Search for Neutrinos from the Sun Using the Reaction ^{71}Ga(ν_e,e^-)^{71}Ge

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A radiochemical ^{71}Ga-^{71}Ge experiment using 30 tons of gallium to determine the primary flux of neutrinos from the Sun has begun operation at the Baksan Neutrino Observatory in the U.S.S.R. Assuming that the extraction efficiency for ^{71}Ge atoms produced by solar neutrinos is the same as from natural Ge carrier, we observed the capture rate to be 20^{+15}_{-20}(stat) ± 32(syst) solar neutrino units (SNU), resulting in a limit of less than 79 SNU (90% C.L.). This is to be compared with 132 SNU predicted by the standard solar model.

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A fundamental problem during the last two decades has been the large deficit of the solar neutrino flux observed in the radiochemical chlorine experiment [1] compared with the theoretical predictions [2,3] based on the standard solar model (SSM). Recent results of the Kamiokande II water Cherenkov experiment [4] 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 [5–9]. The role new neutrino properties may play in the suppression of the high-energy solar neutrino flux, as possibly indicated in the chlorine and Kamiokande II experiments, can be determined by a radiochemical gallium experiment. An experiment using ^{71}Ga as the capture material [10] provides the only feasible means at present to measure low-energy solar neutrinos produced in the proton-proton (*p-p*) reaction. 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.

In this paper we present the first results of the measurement of the solar neutrino flux by the Soviet-American gallium solar neutrino experiment (SAGE). SAGE uses the Gallium-Germanium Neutrino Telescope situated in an underground laboratory at the Baksan Neutrino Observatory of the Institute for Nuclear Research of the Academy of Sciences of the U.S.S.R. in the Northern Caucasus of the U.S.S.R. The main chamber 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 approximately 4700 m water equivalent. The 30 tons of liquid gallium used in the present measurement is contained in four Teflon-lined chemical reactors, each holding about 7 tons of gallium.

The chemical extraction of germanium from liquid metallic gallium was first tested on a small scale in the U.S. [11] and later developed and tested at a 7.5-ton pilot installation in the U.S.S.R. [12]. The experimental layout as well as the chemical and counting procedures have been described previously [13] and are only briefly outlined here.

Each measurement of the solar neutrino flux begins by adding approximately 160 μg of natural Ge carrier to each of the four reactors holding the gallium. After a typical exposure interval of 3 to 4 weeks, the Ge carrier and any ^{71}Ge atoms that have been produced by neutrino capture are chemically extracted from the gallium using the following procedure. A weak hydrochloric acid solution is mixed with the gallium metal in the presence of hydrogen peroxide, which results in the extraction of germanium into the aqueous phase. The extracted solutions from the four separate reactors are combined and reduced in volume by vacuum evaporation. Additional HCl is then added and an argon purge is initiated which sweeps the Ge as $GeCl_4$ from the acid solution into 1.2 liters of H_2O. The Ge is then extracted into CCl_4 and back extracted into 0.1 liter of low-tritium H_2O. The counting gas GeH_4 (germane) is then synthesized and purified by gas chromatography. The efficiency of extraction of the germanium carrier 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% with an uncertainty of ±6%. The GeH_4 is then mixed with a measured quantity of xenon and is 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 2–3 months. ^{71}Ge decays by electron capture to the ground state of ^{71}Ga with an 11.4-d half-life. The low-energy K- and L-shell Auger electrons and x rays produced during electron shell relaxation in the resulting ^{71}Ga atom are detected by the proportional counter. With a typical counter filled with an 80% Xe–20% GeH_4 mixture at 600 Torr, 37% of the decays are observed in the Ge K peak at 10.4 keV and 34% in the L peak at 1.2 keV. Because of considerably higher backgrounds in the L peak, only the K peak has been used in the analysis presented here.

Pulse-shape discrimination based on rise-time measurements is used to separate the ^{71}Ge decays from background. In contrast to the spatially localized ionization produced by Auger electrons or x rays from ^{71}Ge decay, background radioactivity primarily produces fast electrons in the counter which result in extended ionization. Pulses from the counter are differentiated with a time constant of 10 ns. The amplitude of the differentiated pulse is proportional to the product of the amplitude and the inverse rise time of the pulse. For every event in the counter, the energy, the amplitude of the differentiated pulse, and any associated NaI signal are recorded.

The counter is calibrated at 1-month intervals using an external ^{55}Fe source, which illuminates the central part of the counter through a thin side window. The calibration is used to generate an acceptance window for the ^{55}Fe peak in a two-dimensional plot of inverse rise time versus energy. The acceptance cuts in energy and inverse rise time are both 95%. An acceptance window for the ^{71}Ge K peak is then calculated by extrapolating from the ^{55}Fe peak. The extrapolation procedure was verified by filling a counter with $^{71}GeH_4$ together with the standard counter gas.

