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The Soviet-American Gallium Experiment is the first experiment able to measure the dominant flux of low energy p-p solar neutrinos. Four extractions made during January to May 1990 from 30 tons of gallium have been counted and indicate that the flux is consistent with 0 SNU and is less than 72 SNU (68% CL) and less than 138 SNU (95% CL). This is to be compared with the flux of 132 SNU predicted by the Standard Solar Model.

1. Introduction

The discrepancy between the solar neutrino capture rate predicted by Standard Solar Model (SSM) calculations and the ^{37}Ar rate measured by the chlorine experiment in the Homestake Gold Mine has persisted for more than twenty years. Recent calculated values of the flux are 7.9 +/- 2.6 (3σ) SNU (1 solar neutrino unit = 10^{-36} captures/target atom/sec) in the Bahcall-Ulrich SSM[1]. This is to be compared with the measured value in the chlorine experiment, averaged over 1970-1988, which is 2.1 +/- 0.3 SNU[2] (1σ). This deficit has now been corroborated by the Kamiokande II water Cerenkov experiment[3], which observes only 0.46 +/- 0.05 +/- 0.06 of the flux predicted by the Bahcall-Ulrich SSM, in fair agreement with the chlorine result.

Solutions to the "solar neutrino problem" have been put forth which invoke either nonstandard solar models or new particle physics. The ^{37}Cl and Kamiokande experiments are primarily sensitive to the high energy ^{8}B solar neutrinos, whose production rate depends critically on the core temperature of the sun. Numerous non-standard solar models[4] which reduce the core temperature have been suggested, incorporating reduced heavy element abundances, high magnetic fields, turbulent diffusion, continuous mixing, and other effects. However, none of the nonstandard models have been able to reproduce the observed ^{8}B flux and still agree with all other observed features of the sun.

New particle physics, such as neutrino matter oscillations[5,6] and neutrino magnetic moments[7], can also provide an explanation of the "solar neutrino problem".

The low energy neutrinos produced in proton-proton fusion in the Sun, which account for more than 90% of solar neutrinos, are far below the thresholds of the chlorine and Kamiokande experiments. The p-p neutrino production rate in the Sun is fundamentally linked to the

observed solar luminosity, and is insensitive to alterations in the solar models. The need for an experiment capable of detecting these low energy neutrinos has been apparent for many years. Such an experiment may be able to differentiate between solar model and particle physics explanations for the solar neutrino problem.

A radiochemical experiment using ^{71}Ga as the capture material provides a feasible means to measure the p-p flux[8]. The inverse beta decay reaction $\nu_e(^{71}Ga, ^{71}Ge)e^-$ has a Q-value of only 233 keV, allowing efficient detection of p-p neutrinos, which have an endpoint energy of 420 keV.

The SSM calculations of Bahcall and Ulrich[1] show that the dominant contribution to the total expected capture rate in ^{71}Ga (132 +/- 20 SNU) arises from the p-p neutrinos (71 SNU). Contributions by ^{7}Be neutrinos (34 SNU) and ^{8}B neutrinos (14 SNU) are also important. The neutrino spectrum, together with the thresholds for various detectors, is shown in Figure 1.

The current observed luminosity of the Sun corresponds to a neutrino flux of 6×10^{10} $cm^{-2}sec^{-1}$ from the p-p reaction alone. This conclusion is based largely on energetic grounds, and is insensitive to the details of solar model calculations. This p-p flux corresponds to a minimum expected counting rate in the gallium detector of 70 SNU. Thus, observation of significantly less than 70 SNU in the gallium experiment would be very difficult to explain without invoking new neutrino physics.

