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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Status of the Soviet-American Gallium Experiment

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A radiochemical ^{71}Ga–^{71}Ge experiment to determine the primary flux of neutrinos from the Sun began measurements of the solar neutrino flux at the Baksan Neutrino Observatory in 1990. The number of ^{71}Ge atoms extracted from 30 tons of gallium in 1990 and from 57 tons of gallium in 1991 was measured in 12 runs during the period of January 1990 to December 1991. The combined 1990 and 1991 data-sets give a value of $58+17/-24$ (stat) ± 14 (syst) SNU. This is to be compared with $132+7/-5$ SNU predicted by the Standard Solar Model.

1. Introduction

A fundamental problem during the past two decades has been the large deficit of the solar neutrino flux observed in the radiochemical chlorine experiment (Davies *et al.* 1991) compared with the Standard Solar Model (SSM) theoretical predictions (Bahcall & Ulrich 1988; Turcke-Chieze 1988). Recent results of the Kamiokande II water Cherenkov experiment (Hirata *et al.* 1990) have confirmed this deficit. These results may be explained by deficiencies in the solar model in predicting the ^{8}B neutrino flux or may indicate the possible existence of new properties of the neutrino (Bahcall 1989). A radiochemical gallium experiment can help determine the role new neutrino properties may play in the suppression of the solar neutrino flux. An experiment using ^{71}Ga provides the only currently feasible means to measure low energy solar neutrinos produced in the proton–proton (p–p) reaction (Kuzmin 1966).

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Exotic hypotheses aside, the rate of the p–p reaction is directly related to the solar luminosity and is insensitive to alterations in the solar models. An observation in a gallium experiment of a strong suppression of the low energy solar neutrino flux requires the invocation of new neutrino properties.

2. The Baksan gallium experiment extraction procedure

The experimental layout as well as the chemical and counting procedures have been described previously and are only briefly outlined here (Gavrin *et al.* 1989). The experiment is based on counting the ^{71}Ge atoms created by the reaction:

$$\nu_e + {}^{71}\text{Ga} \rightarrow e^- + {}^{71}\text{Ge}$$

on a target of gallium metal. Each measurement of the solar neutrino flux begins by adding approximately 700 μg of natural Ge carrier equally divided among the reactors holding the gallium. After a typical exposure interval of one month, the Ge carrier and any ^{71}Ge atoms that have been produced by neutrino capture are chemically extracted from the Ga using the following procedure. A weak HCl solution is mixed with the Ga metal in the presence of H_2O_2 which results in the extraction of Ge into the aqueous phase. The extracted solutions from the reactors are combined and reduced in volume by vacuum evaporation. Additional HCl is then added and an Ar purge is initiated which sweeps the Ge as $GeCl_4$ from the acid solution into 1.2 l of H_2O. The $GeCl_4$ is then extracted into CCl_4 and back extracted into 0.1 l of low-tritium H_2O. The counting gas GeH_4 (germane) is then synthesized and purified by gas chromatography. The extraction efficiency is measured at two stages of the extraction procedure by atomic absorption analysis. The final determination of the quantity of germanium is made by measuring the volume of synthesized GeH_4. The overall extraction efficiency is typically 80 ± 6 %.

3. Counting procedure

The GeH_4 is then mixed with a measured amount of Xe and inserted into a low-background proportional counter. The proportional counter (with a volume of about 0.75 cm^3) is placed in the well of a NaI detector inside a large passive shield and counted for 2–4 months. ^{71}Ge decays by electron capture to the ground state of ^{71}Ga with an 11.4 day half-life. The low-energy K- and L-shell Auger electrons and X-rays produced during electron shell relaxation in the ^{71}Ge daughter atom are detected by the proportional counter. Pulse shape discrimination based on rise time measurements is used to help separate the ^{71}Ge decays from background. The energy, amplitude of the differentiated pulse, and any associated NaI signal are recorded for each event in the counter. The counter is typically calibrated at one month intervals using an external ^{55}Fe source. The K-peak acceptance window is then determined by extrapolation from the ^{55}Fe peak. The extrapolation procedure was verified by filling a counter with $^{71}GeH_4$ together with the standard counter gas.

