that we are a factor of five away from detecting the calculated rate.

The results of the 1000-gallon experiment may be used to set limits on the extraterrestrial neutrino flux. Since there have been speculations on possible values of the neutrino flux it is interesting to note the limits that can be set as a function of the neutrino energy. Combining our results and the cross sections of Bahcall[4] for the $Cl^{37}(\nu, e^-)Ar^{37}$ reaction, the neutrino flux limits given in Table 1 were calculated. The limit set for 1 MeV neutrinos, barely over threshold, is not very low. On the other hand for 10 MeV neutrinos where the super allowed capture process to form the 5.2 MeV excited state in argon-37 is important, an upper limit of 1×10^{8} cm^{-2} sec^{-1} can be set. This limit allows us to conclude that less than 0.2 percent of the solar energy cycle goes through the formation of Li^4. If Li^4 were stable one would expect its beta decay to He^4 would produce energetic neutrinos which would dominate the solar neutrino spectrum and these would have been observed by the experiment. If the central temperature of the sun were somewhat higher than 16 million degrees the B^8 production would be higher. Using the flux limits tabulated, one concludes the central temperature of the sun is below 19 million degrees.

The limit is given for 100 MeV neutrinos, but above a few hundred MeV the Cl^{37}-Ar^{37} radiochemical method would not be particularly sensitive. This is because the nucleon struck by the incoming neutrino with several hundred MeV energy would leave the nucleus and argon-37 would not be the final product nucleus.

PLANS FOR A LARGE SCALE EXPERIMENT

The sensitivity of the Cl^{37}-Ar^{37} method can be improved by increasing the volume of perchloroethylene used in the detector. We are now planning an experiment using 100,000 gallons or 610 tons of perchloroethylene. A volume of liquid of this magnitude can be processed to remove argon by the same helium sweeping method used in the pilot experiment. However, to accomplish the task in a day it is important to make the process more efficient by improving the contact between the helium gas and the liquid. This will be accomplished by the use of a pump-eductor system, and we plan to be able to remove the argon-37 in 10 hours with better than 90 percent efficiency.

The main problem in scaling up the sensitivity is to keep background effects a factor of at least 50 below the calculated solar-neutrino signal. The major background effect is from cosmic radiation. Cosmic-ray muons produce protons in the liquid, and these protons produce argon-37 by $Cl^{37}(p,n)Ar^{37}$ reaction. The argon-37 production rate by muons has been measured at a depth of 25 m.w.e., and from the known muon intensity and cross section for muon interaction the argon-37 production rate can be calculated as a function of the depth. Figure 4 shows the argon-37 production rate in 100,000 gallons of perchloroethylene from cosmic-ray muons at various depths. Also indicated on this plot is the argon-37 production rate expected from solar neutrinos, and the corresponding rates in various mines in the United States and India. It can be seen from this curve that the detector must be located at a depth of over 4000 m.w.e., or about 4400 feet of rock. Several mines in the United States could be used, and we are now negotiating for the use of one of these mines.

There is a background effect from fast neutrons from the rock wall. These neutrons produce argon-37 in the liquid by (n,p) followed by the $Cl^{37}(p,n)Ar^{37}$ reaction. Fast neutrons are produced by (α,n) reactions and spontaneous fission from the small amounts of uranium and thorium contained in the rock in the parts per million range. We have measured this fast-neutron background effect in two mines, and find the effect is at least a factor of 20 below the expected solar-neutrino signal. However, we are providing a water shield between the rock wall and the tank. This will be actually accomplished by flooding the tank chamber with water. Another source of background arises from small amounts of calcium and sulfur contained in the liquid. However, we find that commercial grade perchloroethylene is free of these impurities and background effects from this source is negligibly small.

