BNL-21837

CONF-760973--1

REPORT ON THE BROOKHAVEN SOLAR NEUTRINO EXPERIMENT*

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Introduction

This report is intended as a brief statement of the recent developments and results of the Brookhaven Solar Neutrino Experiment communicated through Professor G. Kocharov to the Leningrad conference on active processes on the sun and the solar neutrino problem. The report summarizes the results of experiments performed over a period of 6 years, from April 1970 to January 1976.

Neutrino detection depends upon the neutrino capture reaction $^{37}Cl(\nu,e^-)^{37}Ar$ producing the isotope ^{37}Ar (half life of 35 days). The detector contains 3.8×10^5 liters of C_2Cl_4 (2.2×10^{30} atoms of ^{37}Cl) and is located at a depth of 4400 meters of water equivalent (m.w.e.) in the Homestake Gold Mine at Lead, South Dakota, U.S.A. The procedures for extracting ^{37}Ar and the counting techniques used were described in previous reports.[1-3] The entire recovered argon sample was counted in a small gas proportional counter. Argon-37 decay events were characterized by the energy of the Auger electrons emitted following the electron capture decay and by the rise-time of the pulse. Counting measurements were continued for a period sufficiently long to observe the decay of ^{37}Ar.

Experimental

Although standard procedures were followed in recovering and purifying the samples, there were in the course of these experiments a number of important developments that should be mentioned.

There has been a continual development in counting techniques and counter fabrication directed toward a better characterization of the ^{37}Ar decay event,

and obtaining lower counter backgrounds. Pulse rise-time analysis was first used starting with run 18, and has been used in all subsequent experiments.[2] The design of the counters was modified so that the X-rays from the ^{55}Fe source, used to calibrate the energy and rise-time gains, illuminate the active volume of the counter in a more uniform manner. The composition and total pressure of the filling gas and the counter dimensions were varied somewhat to optimize energy resolution and pulse rise-time discrimination of ^{37}Ar decay events. Beginning with run 36 a new anticoincidence counter and shield arrangement was used. To improve the detection of gamma rays a NaI(Tl) crystal 30-cm diameter by 20-cm thick having a well 5-cm diameter and 10-cm deep was used as an anticoincidence counter. The counters were shielded by an annular shield of mercury 20-cm thick. The pulse recording system described in reference 2 was used in all experiments.

Recently we have had success in building counters that have very low total background counting rates. These lower counter backgrounds resulted from various cleaning techniques and choice of materials. The main radioactive contaminants that were apparently eliminated were potassium and tritium. Three counters are in service that have background counting rates in the NaI anticoincidence counter and shield mentioned above of 0.5 counts in 35 days in the energy region 1.5 to 5 keV with fast pulse rise-times. These counters were used in runs nos. 37, 38, and 39. Figure 1 shows the rise-time (amplitude of the differentiated pulse) versus energy plot for the 1st 35-day count of run no. 37.

The 3.8 x 10^5 liter detector tank is located in a chamber set below the exit tunnel so that the space surrounding the tank can be flooded with water to provide a fast neutron shield. This space was filled with water after run 20, and the water was left in place through run 37. Following run 37 the water was removed to inspect the exterior of the tank for corrosion, and give it a protective coating of epoxy paint. The water was replaced after run 39 and will remain in place for the foreseeable life time of the experiment. Measurements of the fast neutron background effect from the surrounding rock (amphibolite and rhyolite containing 0.1 to 5 ppm U and 1.3 to 24 ppm Th) and concrete floor were made with a calcium radiochemical neutron detector that depends upon the $^{40}Ca(n,\alpha)^{37}Ar$ reaction. We estimated from these measurements that the background ^{37}Ar production rate by neutrons in the bare tank is approximately 0.04 per day. This rate is too small to measure directly by water-on versus water-off experiments with the 3.8×10^5 liter tank.

A sample was extracted from the tank on a somewhat irregular schedule because in the course of the experiments there was a continual effort to improve our sensitivity by reducing counter backgrounds and on occasion an experiment was delayed until a lower background counter was available. On the other hand some experiments had a short period of exposure because of the occurrence of an astronomical event of special significance.