4. Extraction history

The experiment began operation in May 1988 when purification of 30 tons of Ga commenced. The large quantities of long-lived ^{68}Ge (half-life = 271 days) produced by cosmic rays while the Ga was on the surface were removed. New extraction

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Table 1. *Statistical analysis of runs*

extraction date	Ga mass/t	best fit (SNU)	Nw2	68 % CL (SNU)	probability (%)
Jan 24, 90	28.7	0	0.367	60	9
Feb 28, 90	28.6	39	0.310	83	13
Mar 29, 90	28.5	90	0.035	175	96
Apr 20, 90	28.4	0	0.060	94	81
May 22, 90	28.3	79	0.073	204	73
Jul 24, 90	21.0	0	0.250	149	19
Jun 28, 91	27.4	8	0.142	100	41
Jul 23, 91	27.4	27	0.079	131	70
Aug 25, 91	49.3	300	0.050	421	96
Sep 23, 91	56.6	48	0.064	91	79
Nov 22, 91	56.3	75	0.088	131	65
Dec 20, 91	56.2	93	0.037	147	95
Combined 1990 and 1991		58	0.094	80	61

procedures were implemented beginning with the January 1990 extraction which resulted in the elimination of radon contamination in the extractions. Monthly extractions were carried out from January through July of 1990 with sufficiently low backgrounds to begin measurements of the solar neutrino flux. The rise time information for the May run was lost due to electronic problems. Although the resulting high background gave essentially no sensitivity to the solar neutrino flux, the May run is shown here for completeness. The extraction sample for the June run was lost due to a vacuum accident. Useful solar neutrino data were not obtained after the July 1990 run due to an engineering test run using a ^{51}Cr calibration source. Following completion of the test run, a total of about 30 tons of new Ga were purified, the gallium used in the previous solar neutrino runs was removed and the chemical reactors were extensively cleaned, and then the chemical extraction system was carefully cleaned. Separate extractions of the new and old Ga were carried out in June and July 1991. Rise time information was lost for the June run due to unstable electronics, but the background was still sufficiently low that a measurement of the solar neutrino flux could be made. Beginning in August 1991, combined extractions of the old and new Ga were begun. The run from October 1991 was lost due to a counter failure.

5. Measurement of the solar neutrino flux

Results from measurements carried out in 1990 and 1991 are reported here. Earlier data taken during 1989 are not presented here due to the presence of radon and residual ^{68}Ge. The data analysis selects events that have no NaI activity in coincidence within the ^{71}Ge K-peak acceptance window. The K-peak acceptance window in energy is a 2 FWHM wide energy cut centred on the K-peak and the inverse rise time cuts are 95 % acceptance. A maximum likelihood analysis (Cleveland 1983) is then carried out on these events by fitting the time distribution to an 11.4-day half-life exponential decay plus a constant rate background. Table 1 shows the results of the maximum likelihood analysis.

The data from each of the 12 extractions are shown in figure 1, which shows the integral plot of events versus time within the ^{71}Ge K-peak acceptance window. In

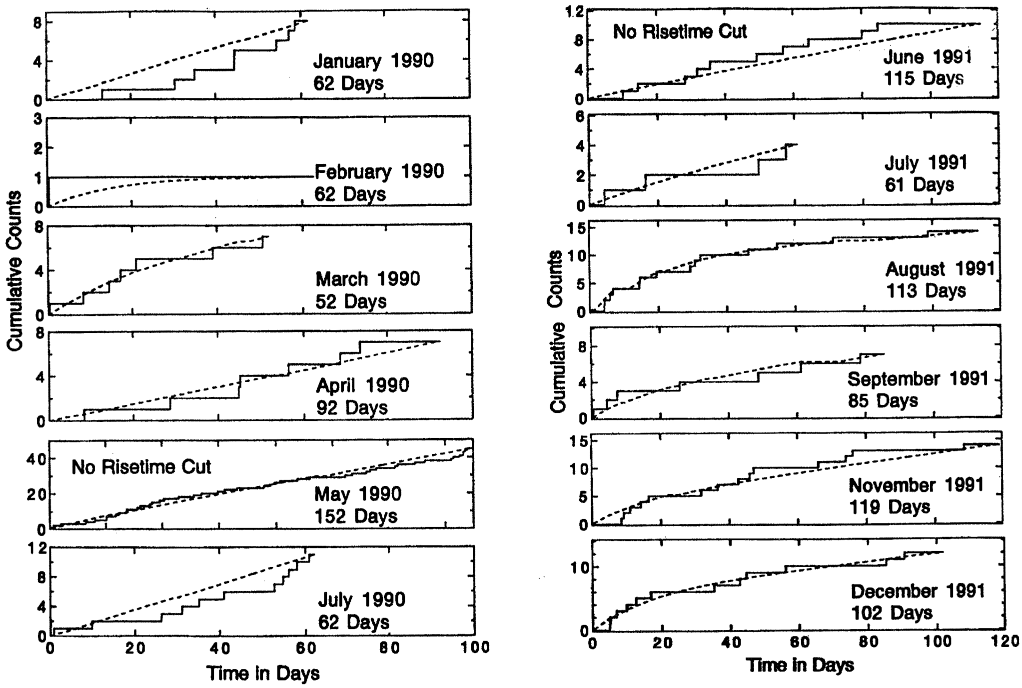

Figure 1, The data for the 12 runs for which results are given in table 1. The plots show the integral number of events recorded up to the given time which satisfy the pulse-height and rise-time cuts for K-peak events. The solid lines are the data, while the dashed curves are the best fit for background plus signal. On these plots a time-independent background would appear as a straight line, while a signal from ^{71}Ge decay appears as a convex-upward curve (see the February 1990 fit, for instance).