The data analysis selects events within the ^{71}Ge K-peak acceptance window which have no NaI activity in coincidence. A maximum-likelihood analysis [14] is then carried out on these events by fitting the time distribution with an 11.4-d half-life exponential decay plus a constant rate background. The total background rate of selected counters from 0.7 to 13.0 keV is approximately 2.0 counts/d, with typical rates in the ^{71}Ge K peak of 0.10 count/d. The total background production rate in the 30 tons of liquid gallium of all germanium activities from external neutrons, internal radioactivity, and cosmic-ray muons has been calculated to be less than 2.5% of the SSM production rate [13], based upon our studies and measurements of these various background processes.

The experiment began operation in May of 1988, when removal of the ^{68}Ge from 30 tons of gallium commenced. Before measurements of the solar neutrino flux could begin, the large quantities of long-lived ^{68}Ge (half-life of 271 d) produced by cosmic rays while the gallium was on the surface had to be removed. The decay of ^{68}Ge cannot be differentiated from those of ^{71}Ge, as ^{68}Ge also decays by electron capture. By the beginning of 1990, the backgrounds had been reduced to levels sufficiently low to begin measurements of the solar neutrino flux. Results from measurements carried out in January, February, March, April, and July of 1990 are reported here. Earlier data taken during 1989 are not presented here due to the presence of radon and ^{68}Ge residual contaminations. The run during May of 1990 was unusable due to an instability in the electronics used and the run during June of 1990 was lost due to a vacuum accident. The data from each of the five extractions are shown in Fig. 1, which shows the integral plot of events versus time within the ^{71}Ge K-peak acceptance window. In this figure, the value of the curve is incremented by one count every time an event occurs. The best-fit line to the data is shown by the dashed line for each of the data sets. The results of the maximum-likelihood statistical analysis are shown in Table I. The Smirnov–Cramer–Von Mises parameter

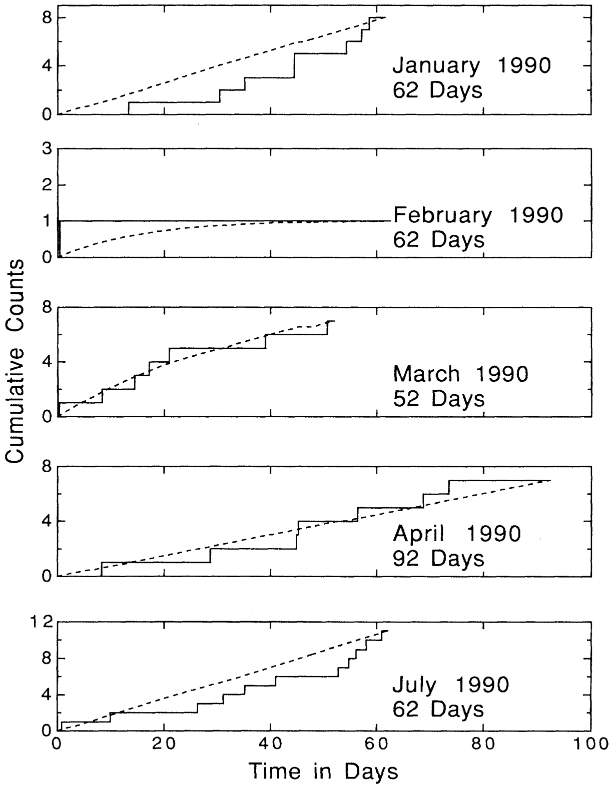

FIG. 1. Time histogram of events in ^{71}Ge K-peak acceptance window.

TABLE I. Statistical analysis of runs.

Extraction date	Best fit (SNU)	Nw^2	Probability (%)	Upper limit 68% C.L. (SNU)	Upper limit 90% C.L. (SNU)
24 Jan	0	0.367	9	60	118
28 Feb	39	0.310	13	83	142
29 Mar	90	0.035	96	175	276
20 Apr	0	0.060	81	94	174
24 Jul	0	0.250	19	149	275
Combined	20	0.223	23	35	60

Nw^2 provides a measure of the goodness of fit [15] 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 comparable 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 I. Thus, for example, we find a statistical probability that 23% of the time we would obtain a worse fit to the combined data.

The systematic uncertainties in the chemical extraction and counting efficiencies were typically 6% and 10%, respectively. These were added in quadrature together with uncertainties in the amount of gallium, exposure time, and dead time to obtain an overall uncertainty in the total efficiency of 14%, which corresponds to uncertainties of 5 solar neutrino units (SNU) (68% C.L.) and 14 SNU (90% C.L.). [1 SNU $=10^{-36}$ capture/(target atom).]