Thus by placing the 10^5 gallons of C_2Cl_4 below 4000 m.w.e., providing fast-neutron shielding and insuring the Ca and S content is low, the expected solar-neutrino signal will be clearly above the background of the detector. If Ar^{37} is observed it may be attributed to a neutrino signal. The expected rate in the 610 tons is about 2 to 8 per day. With our expected sensitivity we can measure the presently calculated solar neutrino flux to 10 percent, or if the signal is below the presently calculated value we will be able to look for fluxes a factor of 10 lower. It would of course be important, if a definite signal is observed, to test whether the neutrinos are indeed coming from the sun. Since this method does not have directional sensitivity, one would have to look for a 7 percent difference in flux resulting from the eccentricity of the earth's orbit. At the levels presently calculated this would not be possible with 10^5 gallons. If a higher rate is observed this test could be made.

The general arrangement of the 100,000 gallon experiment is shown in Fig. 5. Shown here is a tank 20 feet in diameter and 48 feet long in a rock cavity. Provision is made to flood the cavity for a fast-neutron shield. The equipment for purging the liquid with helium will be contained in a separate cavity indicated as the process control room. The pumps for circulating the liquid through the eductor system will be located near the base of the tank but outside of the flooded cavity. We plan to have this apparatus ready for the first experiment early in 1966.

Table 1

Limits on the Extraterrestrial Neutrino Flux

Neutrino Energy in MeV	Cross Section in cm^2	Upper Limit to the Neutrino Flux cm^{-2} sec^{-1}
1	5.5×10^{-46}	$< 3 \times 10^{11}$
5	9.3×10^{-44}	$< 2 \times 10^{9}$
10	2.3×10^{-42}	$< 7 \times 10^{7}$
100	8.3×10^{-40}	$< 2 \times 10^{5}$

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Fig. 1. Spectrum of solar neutrinos, and flux of neutrinos at the earth.

Fig. 2. Photograph of the 1000 gallon experiment in the Barberton limestone mine, Ohio.

Fig. 3. Pulse height spectrum of the argon extracted from the 1000 gallons of perchloroethylene exposed in the Barberton mine. The resolution of the counter for argon-37 is indicated.

Fig. 4. The major background effect in the Cl^{37}-Ar^{37} neutrino detection method is the production of argon-37 by the $Cl^{37}(p,n)Ar^{37}$ reaction in the liquid perchloroethylene by protons arising from the interactions of cosmic ray muons. The plot shows the cosmic ray muon produced argon-37 as a function of the depth in meters of water equivalent. The depths of several mines in the United States are shown that would afford sufficient cosmic ray shielding for a solar neutrino experiment. The Kolar mine in India is the deepest mine in the world.

Fig. 5. Schematic layout for the Brookhaven Solar Neutrino experiment.