this figure, the value of the curve is incremented by one count every time an event occurs and thus shows the time distribution of ^{71}Ge-like events. The best fit line to each data-set is shown by the dashed line. The Smirnov–Cramer–Von Mises parameter Nw^2 provides a measure of the goodness of fit (Marshall 1958), which is independent of the binning of the data. For this parameter, it is expected that 50% of the fits should have values greater than 0.119, and 50% less than 0.119. (In some sense, one can consider a Nw^2 value of 0.119 as being analogous to a χ^2 value of 1.0.) The probability that a measurement would exceed the value of Nw^2 determined for each of the runs is also given in table 1.

6. Systematic effects

The systematic uncertainties in the chemical extraction and counting efficiencies were typically 6% and 10%, respectively, corresponding to a 7 SNU uncertainty. The systematic uncertainty in extrapolating the inverse rise time cuts is estimated using a cut that includes all events not in coincidence with the NaI counter which are within the energy cut of the K-peak acceptance window with no cut made on inverse rise time. This results in an uncertainty of 9 SNU (68% CL) for the combined 1990 and 1991 data.

In the 1990 data set in which there was an apparent increase in the background at late counting times (see figure 1) for some runs. The uncertainty in the background determination under the ^{71}Ge decay curve due to possible time variations of the counter background was checked in a number of ways (Abazov *et al.* 1991). All tests are consistent with the hypothesis that the apparent increase in background at late times is purely a statistical fluctuation. However, such a fluctuation could suppress the signal by causing an overestimation of the background at early times. To minimize any assumptions, an uncertainty for any possible time variation of the background for the 1990 data was assigned to be 30 SNU (68% CL). A possible time variation of the background was checked for in the 1991 data and the combined 1990 and 1991 data and none was found. As there is no evidence for any time variation in the 1991 or the combined 1990 and 1991 data, it is assumed that the background is constant in time and no systematic uncertainty is assigned for a possible time variation in the background to the combined 1990 and 1991 data-sets. The final possible systematic effect is due to possible background reactions which could produce ^{71}Ge and the possible presence of radon, which can mimic a ^{71}Ge signal. The total background production rate in 30 tons of liquid gallium metal of all germanium activities has been calculated to be less than 2.5% of the SSM production rate (Gavrin *et al.* 1989), resulting in an uncertainty of 3 SNU (68% CL). The data has been examined to search for a possible presence of radon. Checks included looking at overflow events, looking outside of the K-peak acceptance window, looking for delayed coincidences of events, and fitting the data to allow for both ^{71}Ge and radon. A systematic uncertainty for the presence of radon of 8 SNU (68% CL) was assigned.

7. Results

The results (Abazov *et al.* 1991) of the analysis of the five runs with rise time selection in the 1990 data indicated a flux of solar neutrinos of only 20 SNU (statistically one sigma above zero). However, the large systematic uncertainties of a possible time variation of the background led to an upper limit of the ^{71}Ga capture rate of 79 SNU (90% CL). With the additional data from 1991, it appears that the increased count rates at late times observed in some of the runs were simply statistical fluctuations. Monte Carlo simulations of the data indicate that both the 1990 and 1991 data are statistically distributed as expected with a central value of 58 SNU. For the combined 1990 and 1991 data, the rate was determined to be: ^{71}Ga capture rate $= 58+17/-24$ (stat) ± 14 (syst) SNU. This assumes that the extraction efficiency for ^{71}Ge atoms produced by solar neutrinos is the same as that measured using natural Ge carrier. This corresponds to 24 counts assigned to ^{71}Ge decay, compared to the SSM prediction of 55 counts.