Results

The counts observed in the ^{37}Ar energy-rise-time region are listed in Table 1 for a series of counting periods of approximately 35 days duration. Table 2 lists the initial and final date of the exposure, and the calculated number of ^{37}Ar atoms present in the tank at the time of purging. In these calculations the normal corrections for decay of ^{37}Ar, counting efficiency, and argon recovery efficiency were made. The counter background was determined using the recorded counting rates for the periods of time after the ^{37}Ar decayed, periods III or later whenever possible. The errors noted are derived from the square roots of the number of recorded counts. The combined error in recovery efficiency, counter efficiency and decay corrections is less than 10 percent. This table contains all experimental da for this period obtained when the tank was exposed to the presumed natural neutrino radiation. The missing run numbers correspond to experiments in which a neutron source was placed in the tank or an ^{37}Ar source was deliberately introduced.

The ^{37}Ar production rate was calculated from the period of exposure and the number of atoms in the tank at the time of purge, presuming a non-varying neutrino flux during the exposure interval. If there were any fluctuations, say from pulsed sources of neutrinos or sudden changes in cosmic ray production, this calculation of ^{37}Ar production rate would not be correct. We would like to emphasize that we have designated all counts in the ^{37}Ar region less counter background as ^{37}Ar decays. If there are spurious counts, the rates listed would be too high. Criteria for testing whether counts with the correct pulse rise-time and energy (fwhm) for ^{37}Ar decay are indeed ^{37}Ar are that (1) the energy spectrum of the fast events has an ^{37}Ar distribution, (2) the counting rate decays with a 35-day half life, and (3) the time distribution of the occurrence of counts is consistent with a 35-day activity. The energy spectrum of fast counts has a clear ^{37}Ar-like distribution in run 27, and in the runs in which very low background counters were used, nos. 37, 38 and 39. Only in run 27 were there a sufficient number of counts to test for decay, and the rate listed for this run was obtained from a least-squares fit of the counting data. The time distribution of the counts in runs 36, 37, 38 and 39 has been examined, and has been found to be reasonably statistically distributed for runs 36 and 37. However, in run 38 no counts were observed in the first 20.8 days of counting, though a total of 9 decay events were observed during the first 70 days of counting. If all events are ^{37}Ar decays following a binomial distribution in time, the probability of not observing any decays in the first 20.8 days of run 38 is approximately 0.01.

During run 38 there were some spurious noise counts attributable to the counter and the particular gas filling. These noise pulses could be identified by an electronic criterion, namely the time difference between the peaking times of the energy amplifier and the rise-time differentiating amplifier. Although those noise pulses could be eliminated by this criterion, we are not absolutely certain that all such noise pulses were eliminated from the data. The first two counts in run 39A occurred 22.71 and 22.78 days after the end of purge. The probability of occurrence of this short an interval between counts is only 0.006 for the calculated number of atoms given in Table 2.

The ^{37}Ar production rates are plotted in figure 2. It may be observed that runs 18 and 19 are high, then there is a long period in which the rate is low, essentially at the cosmic ray background level, with only one high value, run 27, and then runs 36 and 37 are high. Note that although the water shield was not in place for runs 18, 19, 20, 38 and 39, a fast neutron background rate correction was not applied. A test was made at the time run 39 was performed to see if the ^{37}Ar was indeed coming from the 3.8×10^5 liter tank. First, immediately prior to run 39 the argon collection system was purged, the argon sample collected, purified, and counted. Following this preliminary purge the sample was collected from the tank in the usual way, run 39A. Finally the tank was purged a second time, run 39B, to test for residual ^{37}Ar that might remain in the tank. The counts observed are given in Table 1. It is clear even with the low number of recorded events that run 39A, as expected, had the highest counting rate of any of the three samples collected.

There is a possible source of contamination that could have affected runs 27, 36 and 37. Molecular sieve, containing 0.1 percent calcium, is used as an adsorber, and if this material is exposed to cosmic ray produced neutrons some ^{37}Ar will be produced by ^{40}Ca(n,α)^{37}Ar reaction. Normally the material that we use is stored for a long period of time underground before use. Just before a run it is thoroughly heated (350°C) and evacuated in our processing system. In runs 36 and 37 molecular sieve recently brought underground was used. Our records indicate run 27 could also have been contaminated in this way. In all other experiments reported ^{37}Ar contamination from this source is very much less likely. Now that we realize this possible source of contamination we can be certain that ^{37}Ar contaminated molecular sieve will not be used in future experiments. An experimental determination of the ^{37}Ar remaining in molecular sieve after baking and evacuating will be carried out in the near future to help evaluate the magnitude of the effect on these experiments. Starting with run 40 a charcoal absorber at room temperature will be used in place of the molecular sieve.