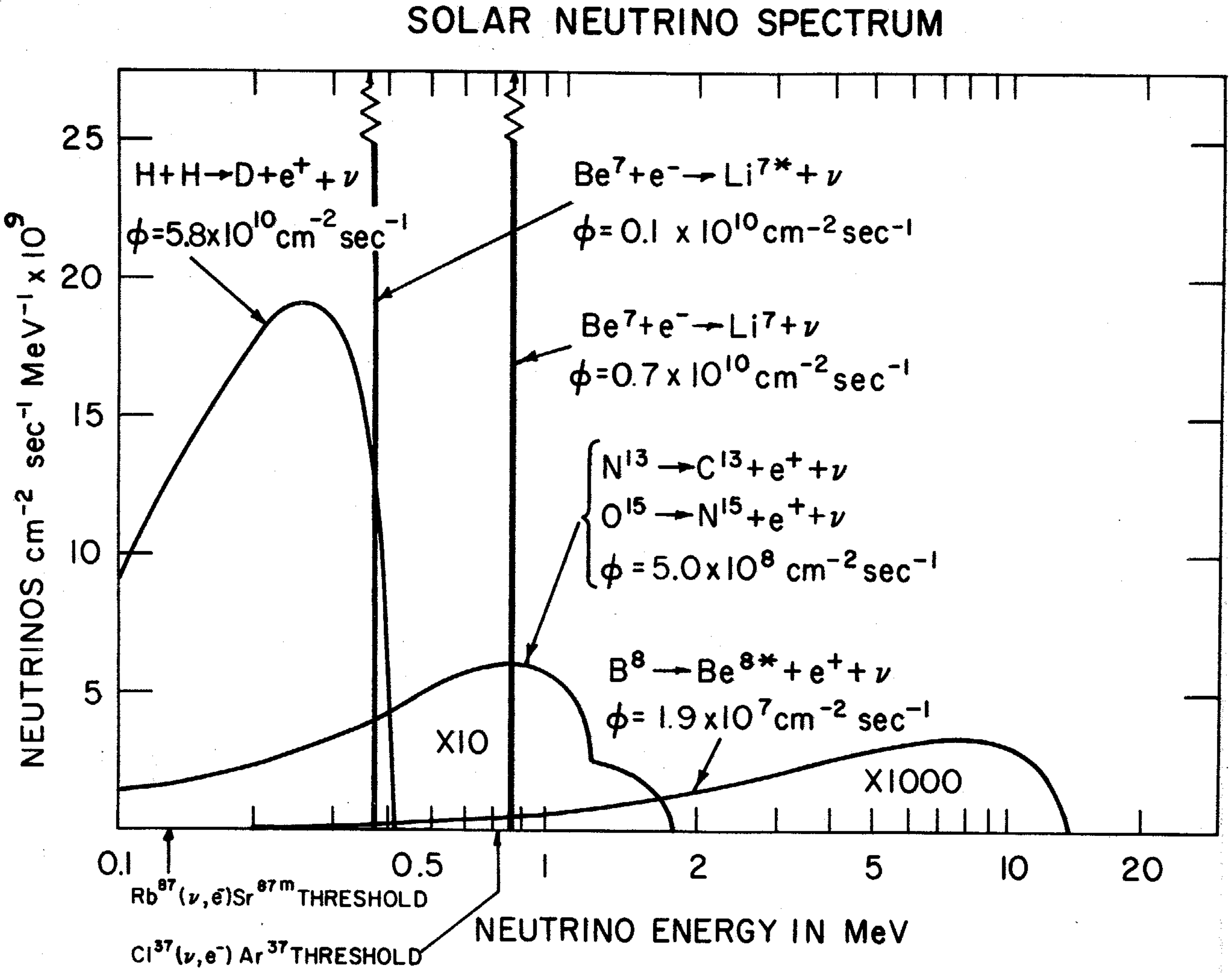
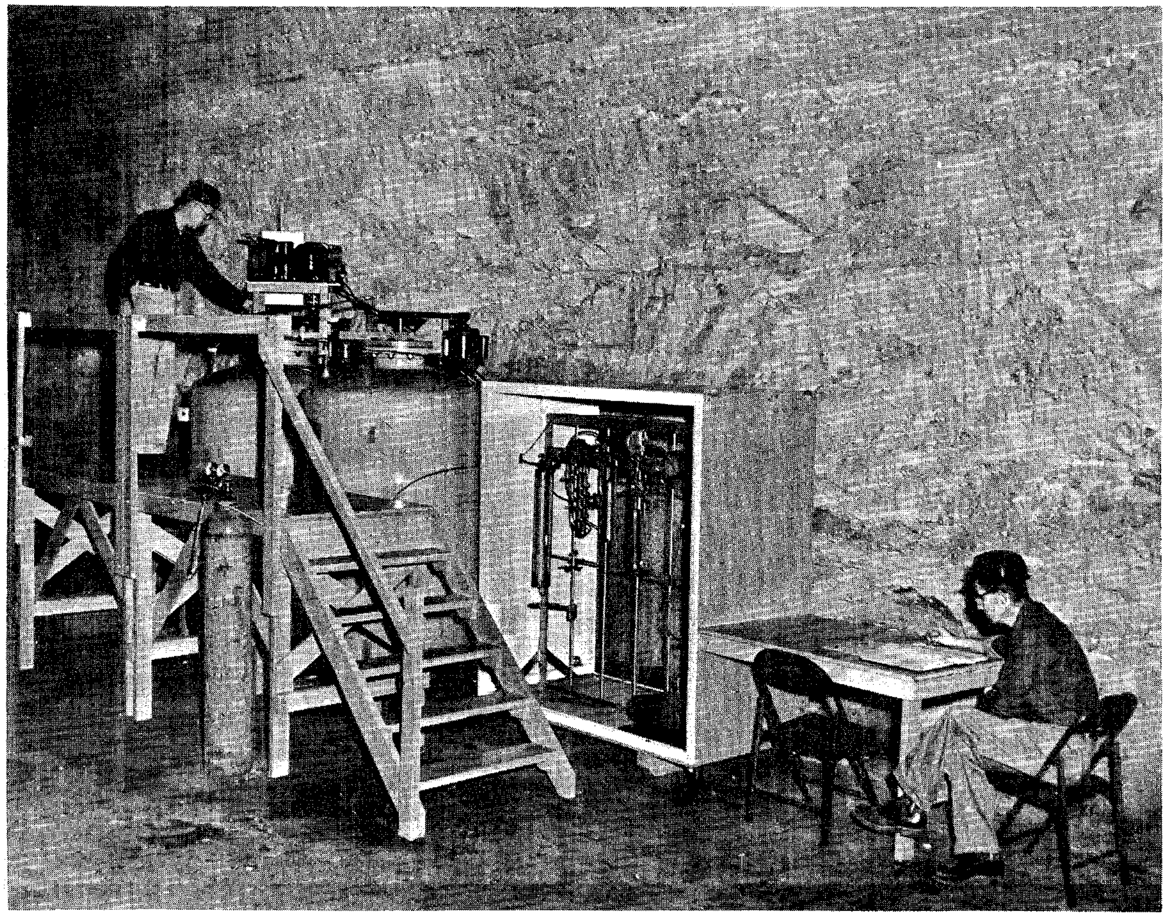