8. Extraction efficiencies

While all available information leads one to expect that the extraction efficiency for ^{71}Ge atoms produced by solar neutrinos should be the same as for the carrier, it is important to test this assumption. A test to search for possible losses in the extraction of ^{71}Ge atoms was carried out by doping the Ge carrier with a known number (6555 ± 359) of ^{71}Ge atoms. The doped carrier was added to one of the reactors holding 7 tons of gallium, three successive extractions were carried out, and the number of ^{71}Ge atoms in each extraction was determined by counting. The overall chemical extraction efficiency was determined to be 101 ± 5%, while that for the ^{71}Ge was $99+6/-8$%, indicating that the extraction efficiency of the natural Ge carrier and ^{71}Ge track closely.

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The measurement with the ^{71}Ge doped carrier does not test for possible losses which might occur during the formation process. In inverse beta decay, the resultant ^{71}Ge atom may be in an excited state and in some fraction, the ^{71}Ge atom is ionized. It is possible, albeit very unlikely, that these excitations may drive some chemical reaction which may result in the ^{71}Ge atom being tied up in a chemical form which we cannot efficiently extract. That atoms which have been produced in excited states can be extracted from metallic gallium has been demonstrated at some level during the clean-up of the gallium, as we efficiently extracted in excess of 99.9% of the cosmogenic ^{68}Ge.

We are currently carrying out a set of measurements in which we look at beta decay of Ga isotopes in the gallium. In the sudden impulse approximation, atomic excitations of an atom during beta decay should be the same as those in inverse beta decay. In this experiment, we have taken a few grams of gallium from the reactors and then chemically removed all of the residual Ge carrier. The gallium was then irradiated to form several mg each of ^{70}Ga and ^{72}Ga by (n, γ) reactions. The ^{70}Ga and ^{72}Ga subsequently decay to stable ^{70}Ge and ^{72}Ge with half-lives of 21.1 min and 14.1 h, respectively. The gallium metal is kept liquid (in order to simulate conditions in the solar neutrino runs) and allowed to sit for a few weeks so that all of the ^{70}Ga and ^{72}Ga has decayed. The stable ^{70}Ge and ^{72}Ge are then extracted from the irradiated gallium using the same procedure as in the full scale solar neutrino runs. Both the absolute amounts of ^{70}Ge and ^{72}Ge and their ratio are determined by mass spectroscopy. Preliminary results show the efficiencies for ^{70}Ge and ^{72}Ge to be 98% and 92%, respectively, with uncertainties of ± 10%. Thus, it appears that ^{70}Ge and ^{72}Ge are formed in the amounts expected. Finally, an experiment using a neutrino source is planned to test the overall extraction efficiency *in situ*. A suitable neutrino calibration source can be made using ^{51}Cr, which decays with a 27.7 day half-life by electron capture, emitting monoenergetic neutrinos of 751 keV (90.2% BR) and 426 keV (9.8% BR). An engineering test run with a lower-intensity ^{51}Cr source was carried out during the fall of 1990. A full-scale calibration run is scheduled for 1994 using a 1-MCi ^{51}Cr source.

9. Current status and future plans

With the combined 1990 and 1991 data-sets, SAGE is observing a signal consistent with ^{71}Ge produced by solar neutrinos. The first results from SAGE, and the data from 1991 appear consistent taking into account the systematic uncertainties. The combined data-sets show a good overall fit to a value of 58 SNU. However, these results are still based on limited statistics and assume that the extraction efficiency for ^{71}Ge atoms produced by solar neutrinos is the same as that measured using natural Ge carrier. It is clearly necessary to accumulate more data with higher signal to noise and better efficiencies, as well as to test the extraction efficiency with a ^{51}Cr artificial neutrino source.

Intensive work has been carried out to reduce noise pulsing and backgrounds in the L peak. Preliminary data indicates that beginning with the September 1992 run, we are able to count the L peak, which will almost double our counting efficiency. Preparations are also underway to fully calibrate the system using an artificial ^{51}Cr source. We expect to be able to carry out this experiment in 1994. Finally, we are continuing to study possible systematic effects from the data, including additional studies of possible background sources and Monte Carlo simulations.

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10. Conclusions

Different SSMs predict that the total expected capture rate in ^{71}Ga to be in the range of 125 to 132, with the dominant contribution (71 SNU) coming from the p–p neutrinos. The minimum expected rate in a Ga experiment, assuming only that the Sun is presently generating nuclear energy at the rate at which it is radiating energy, is 79 SNU. Observation of significantly less than 79 SNU in a gallium experiment is difficult to explain without involving new neutrino properties. The first measurements from a gallium solar neutrino experiment have observed fewer ^{71}Ge atoms than predicted by the SSM. From the 1990 and 1991 data, we observe only 44% of the predicted flux. Assuming the extraction efficiency for ^{71}Ge atoms produced by solar neutrinos is the same as for natural Ge carrier, the first measurements indicate that the flux may be less than that expected from p–p neutrinos alone.

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