If the variations in ^{37}Ar production rates plotted in figure 2 are regarded as statistical variations, then one can obtain an average rate useful for setting an upper limit on the solar neutrino flux. Averaging all results we obtain the following results:

^{37}Ar atoms/day

Average ^{37}Ar production rate all runs = 0.32 ± 0.08

Cosmic ray production rate (muons + ν_μ) Ref. 4 = 0.08 ± 0.024

^{37}Ar production rate above the cosmic ray background ascribable to solar neutrinos = 0.24 ± 0.09

$$\Sigma\phi\sigma = 5.24(0.24 \pm 0.09) = 1.3 \pm 0.4 \text{ SNU}$$

In view of uncertainties described above and uncertainties in background processes we regard this result as a 1σ upper limit to the solar neutrino flux of 1.7 SNU. (SNU ≡ solar neutrino unit, 10^{-36} captures per sec per ^{37}Cl atom).

Discussion

The upper limit of 1.7 SNU given above can be compared to the rate calculated for the standard model of 5.8 SNU ±30%. The low Z model[5] forecasts a rate of 1.4 SNU that is consistent with our result. Several authors have discussed the reasonableness of the low Z model in terms of the evolution of the solar system[6] and the possible collection of high Z matter on the solar surface from the galaxy.[7] There are many other solar model calculations that give low solar neutrino fluxes. These models and other possible explanations of low neutrino fluxes are discussed in various excellent review articles.[8]

It is of interest to note that a number of the experimental runs were timed to search for neutrino fluxes from astronomical events. Run no. 32 was performed to search for a neutrino flux corresponding to the unique pulse recorded by Lande and his associates in their water Cerenkov counters in the Homestake Mine.[9] We concluded from our measurements that if the set of pulses observed by the water Cerenkov counters were produced by anti-neutrinos, then the flux of neutrinos was lower by at least a factor of four.[9] Since the large solar flare of August 2, 1972 occurred during the exposure period of run 27 we decided to search for increased ^{37}Ar production which might result from the large solar flare of July 15, 1974. However, run 35, which corresponds to this flare, is one of the low ones, but with a large statistical error. Run no. 38 was performed to search for a neutrino flux from Nova Cygnus 1975. If we assume the 36 atoms observed in run 38 were produced by this event, we estimate an integrated flux of neutrinos of 6×10^{10} cm^{-2}. For this estimate we have used a neutrino capture cross-section of 3×10^{-40} cm^{2}, the average cross-section for neutrinos with a Maxwell-Boltzmann energy distribution having an effective temperature corresponding to kT = 10 MeV. This is not a very meaningful limit since current thinking on nova bursts does not consider a nova to be an intense pulsed neutrino source.

Future Plans

In past experiments the tank was exposed for periods of several ^{37}Ar half lives to obtain a rate nearly equal to that of secular equilibrium. Since the data obtained indicate that there may be fluctuations in the ^{37}Ar production rate, it is desirable to make shorter exposures and thus define more closely the time of any fluctuation. We believe it is possible to make measurements every 35 days with counters that have backgrounds that are nearly zero for ^{37}Ar-like events. For a period of one year we plan to purge the tank every 35 days, and to search for possible fluctuations. This procedure will have the added advantage of essentially doubling the number of recorded counts per year which will result in a higher statistical accuracy in the ^{37}Ar production rate. Run no. 40 is the first run in this series, five runs have been made to date.

The cosmic ray background of 0.08 ^{37}Ar atoms/day (equivalent to 0.4 SNU) is an important correction that must be applied to the measured ^{37}Ar production rate in the solar neutrino detector. We plan to perform a series of measurements with tanks of C_2Cl_4 and also with a radiochemical fast neutron ^{40}Ca detector at various depths underground to obtain a better value for the cosmic ray muon background. In addition direct measurements of the ^{37}Ar production by muons have been made using accelerator beams at 8.5, and 200 GeV.