SOLAR NEUTRINO SPECTRUM
NEUTRINOS cm^{-2} sec^{-1} $MeV^{-1} \times 10^{9}$
25
20
15
10
5
$H+H \rightarrow D+e^{+}+\nu$
$\phi=5.8\times10^{10} cm^{-2} sec^{-1}$
$Be^{7}+e^{-} \rightarrow Li^{7*}+\nu$
$\phi=0.1\times10^{10} cm^{-2} sec^{-1}$
$Be^{7}+e^{-} \rightarrow Li^{7}+\nu$
$\phi=0.7\times10^{10} cm^{-2} sec^{-1}$
$N^{13} \rightarrow C^{13}+e^{+}+\nu$
$O^{15} \rightarrow N^{15}+e^{+}+\nu$
$\phi=5.0\times10^{8} cm^{-2} sec^{-1}$
$B^{8} \rightarrow Be^{8*}+e^{+}+\nu$
$\phi=1.9\times10^{7} cm^{-2} sec^{-1}$
X10
X1000
0.1
0.5
1
2
5
10
20
$Rb^{87}(\nu,e^{-})Sr^{87m}$ THRESHOLD
$Cl^{37}(\nu,e^{-})Ar^{37}$ THRESHOLD
NEUTRINO ENERGY IN MeV