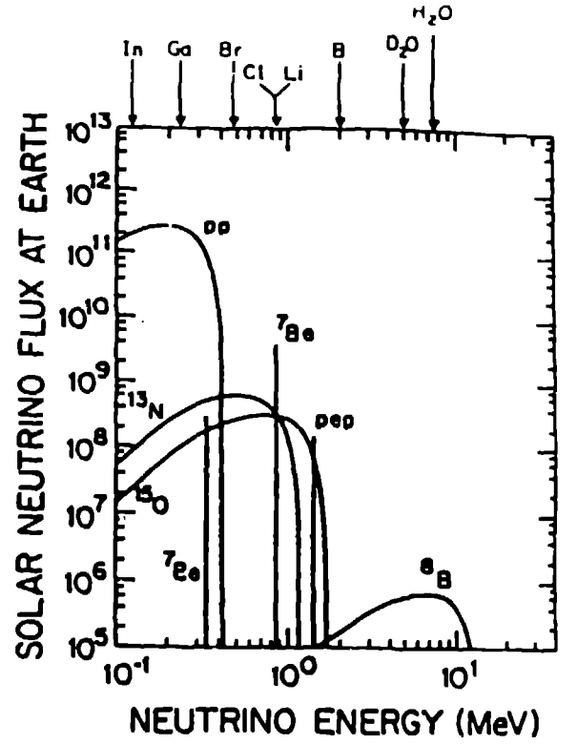

FIGURE 1
The Solar Neutrino Spectrum

2 THE BAKSAN GALLIUM EXPERIMENT

2.1. The Baksan Neutrino Observatory

The Soviet-American gallium solar neutrino experiment is situated in an underground laboratory specially built in the Baksan Valley of the Northern Caucasus, USSR. The laboratory is 60 m long, 10 m wide, and 12 m high. It is located 3.5 km from the entrance of a horizontal adit driven into the side of Mount Andyrchi, and has an overhead shielding of 4700 mwe. The laboratory is lined with a 6 mm steel shell and 60 cm of low-radioactivity concrete.

2.2. Extraction Procedure

The extraction is based on the fact that gallium melts at 29.8 C. The low melting point makes it possible to keep the gallium in its liquid form and is central to the extraction. The gallium is contained in chemical reactors, each with internal volume 2 m^3 and lined with teflon. The reactors are provided with heaters that maintain the temperature just above the gallium melting point. Each reactor holds about 7 tons of gallium.

The chemical extraction process from metallic gallium was first developed by Davis in the US[9] and later fully tested in a pilot experiment in

the USSR. The process has been described in detail elsewhere[10] and will only be briefly described here. At the beginning of each run, approximately 120 micrograms of natural Ge carrier is added to each reactor in the form of a solid Ga-Ge alloy. The reactor contents are stirred so as to thoroughly disperse the carrier throughout the Ga metal. After a suitable exposure interval (typically 4 weeks), the Ge carrier and any ^{71}Ge atoms that have been produced by neutrino capture are chemically extracted from the gallium.

Mixing gallium metal with a weak acidic solution in the presence of an oxidizing agent results in the extraction of germanium into the aqueous phase. The extraction process begins by adding to each reactor an extraction solution containing 1 kg of HCl, 5.2 kg of H_2O_2, and 68.8 kg of H_2O. The mixture is intensively stirred and the Ga metal turns into a fine emulsion. The Ge dissolved in the Ga migrates to the surface of the emulsion droplets. In approximately 10 minutes, the H_2O_2 is consumed: almost all of the emulsion spontaneously breaks down and the phases separate.

All of the extracts from the separate reactors are combined, and the Ge is then concentrated by vacuum distillation. The concentrated extract is then transferred to a glass vessel that is part of a sealed gas flow system. Purified 12N HCl is added to this solution to raise the HCl concentration to 9N, and an argon purge is initiated which sweeps the Ge as $GeCl_4$ from this acid solution into a volume of 1.0 l of H_2O. A solvent extraction procedure is then used to first extract the Ge into CCl_4 and then back-extract it into H_2O.

The next step of the procedure is to synthesize the counting gas GeH_4 (germane). A measured quantity of xenon is added, and this mixture is inserted into a sealed proportional counter with volume of about 0.75 cm^3. The GeH_4 sample is then counted for 2-3 months.

The efficiency of extraction of germanium from the reactors is measured at two stages of the extraction procedure by atomic absorption analysis. A final determination of the quantity of germanium is made by measuring the volume of synthesized GeH_4. The uncertainty in the extraction efficiency is typically +/- 6%. The overall extraction efficiency is typically 80% and is stable and reproducible. The standard procedure is to conduct three extractions in series within a period of 5 days without adding additional carrier to the reactors. The GeH_4 samples from each of these three extractions are then usually counted separately. In addition, "blank" runs are carried out before and after these three extractions by sweeping the concentrated HCl solution used in the extraction. This is to ensure that no additional activity is entering from the HCl or is being removed from the extraction system.