Jacobs[10] has proposed that neutrinos are not detected by the present solar neutrino detector because the ^{37}Ar produced by neutrino capture does not rapidly become a neutral argon atom, but is chemically bound or retained in polymers. Although these argon binding processes are extremely unlikely,[11] an experiment testing their existence is in progress. Tetrachloroethylene labeled with ^{36}Cl (7 millicuries) has been synthesized and will be placed in a 50-liter iron tank to measure the rate of generation of ^{36}Ar. Periodically the tank will be purged with helium gas and the extracted ^{36}Ar measured by neutron activation. This test should be a valid check on the chemical fate of an argon atom produced by low energy neutrino capture.

We have proposed measuring the neutrino capture cross-section using μ^+ decay neutrinos from the beam stop of the Los Alamos Meson Facility. We have studied various background effects for this experiment, but it now appears that the neutrino room will not be available to us for at least two years. We would like to mention that L. W. Alvarez[12] has proposed testing our detector with an intense source of ^{65}Zn neutrinos (E_ν = 1.45 MeV). A source of 10^6 curies would be required to obtain a signal corresponding to 10 SNU. Exposing our detector directly to a neutrino source would test both the calculated neutrino capture cross-section and the chemical procedures. Although this is a feasible experiment, because of the cost and source handling difficulties underground, we have decided for the present not to expend our resources on this experiment. Also we feel that there is little doubt that our chemical recovery procedures are effective for collecting ^{37}Ar produced by neutrino capture and that the previously mentioned C_2Cl_3 ^{36}Cl test should be an adequate check. The ^{65}Zn test would also check the cross-section calculations that determine the basic neutrino detection sensitivity. Yet there appears to be little question that the physical principles and the details of the calculations are correct.[13]

Old and New Proposals for Solar Neutrino Detection

The results reported from the Brookhaven Solar Neutrino experiment show that the flux of energetic neutrinos from the sun is lower than anticipated from the theory. Although there has been a large drop in the theoretically calculated neutrino flux in the last eight years, the present standard theory remains in disagreement with the experiment, and it is not apparent whether the solution to the problem lies in solar physics, nuclear reactions, or neutrino physics. Clearly a new experiment is needed which is capable of observing the neutrinos from the H + H reaction or its electron capture branch (PeP). The flux of these neutrinos are forecast with great confidence by the current theories.

V. A. Kuzmin[14] pointed out that the reaction ^{71}Ga $(\nu,e^-)^{71}$Ge with its low threshold and favorable cross-section could be used to measure the abundant H-H neutrinos. For such an experiment chemical separation techniques exist that can be used, the counting of ^{71}Ge is relatively easy, and various background effects are small. The major difficulty is obtaining about 50 tons of gallium for the experiment. The possibility of using the super-allowed neutrino capture reaction ^{7}Li$(\nu,e^-)^{7}$Be has been discussed for many years. There are suitable chemical extraction techniques available, but the counting of ^{7}Be at rates of one per day is a difficult problem.[15] Recently Zakharov[16] has pointed out that the background from alpha emitters is a serious problem requiring that the U, Th levels should be below 5×10^{-11} g/g LiCl solution. The cosmic ray muon production of ^{7}Be from oxygen and chlorine is another serious background effect that needs evaluation. The main problems with a lithium solar neutrino detector are the counting of ^{7}Be and the background effects. The third possibility is to build a larger ^{37}Cl experiment. If an experiment were built five times larger than the present one, then a signal in the range of 1 to 2 SNU could be measured readily and the ultimate sensitivity would be sufficient to observe the 1.44-MeV neutrinos from the PeP reaction. A past worry that the background from cosmic ray produced ν_μ would be serious has been alleviated by the recent calculations of Domogatsky and Eramzhyan[17] who show that the background from these neutrinos is small. Building a ^{37}Cl experiment of this size is certainly feasible and the only technical difficulty is locating it deep enough to reduce the cosmic ray muon background (approximately 7000 m.w.e.).