FIGURE 1



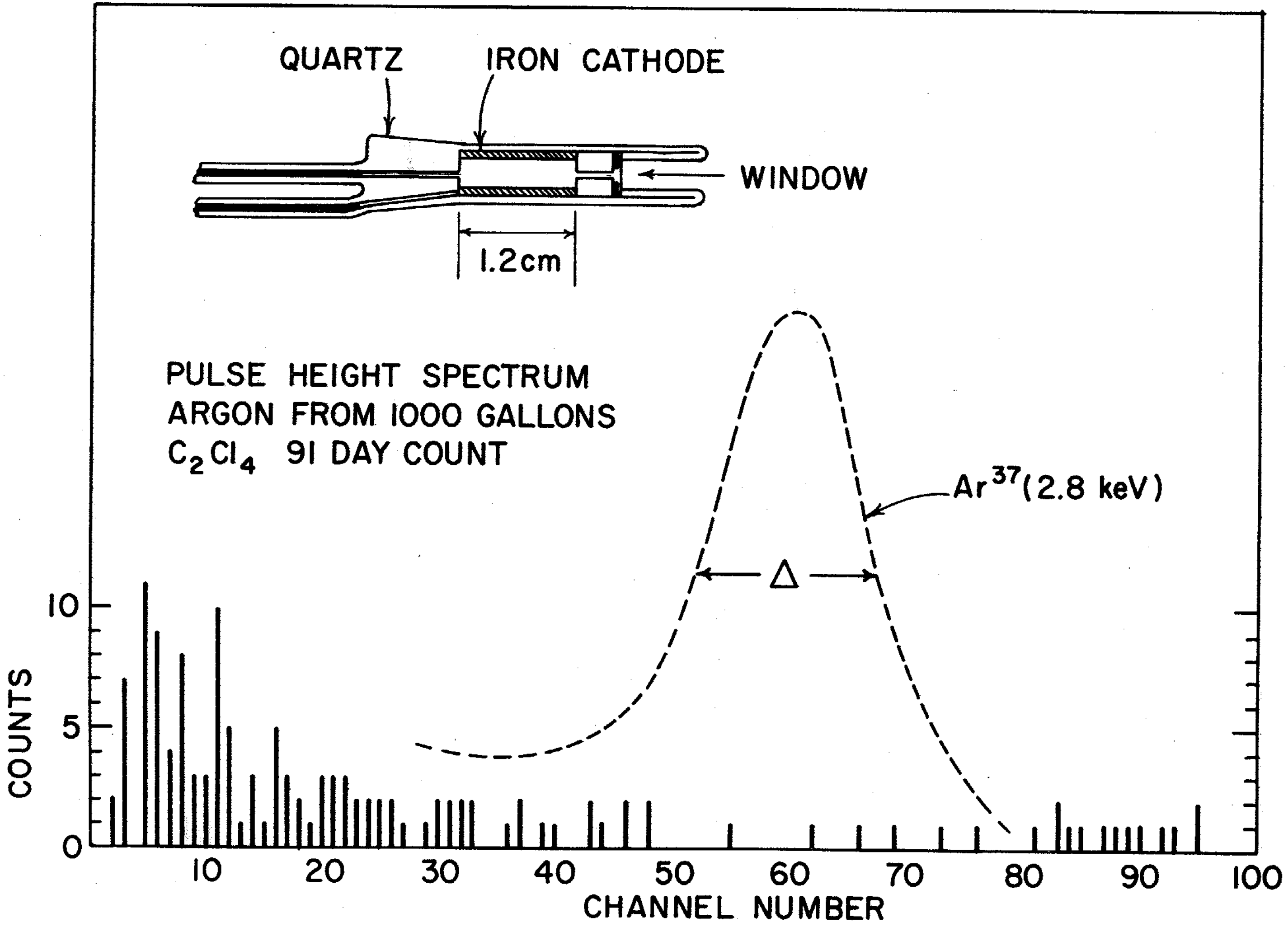