2.2. ^{71}Ge Background

The main source of ^{71}Ge in the reactors other than from solar neutrinos is from protons arising as secondary particles produced by *i)* external neutrons, *ii)* internal radioactivity, and *iii)* cosmic ray muons. These protons can initiate the reaction $^{71}Ga(p,n)^{71}Ge$. Extensive work has gone into measurements and calculations of these background channels and indicate that the total background production rate of ^{71}Ge is less than 0.025 atoms/day in 30 tons of gallium i.e., less than 2.5% of the SSM production rate.

Since these sources of ^{71}Ge background have been made small, the major difficulty for the experiment is the need to remove from the gallium the large quantities of long lived ^{68}Ge (half life = 271 days) produced by cosmic rays while the gallium was on the surface. ^{68}Ge decays only by electron capture, so its decays cannot be differentiated from those of ^{71}Ge. The subsequent decay of ^{68}Ga (half life = 1.16

hours) is by positron emission in 90% of the cases. The ^{68}Ga decays can generally be identified by risetime analysis of the counter pulse and by detection of a coincidence pulse in the surrounding NaI crystal.

2.3. Counting

The SSM predicts a production rate of 1 ? ^{71}Ge atoms/day in 30 tons of Ga. At the end of a 4 week exposure period, an average of 16 ^{71}Ge atoms will be present. Under normal conditions, there is a one day delay between the end of exposure and the beginning of counting. Taking this delay into account and folding in the chemical extraction and detector counting efficiencies, then the mean number of detected ^{71}Ge atoms expected in each run is only 4.0. Thus, the counting backgrounds must be kept to a small fraction of a count/day.

The counting of the ^{71}Ge decays has been described in detail elsewhere[10] and will only briefly be described here. ^{71}Ge decays by electron capture to the ground state of ^{71}Ga with an 11.4 day half life. The only way to observe this decay is to detect the low-energy Auger electrons and x-rays produced during electron shell relaxation in the resulting ^{71}Ga atom. K capture gives Auger electrons with an energy of 10.4 keV (41.5% of all decays), 9.2 keV x-rays accompanied by 1.2 keV Auger electrons from the subsequent M-L transition (41.2% of all decays), and 10.26 keV x-rays accompanied by 0.12 keV Auger electrons (5.3% of all decays). L and M capture give only Auger electrons with energies of 1.2 keV and 0.12 keV, respectively

The low-energy electrons are detected in a small-volume proportional counter. If xenon is mixed in with the germane to increase the probability of capturing some of the 9 keV x rays, then (with a 90%-10% mixture of Xe-GeH_4) 41% of the decays are in the L peak and 41% are in the K peak Due to considerably higher backgrounds in the L peak, only the K peak has been used in the analysis presented here.

The major source of background in the counters is local radioactivity. The counters are therefore made from materials especially selected to have a low content of Ra, Th, and U and are housed in large passive shields. To further reject background events, 13 of 19 counting channels have an active NaI detector around the proportional counter.

Background radioactivity primarily produces fast electrons in the counter. In contrast to the localized ionization produced by the Auger electrons from ^{71}Ge decay, these fast electrons give an extended ionization signal as they traverse the counter interior. Since the risetime of the induced pulse increases with the radial extent of the ionization distance, it is possible to use pulse shape discrimination to separate the ^{71}Ge decays from the background. This is achieved by differentiating the pulse with a time constant of about 10 nanoseconds and measuring the resulting amplitude. One of the three counting systems also employs a gigahertz transient digitizer to measure the full pulse waveform for a microsecond.

Good rejection of background events is obtained with a counting mixture of 10% GeH_4 and 90% Xe. This gas mixture gives a resolution of 18-21% at 5.9 keV, with a measured total counting efficiency in a 2 FWHM window around 10.4 keV of 36%. This efficiency includes geometrical effects inside the counter and excludes events whose risetime is outside a 95% acceptance window.