Recently two other suggestions for solar neutrino detection have appeared. M. Freedman and his associates[18] have suggested using the $^{205}\mathrm{Tl}(\nu,e^-)^{205m}\mathrm{Pb} \rightarrow {}^{205}\mathrm{Pb}$ reaction (threshold 46 keV) that leads to the isotope $^{205}\mathrm{Pb}$ with a half life of 1.6×10^7 years. This approach has the advantage of giving information about the solar neutrino flux in the past, but has the disadvantage of requiring the experimenter to use a naturally occurring thallium mineral. The problems of obtaining a suitable sample and of developing a technique for measuring $^{205}\mathrm{Pb}$ are formidable, but the prospects are hopeful. R. S. Raghavan[19] has proposed a direct counting detector based upon the $^{115}\mathrm{In}(\nu,e^-)^{115m}\mathrm{Sn} \rightarrow {}^{115}\mathrm{Sn}$ reaction. The attractive feature of this reaction is that $^{115m}\mathrm{Sn}$ decays by emitting two successive gamma with energies 116 and 498 keV making it possible to use a triple coincidence technique to reduce detector background. The reaction has a low threshold 128 keV and could be used to observe neutrinos from the H-H reaction.

Although there are many new ideas for observing neutrinos, it appears that the original $^{37}\mathrm{Cl}$-$^{37}\mathrm{Ar}$ method suggested by Pontecorvo 28 years ago is the simplest from a technical viewpoint, and may even be the best for observing neutrinos from the basic proton reaction in the sun.

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*Research carried out under the auspices of the United States Energy Research and Development Administration under Contract No. E(30-1)-16

Table 1. Decay of Counts with Correct Rise-time and Pulse Height

Run No.	Counting Periods, approx. 35 days each						
	I	II	III	IV	V	VI	VII
18	5	5	2	1	1		
19	10	5	4	4	3	3	4
20	3	1	3	0	1		
21	1	3					
22	2	2	3				
23	4	0	1 (poor run)				
24	2	1	1	0	0	1	0
27	11	6	4	3	1	2	
28	4	(pulse height drift)					
29	6	1	5	2	3		
30	1	5	1	3	4	1	2
31	1	0	1	1			
32	1	1	1	1			
33	3	2	2	1			
35	0	4	2				
36	4	6	3	2	0	0	1
37	6	3	3	0	0	1	
38	7	3	4				
39P	0	4	preliminary purge				
39A	6	2	3	2			
39B	0	1	2nd purge				

Table 2. Summary of Results

Run No.	Period of Exposure	^{37}Ar Atoms in Tank at End of Purge	^{37}Ar Production Rate per Day	
18	Apr. 12 - Nov. 14, 1970	30 ± 13	0.60 ± 0.26	without water shield
19	Nov. 14, 1970 - Mar. 6, 1971	29 ± 14	0.63 ± 0.30	
20	Mar. 6 - June 17, 1971	8 ± 10	0.19 ± 0.22	
21	June 17 - Oct. 2, 1971	5 ± 16	0.11 ± 0.36	
22	Oct. 2 - Dec. 13, 1971	1 ± 12	0.03 ± 0.26	
23	Dec. 13, 1971 - Mar. 2, 1972	-5 ± 30	-0.12 ± 0.75	
24	Mar. 2 - May 18, 1972	10 ± 9	0.25 ± 0.23	
27	July 7 - Nov. 5, 1972	55 ± 18	1.19 ± 0.40	
28	Nov. 5, 1972 - Jan. 26, 1973	16 ± 16	0.40 ± 0.40	
29	Jan. 26 - Apr. 14, 1973	10 ± 15	0.25 ± 0.38	
30	Apr. 14 - Aug. 31, 1973	8 ± 11	0.17 ± 0.23	
31	Aug. 31 - Dec. 13, 1973	-12 ± 18	-0.28 ± 0.40	
32	Dec. 13, 1973 - Jan. 25, 1974	-1 ± 9	-0.05 ± 0.33	
33	Jan. 25 - June 26, 1974	15 ± 13	0.31 ± 0.27	
35	July 1 - Aug. 3, 1974	2 ± 14	0.08 ± 0.58	
36	Aug. 3, 1974 - Feb. 13, 1975	27 ± 12	0.68 ± 0.30	
37	Feb. 13 - June 14, 1975	33 ± 13	0.81 ± 0.32	without water shield
38	June 14 - Sept. 24, 1975	23 ± 14	0.53 ± 0.32	
39	Sept. 24, 1975 - Jan. 23, 1976	17 ± 12	0.39 ± 0.26	