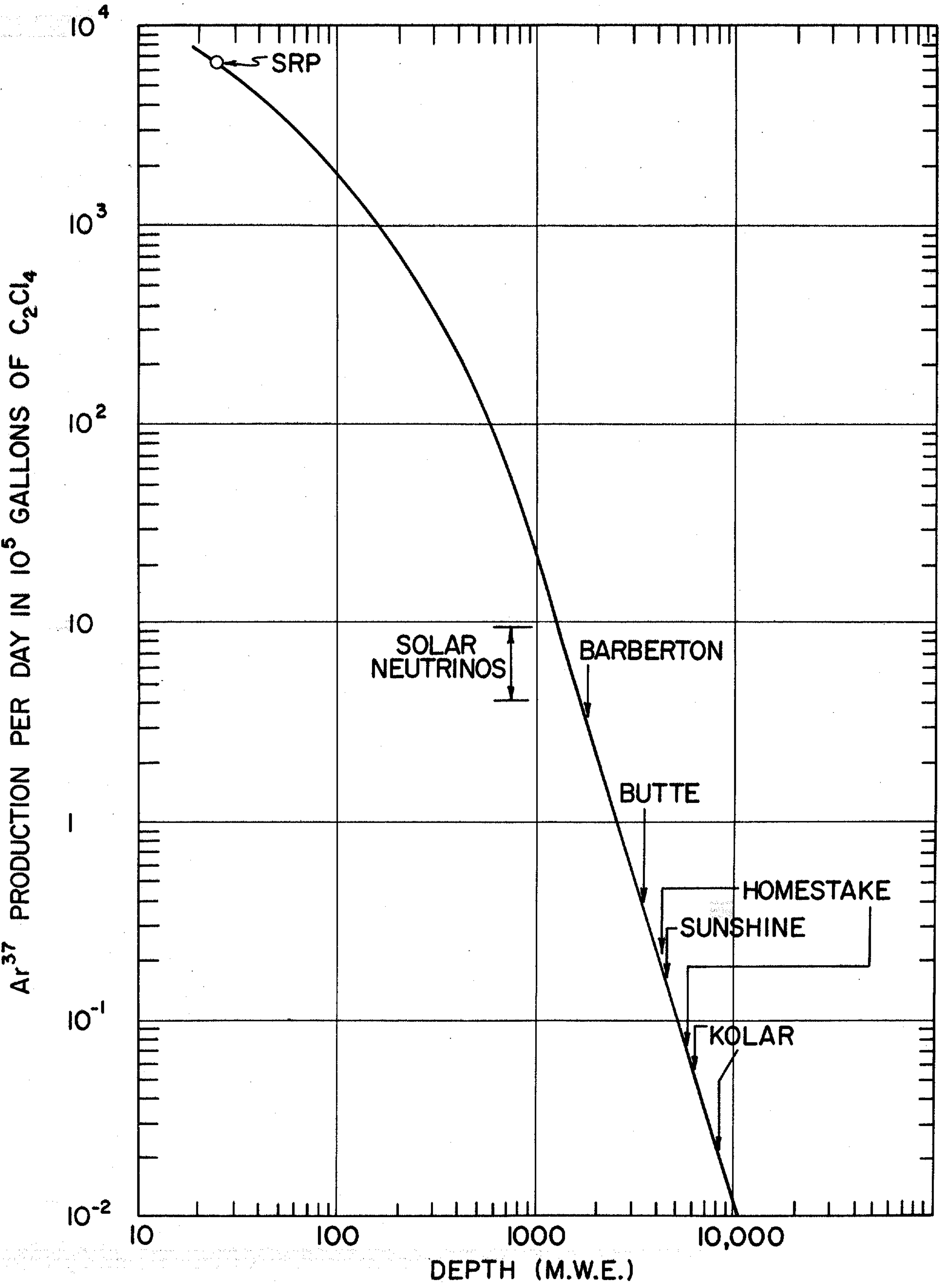