The total background rate of selected counters filled with 90% Xe, 10% GeH_4 has been measured in the energy interval of 0.7-13.0 keV to be approximately 1.5 cts/day. The count background in the ^{71}Ge K peak acceptance window is approximately 1 event per month.

2.4 Data for Calibration

After filling a counter with the GeH_4-Xe mixture, the counter is calibrated using an external ^{55}Fe source, which illuminates the central part of the counter through a thin side window. The uniformity of the counter response has been checked over a limited region by first calibrating the counter with the ^{55}Fe source at 90° to the counter and then at +/- 45° along the axis of the counter. This is done to ensure that the counter performance at the window position has not been degraded by polymerization of Ge compounds on the anode wire due to repeated exposure to the source at the window position. Calibrations of the counters are repeated at approximately one month intervals. The stability of the counters used in the data reported here was quite good, with typical gain variations observed of 3-4%. These gain variations did not affect the results of the analysis of any of the runs reported here.

The ^{55}Fe calibration is used to generate a two dimensional plot of inverse risetime versus energy. A rectangular acceptance window is then calculated around the 5.9 keV ^{55}Fe peak which accepts 2 FWHM in energy centered around the Fe energy peak, and 95% of the risetime distribution. The position of the acceptance window for the ^{71}Ge K peak is calculated by first determining any offsets by fitting the ^{55}Fe spectrum from the centroid of the Xe escape peak at 1.4 keV to well above the 5.9 keV ^{55}Fe peak. The centroid of the acceptance boxes for the ^{71}Ge K peak is then determined by scaling from the ^{55}Fe peak. The width of the ^{71}Ge K peak window is determined by scaling the width in energy as the square root of the energy and setting the width in risetime to be constant and equal to the width for the ^{55}Fe peak. In order to check this extrapolation procedure, a counter was filled with the standard GeH_4-Xe mixture in which the Ge had been activated in the Los Alamos Omega West reactor. This provided an internal calibration source of ^{71}Ge in the counter gas with a total counting rate of less than 10 cts/s. All of the counting systems were calibrated using this counter. The spectrum from this counter taken simultaneously with the external ^{55}Fe source in shown in Figure 2. The acceptance boxes for the ^{55}Fe and the ^{71}Ge K peak are marked and this data clearly shows that the extrapolation method used is correct. The peaks occur all with the same risetime since they are all due to low energy x-rays which produce point ionization in the counter. Events with lower values of 1/risetime are due to background pulses which produce extended ionization in the counter.

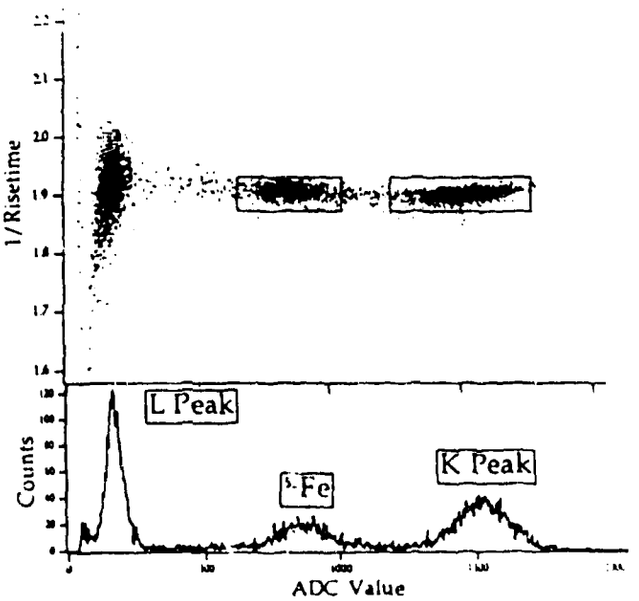

FIGURE 2
Calibration Spectrum Using External ^{55}Fe and Inter al ^{71}Ge Sources.

2.5. Analysis

The analysis searches for events which are within the ^{71}Ge K peak acceptance window and which have no NaI activity in coincidence. A maximum likelihood analysis is then carried out on these events by fitting the time distribution to an exponential decay with an 11.4 day half-life and a constant background.