The uncertainty in background determination under the ^{71}Ge decay curve due to possible time variations of the counter background was checked by analyzing different time periods of the K-peak data and by searching for any possible time dependence of data with energies outside of the K peak. All tests were consistent with a background which is constant in time. Nonetheless, in order to conservatively assign a systematic uncertainty to any possible time variation, we fitted the time distribution of the combined data set for events in the K-peak window with a first-order polynomial expansion in time of the background rate. We then generated Monte Carlo data sets using the upper 68% and 90% C.L. limits of the parameters from the fit. We analyzed the time-dependent Monte Carlo data assuming that the background rate was constant in time and determined the maximal change in the limits set on the ^{71}Ge rate to be 30 SNU (68% C.L.) and 35 SNU (90% C.L.). This corresponds to an uncertainty of approximately one event per run being assigned incorrectly to signal rather than background due to a possible time variation in the background.

The uncertainty in extrapolating the energy and inverse rise-time cuts was determined by fitting the data using a cut which includes all events not in coincidence with the NaI counter with an energy above the low-energy window of the K peak. The fit to the combined data with this cut gave a best fit of 0 SNU and limits of 45 SNU (68% C.L.) and 83 SNU (90% C.L.). The difference between these limits and those determined using the normal energy and inverse rise-time cuts was taken as the systematic uncertainty in extrapolating from the ^{55}Fe calibrations. This results in uncertainties of 10 SNU (68% C.L.) and 23 SNU (90% C.L.).

The results of the analysis are, assuming that the extraction efficiency for ^{71}Ge atoms produced by solar neutrinos is the same as that measured using natural Ge carrier,

$$^{71}\text{Ga capture rate} = 20^{+15}_{-20}(\text{stat}) \pm 32(\text{syst})\ \text{SNU}\,.$$

Upper limits were determined by adding the statistical and systematic errors in quadrature and then adding this linearly to the best-fit value. The upper limits are

$$^{71}\text{Ga capture rate} < 55\ \text{SNU (68\% C.L.)}\,,$$

$$< 79\ \text{SNU (90\% C.L.)}\,.$$

In terms of the total number of ^{71}Ge atoms observed, these values correspond to a best fit of 2.6 atoms observed. The SSM predicts a production rate of 1.2 ^{71}Ge atoms/d in 30 tons of Ga, corresponding to a total 17.0 atoms expected for the runs reported here. In fact, if one assigns all events within the K-peak acceptance window during the first two ^{71}Ge half-lives to be signal with no background, one observes only 9 events in total, compared to 13 events predicted by the SSM in this time period.

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 compared with the natural Ge isotopes was carried out in which the Ge carrier was doped with a known number 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. Table II shows the results of this measurement, and indicates that the extraction efficiency of the natural Ge carrier and ^{71}Ge

TABLE II. Extraction efficiency of Ge carrier and ^{71}Ge.

			Efficiency (%)	
Run	Carrier (μg)	^{71}Ge atoms	Carrier	^{71}Ge
Amount Added	525 ± 26	6555 ± 359		
1	410 ± 10	5188 ± 195	78 ± 4	79 ± 5
2	97 ± 2	1131 ± 107	84 ± 20	84 ± 26
3	21 ± 1	< 200		
Sum	528 ± 10	6519^{+222}_{-422}	101 ± 5	99^{+6}_{-8}

track very closely. The third extraction had a sensitivity of only 200 atoms detected due to electronic problems with one channel of the counting system. The half-life of ^{71}Ge in this extraction test was measured to be 11.0 ± 2.4 d, in good agreement with the known half-life of 11.4 d. A more extensive series of tests were performed at our surface laboratory near Moscow during the development of the radiochemical procedure using a module similar to the present detector which contained 7 tons of gallium. In these tests, various germanium activities produced by cosmic rays were extracted. These tests showed that the radiochemical procedures used are valid and indicated that the natural germanium carrier yield should effectively measure the extraction efficiency of neutrino produced ^{71}Ge. Several additional tests are planned including an experiment using a neutrino source, which is scheduled in 1992 with a 1-MCi ^{51}Cr source. An engineering test run using a lower-intensity ^{51}Cr source has been completed, but yielded insufficient data to allow a determination of the extraction efficiency.

Now let us compare the data obtained with the predictions of the SSM. Different SSMs predict that the total expected capture rate in ^{71}Ga is in the range of 125 ± 5 SNU (1σ) [3] to 132^{+20}_{-17} SNU (3σ) [2], 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 [16]. Observation of significantly less than 79 SNU in a gallium experiment is difficult to explain without invoking new neutrino properties.

The first measurements from a gallium solar neutrino experiment have observed fewer ^{71}Ge atoms than predicted by the SSM. If 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. Thus, the solar neutrino problem may also apply to the low-energy *p-p* neutrinos, indicating the existence of new neutrino properties.

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