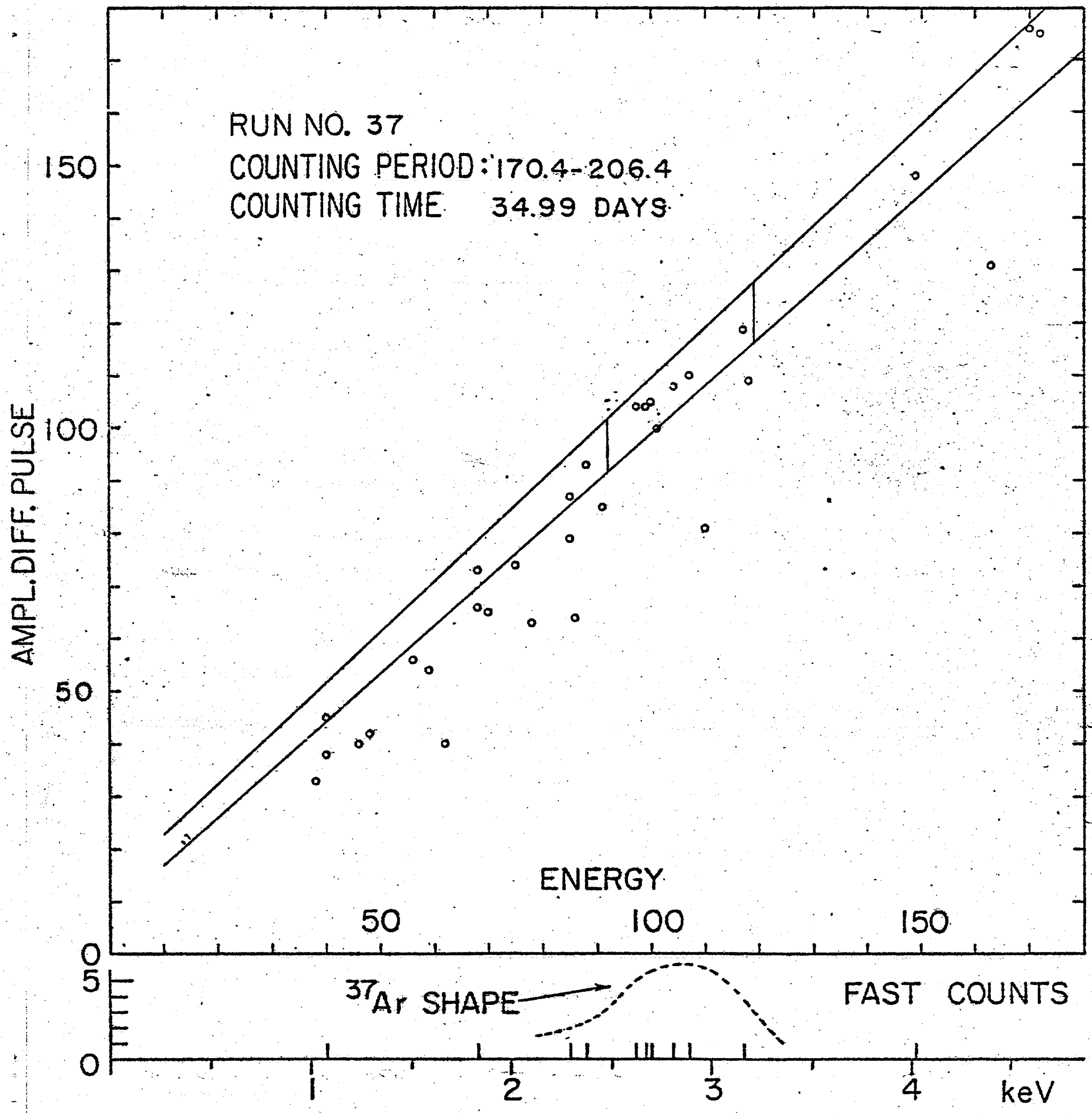
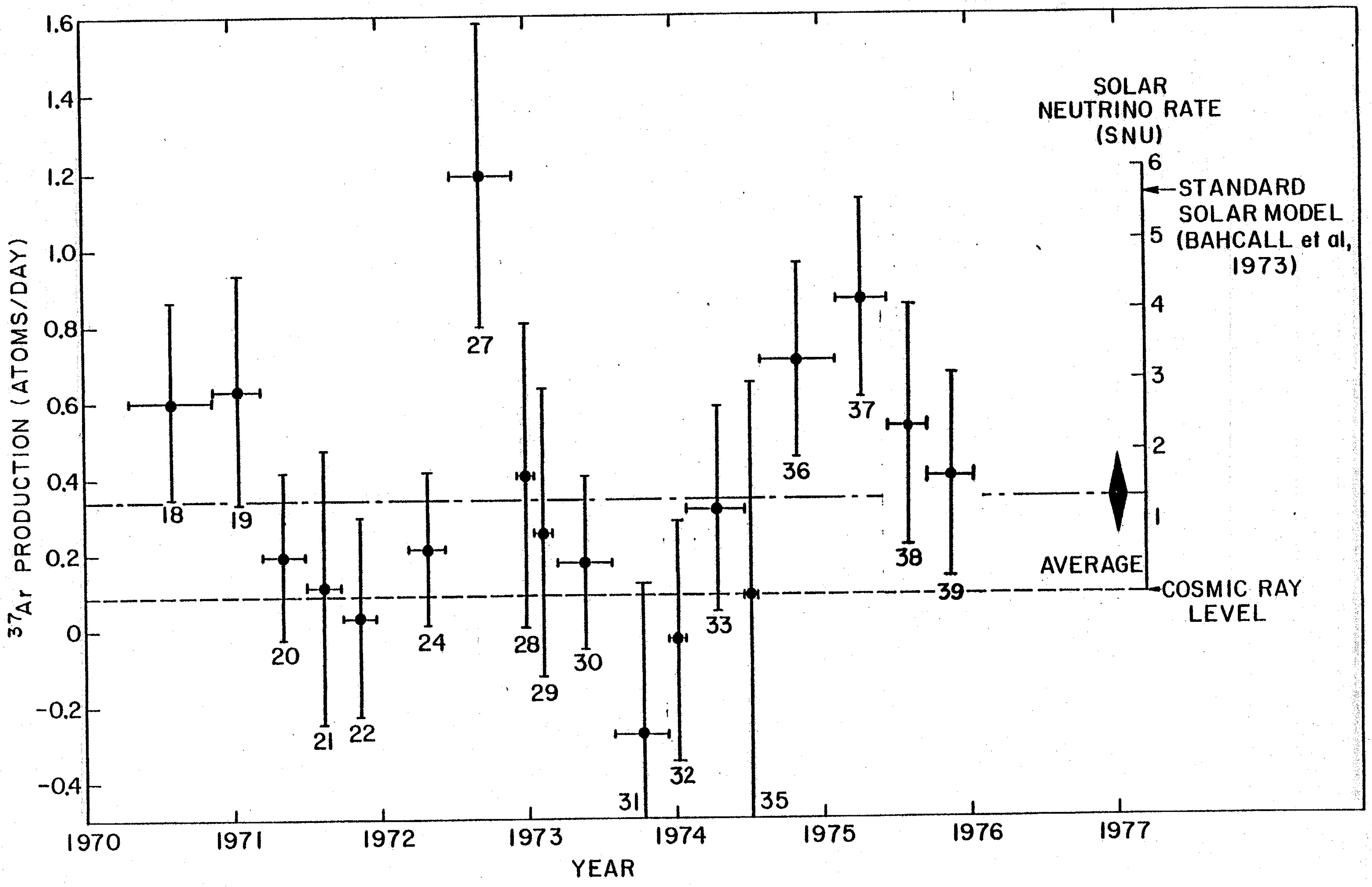

RUN NO. 37
COUNTING PERIOD: 170.4-206.4
COUNTING TIME 34.99 DAYS
AMPL. DIFF. PULSE
150
100
50
0
ENERGY
50
100
150
5
0
^{37}Ar SHAPE
FAST COUNTS
1
2
3
4
keV

Fig. 1



1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
-0.2
-0.4
^{37}Ar PRODUCTION (ATOMS/DAY)
1970
1971
1972
1973
1974
1975
1976
1977
YEAR
18
19
20
21
22
24
27
28
29
30
31
32
33
35
36
37
38
39
SOLAR NEUTRINO RATE (SNU)
6
5
4
3
2
1
STANDARD SOLAR MODEL (BAHCALL et al, 1973)
AVERAGE
COSMIC RAY LEVEL

Fig. 2