3. EXTRACTION HISTORY

The experiment began operation in May of 1988, when removal of the ^{68}Ge from 30 tons of gallium commenced. The ^{68}Ge activity in the first extraction from the 30 tons of Ga was 7700 cts/day in the Ge K-peak. The chemical extraction efficiency and ^{68}Ge counting rate were monitored during most of the initial extractions and showed that the ^{68}Ge rates tracked the chemical extraction efficiency for the first nine or ten extractions. However, beginning with the extractions in January 1989, it became clear that there was a source of long lived residual activity which did not decrease rapidly with further extractions. The level of this activity was about one count/day in the Ge K peak. Although the source of this activity has not been definitely identified, exhaustive testing indicated that it came from either the reactor vessels or the gallium. The most likely possibility is that there was some diffusion of long-lived ^{68}Ge from the original dirty gallium into the teflon liners. Further extractions continued to slowly reduce this background. Each reactor has now undergone at least 20 extractions and in recent runs, the activity in the Ge K-peak has typically been less than 0.2 cts/day.

With the extractions beginning in April 1989, the analysis indicated the presence of several counts per run with a half life reasonably consistent with ^{71}Ge. However, as statistics from additional extractions in June, September, October, and December 1989 built up, the best fit to the half-life was determined to be 4 +/- 1 day, which is consistent with radon rather than ^{71}Ge. Subsequently a large, ultra low background hyper pure germanium solid state detector was installed at the experiment and used to assay all of the reagents. It was found that the water used in the germane synthesis did indeed contain some radon. To eliminate the radon, new extraction procedures were implemented beginning with the January 1990 extraction. These procedures included using old, distilled tritium free water and additional purification of other reagents to remove radon. These procedures resulted in the elimination of the radon contamination in the extractions.

4. MEASUREMENTS OF THE SOLAR NEUTRINO FLUX

4.1. Statistical Analysis

Extractions from the 30 tons of gallium were carried out in January, February, March, and April of 1990 using the new procedures described above. Data from earlier extractions is not included in the analysis here due to the radon contamination of the data. The data from the January 1990 extraction in the region of the ^{71}Ge K peak is shown in Figure 3.

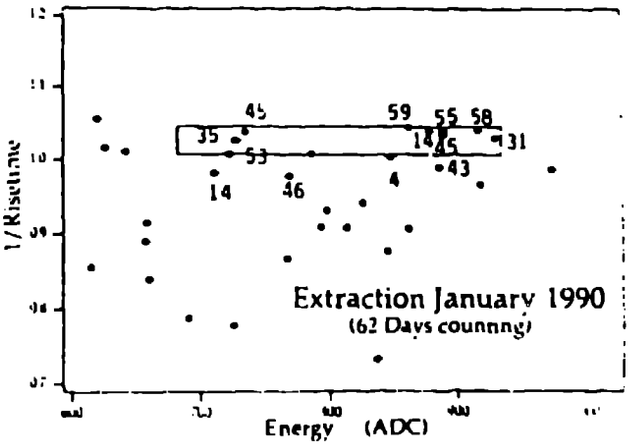

FIGURE 3
Blowup of Risetime^{-1} versus Energy for the January Extraction Data. Dots correspond to events which have associated NaI activity.

The acceptance window shown was determined using the extrapolation procedures from ^{55}Fe described above. The date at which each event occurred after the start of counting is shown next to the event. It is clear from the data that there are essentially no early time events consistent with a ^{71}Ge half life of 11.4 days within the acceptance window. This conclusion remains true

even if one includes all of the events outside the acceptance window. The same conclusion is reached when the February, March, and April runs are examined.

The results of the maximum likelihood analysis are shown in Table 1. We note that the best fit value of 29 SNU for the February run is due to the occurrence of one event in the first day of counting within the acceptance window. When one fits all four data sets simultaneously, the maximum likelihood analysis finds that this count is consistent with background. Thus, the best fit value for the sum of all four runs is 0 SNU, i.e., the maximum likelihood fit describes the data best by assigning all counts to background.

Table 1. Statistical Analysis
(* indicates run is still counting)

RUN	BEST FIT	68% CL	95% CL
JAN	0 SNU	80 SNU	166 SNU
FEB	29	105	191
MAR*	0	139	251
APR*	0	163	287
SUM	0 SNU	55 SNU	105 SNU

4.2. Systematic Effects

Systematic effects fall into three categories: uncertainties in efficiencies, a possible variation in time of the detector background causing an incorrect background subtraction, and uncertainties in the extrapolation of the ^{71}Ge K peak acceptance window from the ^{55}Fe calibration.