QUARTZ
IRON CATHODE
WINDOW
1.2cm
PULSE HEIGHT SPECTRUM
ARGON FROM 1000 GALLONS
C_2Cl_4 91 DAY COUNT
Ar^{37}(2.8 keV)
Δ
COUNTS
0
5
10
10
20
30
40
50
60
70
80
90
100
CHANNEL NUMBER

FIGURE 3



SRP
SOLAR NEUTRINOS
BARBERTON
BUTTE
HOMESTAKE
SUNSHINE
KOLAR
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10
100
1000
10,000
DEPTH (M.W.E.)
Ar^{37} PRODUCTION PER DAY IN 10^5 GALLONS OF C_2Cl_4

FIGURE 4

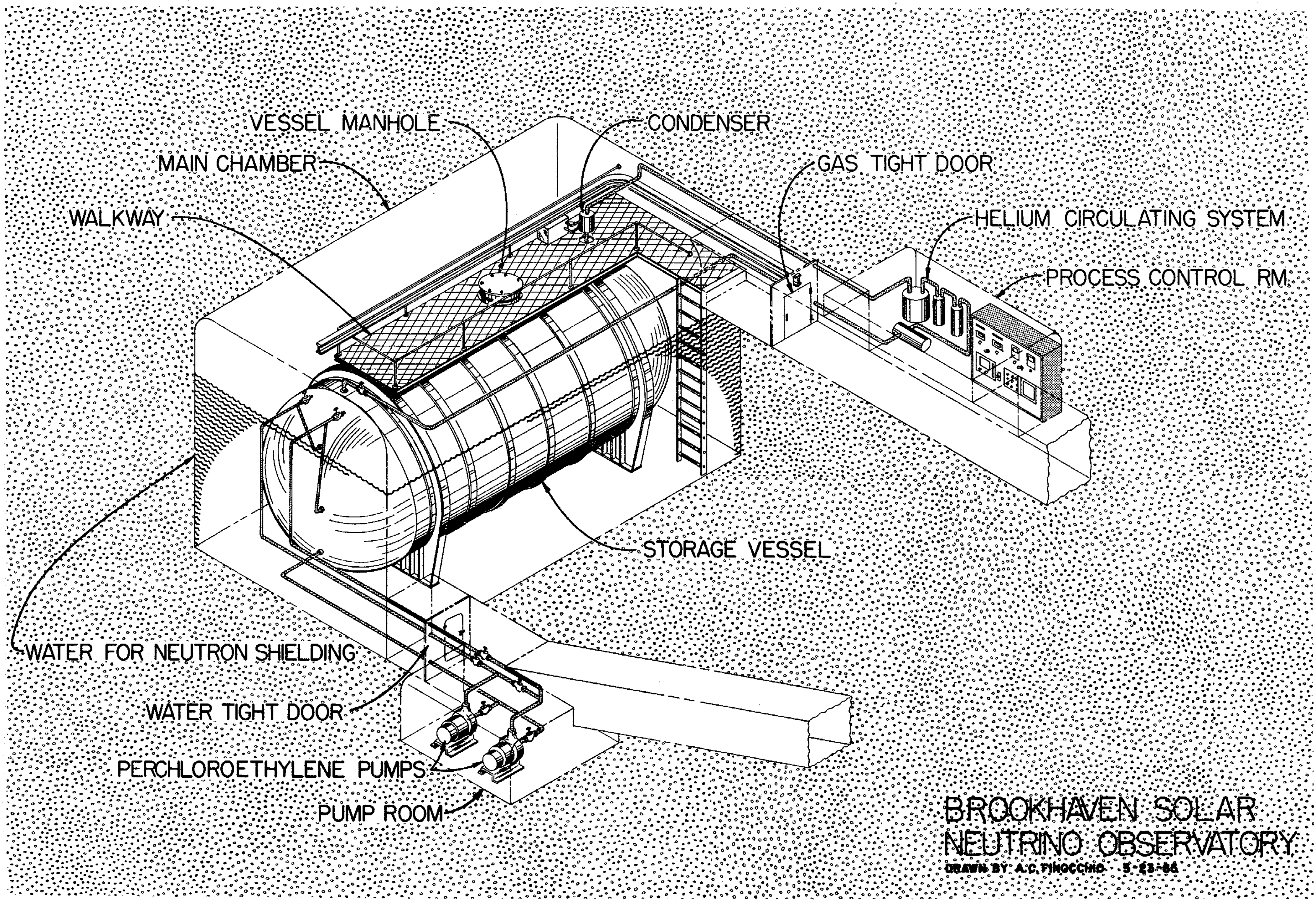

VESSEL MANHOLE
CONDENSER
MAIN CHAMBER
GAS TIGHT DOOR
WALKWAY
HELIUM CIRCULATING SYSTEM
PROCESS CONTROL RM.
STORAGE VESSEL
WATER FOR NEUTRON SHIELDING
WATER TIGHT DOOR
PERCHLOROETHYLENE PUMPS
PUMP ROOM
BROOKHAVEN SOLAR
NEUTRINO OBSERVATORY
DRAWN BY A.C. FINOCCHIO 5-23-66

FIGURE 5