Uncertainties in efficiencies include uncertainties in the amount of gallium (0.5%), the exposure time (0.1%), the delay time between start of the extraction and the start of counting (0.5%), dead time in the counting system (0.5%), amount of Ge carrier introduced (5%), amount of extracted Ge carrier (3%), detector efficiency (19%), risetime cut acceptance (5%), and energy cut acceptance (5%). The total systematic error due to efficiencies is determined by adding these uncertainties in quadrature to obtain a total uncertainty of 21% (12 SNU, 68% CL) and 42% (44 SNU, 95% CL).

The uncertainty in background subtraction under the ^{71}Ge decay curve due to time variations of the counter background was checked in two ways. First, the data from the ^{71}Ge K peak was analyzed using only the first 30 days of data and the increase in the limit was only 5 SNU (68% CL). Second, in order to get better statistics, the events within the ^{55}Fe acceptance window were also split into two time periods of 30 days each and the maximum allowed variation was determined. This variation was then converted into a maximum allowed variation in the background rate for the ^{71}Ge K peak, assuming that the change in background rate is independent of energy. This gave a maximum change in the ^{71}Ge rate of 19 SNU (68% CL) and 35 SNU (95% CL). To be conservative, we used the larger number (19 SNU) of the two techniques in determining the uncertainty in time variations in the background rate.

We note that the data is totally consistent with a constant background and no ^{71}Ge decays. The first 30 days of data (about three ^{71}Ge half lives) has 8 counts in the ^{71}Ge K peak and the second 30 days has 7 counts. The second 30 day period must be corrected from 7.0 to 8.3 counts due to the fact that the March and April runs have so far counted only for 52 and 39 days respectively.

The uncertainty in the position of the ^{71}Ge acceptance window by extrapolating from the position of the ^{55}Fe acceptance window results in an uncertainty of which events are to be considered as candidates for ^{71}Ge decay. While there is a very small uncertainty in determining the acceptance limits in energy, the uncertainty in the extrapolation for the acceptance limits on the risetime of the events may be

appreciable. This uncertainty is due largely to nonlinearities and offsets in the risetime electronics. However, there is a limiting bound to the position of the window on risetime: no real pulse can have a risetime which is faster than for point ionization in the counter. Occasionally, there can be noise pulses with a faster risetime, but such noise pulses are extremely rare in the K peak region (less than one or two per month). Thus, the maximum uncertainty in the ^{71}Ge rate can be determined by shifting the position of the acceptance window in risetime^{-1} down (see Figure 3) until one starts to exclude some of the events. By shifting the acceptance window in inverse risetime down, one includes additional background events, but ensures that no possible ^{71}Ge candidate events are excluded by the cut. This procedure is the most conservative one possible since it maximizes the background included within the cut without excluding any possible ^{71}Ge candidates.

The data for each extraction was then reanalyzed with the shifted acceptance window and the change in the best fit and upper limits was determined. The value for the best fit did not change, due to the fact that there are simply very few early time events, within either the unshifted or shifted acceptance windows. The change in the upper limits for all four extractions combined together was determined to be 13 SNU (68% CL) and 19 SNU (95% CL).

4.3. Initial Results

The combined data from all four extractions is shown in Figure 4, which shows the integral time plot of events within the ^{71}Ge K peak acceptance window. In this figure, the value of the curve is incremented by one count every time a candidate event occurs. Also plotted is a straight line, which corresponds to a constant background. One observes that this provides a good fit to the data. The curved line corresponds to the exponential decay of ^{71}Ge purely at the level predicted by the SSM and does not include any background. The fact that the data falls well below this line indicates there is a deficit of solar neutrinos. In fact, even if one ascribes all of the candidate events to be signal, the total observed number of counts is still one half of that predicted by the SSM.

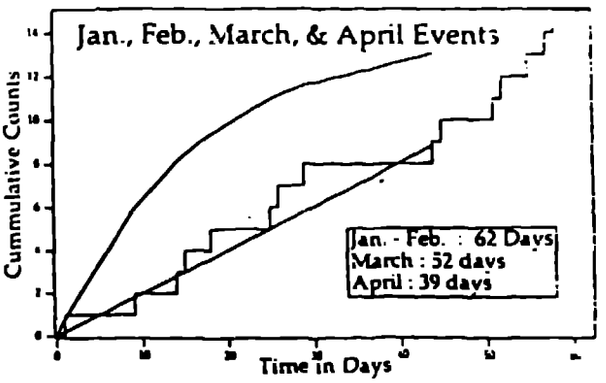

FIGURE 4
Integral Plot of ^{71}Ge K Peak Events.

The overall best fit value and upper limits to the solar neutrino flux was determined as follows. The best fit value was determined by a combined analysis of four extractions. The upper limits were determined by adding the statistical uncertainties (55 SNU) in quadrature with the systematic uncertainties due to efficiencies (12 SNU) and time variation of the background (19 SNU). The systematic uncertainty in determining the risetime acceptance window (13 SNU) was then added linearly to the above uncertainty. While this is very conservative, it takes into account the possibility that there may be a systematic bias in the way in which we determine the acceptance windows. The results of the analysis of the four runs, expressed both in SNU and as a fraction of the SSM, are.

(where A = $\frac{^{71}\text{Ge extraction efficiency}}{\text{Carrier extraction efficiency}}$)

BEST FIT	68% CL	95% CL
0 SNU	72 SNU / A	138 SNU / A
0.0 SSM	0.[illegible] SSM / A	1.05 SSM / A

The factor A is included since it has not yet been demonstrated that the extraction efficiency of the ^{71}Ge produced in inverse beta decay by solar neutrinos is equal to the extraction efficiency determined using the natural Ge carrier added to the reactors. It is certainly to be expected that A ~1, and no viable physical mechanism has been postulated in which A could be different than 1. Nonetheless, the factor A is included in order to explicitly identify the one assumption made in determining the stated limits.

4. FUTURE PLANS

Monthly extractions from the 30 tons of gallium will continue. At the same time, further tests to understand the source of the remaining background will be conducted, and the detector will be expanded to the full 60 tons of gallium. The additional 30 tons is now stored underground and will be installed into reactors shortly. During the purification of this additional gallium to remove ^{68}Ge, studies will be carried out to optimize the chemical extraction efficiency.

The ^{71}Ge L peak data is presently being analyzed. If the background can be reduced further, either by identification and elimination of the background source in the experiment, or by improved analysis techniques, the counting efficiency in the experiment could be almost doubled.

The number of channels in the present counting systems is being increased to allow for longer counting times for each extraction and to allow additional systematic checks of reagents, counter backgrounds, etc. to be carried out.

Significant quantities of stable ^{72}Ge and ^{73}Ge isotopes are available that will be used sequentially for the Ge carrier. Mass spectrometric analysis of the isotopes in the germanium extracted from the reactors should yield an improved understanding of the chemical process.

As an initial test of the extraction process, we plan to shortly dope one of the reactors with a known number of ^{71}Ge atoms along with the natural Ge carrier and compare the extraction efficiencies. A final calibration of the detector is planned using a ^{51}Cr neutrino source. It is expected that an activity of 0.8 MCi will be obtained by irradiating about 200 g of enriched chromium (86% ^{50}Cr) in the Soviet reactor SM-2 (thermal flux = 3.2×10^{15} neutrons cm^{-2} sec^{-1}). Approximately 400 decays from the ^{71}Ge atoms produced by this source are expected to be detected, yielding a statistical accuracy in the calibration of 5%. This calibration experiment is expected to occur in early 1992.

5. SUMMARY

The first data from a gallium solar neutrino experiment is consistent with no solar neutrino induced events being observed. The initial data indicates that the flux may be less than that expected from p-p neutrinos alone, thus indicating that the solar neutrino problem also applies to the low energy p-p neutrinos. However, the statistics are limited and additional systematic checks are planned to check extraction efficiencies. It is anticipated that within the next year the SAGE experiment will be able to definitively determine whether the flux of low energy solar neutrinos is sufficiently low to indicate the need to invoke new particle physics in order to explain the solar neutrino problem.

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