Measurement of the solar neutrino capture rate in SAGE

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Combined analysis of the data of 92 runs of SAGE during the 12-year period January 1990 through December 2001 gives a capture rate of solar neutrinos with energy more than 233 keV of $70.9^{+5.3}_{-5.2}$ (stat.) $^{+3.7}_{-3.2}$ (syst.) SNU. This represents only 55% of the predicted standard solar model rate of ∼130 SNU. The results of individual runs as well as the results of combined analysis of all runs during yearly, monthly, and bimonthly periods are presented. No compelling evidence for temporal variations is observed. By an analysis of the SAGE results combined with those from all other solar neutrino experiments, we make the first estimate of the electron neutrino *pp* flux that reaches the Earth to be $(4.6 \pm 1.2) \times 10^{10}/(\text{cm}^2\ \text{s})$. Assuming that neutrinos oscillate to active flavors the *pp* neutrino flux emitted in the solar fusion reaction is approximately $(7.6 \pm 2.0) \times 10^{10}/(\text{cm}^2\ \text{s})$, in agreement with the standard solar model calculation of $(5.95 \pm 0.06) \times 10^{10}/(\text{cm}^2\ \text{s})$.

1. INTRODUCTION

SAGE is well known as an experiment able to measure and monitor the low-energy part of the solar neutrino spectrum. This is because it is mainly sensitive to its principal component – the flux of *pp* neutrinos. The SAGE results have been presented at previous Neutrino and TAUP conferences and at many other meetings since 1990 [1–6]. The deficit of neutrinos in the high-energy part of the solar neutrino spectrum compared to the prediction of the standard solar model [7,8], as discovered by the chlorine experiment [9] and confirmed by the Kamiokande [10] experiment, has been shown by SAGE to extend to the low-energy part of the spectrum. The SAGE experimental layout and procedures are fully described in our article in Physical Review C [11] and we refer the reader who wishes further detail to that publication.

In our latest article submitted this spring to JETP [12] we summarized our measurements during slightly more than half of the 22-year cycle of solar activity (the period January 1990 through December 2001). Here we briefly discuss the general principles of the experiment, give the statistical analysis of all data, present our determination of the *pp* solar neutrino flux, and conclude with the current implications of the SAGE results for solar and neutrino physics using the latest results of SuperKamiokande [13] and SNO [14]. My talk is based mainly on the JETP article and in addition I give the complete table of all individual SAGE runs.

2. OVERVIEW OF THE SAGE EXPERIMENT

2.1. The laboratory of the gallium-germanium neutrino telescope

The SAGE experiment is situated in a specially built deep underground laboratory at the Baksan Neutrino Observatory (BNO) of the Institute for Nuclear Research of the Russian Academy of Sciences in the northern Caucasus mountains. It is located 3.5 km from the entrance of a horizontal adit excavated into the side of a mountain. The rock gives an overhead shielding equivalent to 4700 m of water and reduces the muon flux by a factor of 10^7. The measured muon flux is

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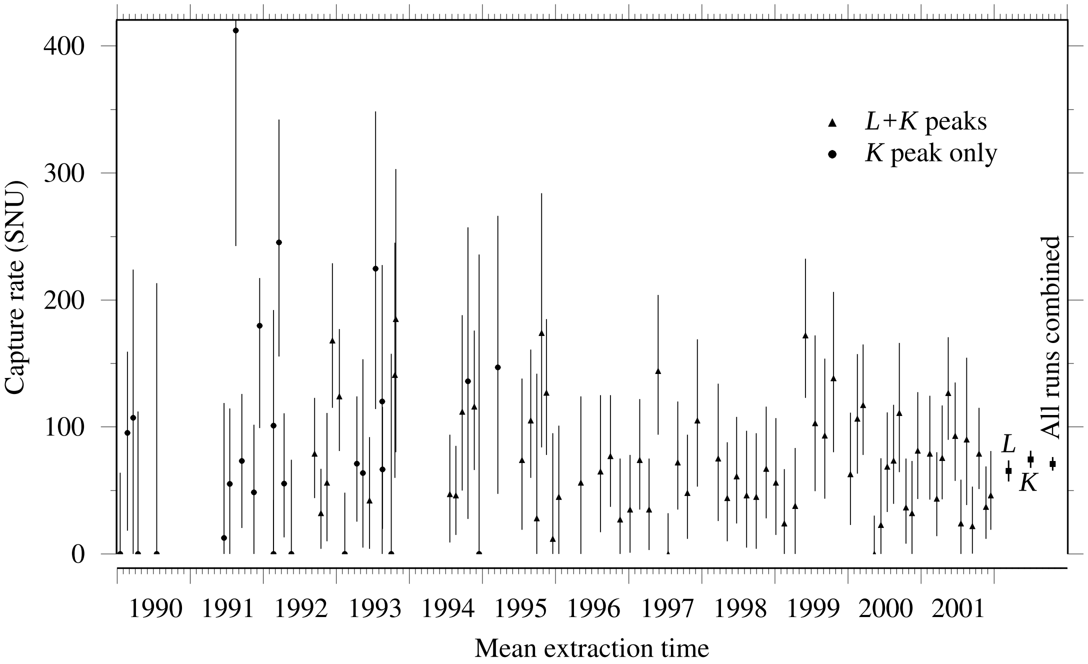

Figure 1. Capture rate for all SAGE extractions as a function of time. Error bars are statistical with 68% confidence. The combined result of all runs in the L peak, the K peak, and both L and K peaks is shown on the right side.

$(3.03 \pm 0.10) \times 10^{-9}/(\mathrm{cm}^2\ \mathrm{s})$.

2.2. Experimental procedures

SAGE measures the capture rate of solar neutrinos with the reaction $^{71}\mathrm{Ga}(\nu_e, e^-)^{71}\mathrm{Ge}$ [15]. The mass of gallium used at the present time is about 50 tonnes. It is in the form of liquid metal and is contained in 7 chemical reactors. A measurement of the solar neutrino capture rate begins by adding to the gallium a stable Ge carrier. The carrier is a Ga-Ge alloy with a known Ge content of approximately 350 μg and is distributed equally among all reactors. After a typical exposure interval of four weeks, the Ge carrier and ^{71}Ge atoms produced by solar neutrinos and background sources are chemically extracted from the Ga using procedures described in [11]. The final step of the chemical procedure is the synthesis of germane (GeH_4), which is used as the proportional counter fill gas with an admixture of (80–90)% Xe. The total efficiency of extraction is the ratio of mass of Ge in the germane to the mass of initial Ge carrier and is typically in the range of (80–90)%. The systematic uncertainty in this efficiency is 3.4%, mainly arising from uncertainties in the mass of added and extracted carrier. The proportional counter is placed in the well of a NaI detector that is within a large passive shield and is counted for a typical period of 4–6 months.

3. STATISTICAL ANALYSIS OF SOLAR DATA

Based on criteria described in [12] a group of events is selected from each extraction that are candidate ^{71}Ge decays. These events are fit to a maximum likelihood function [16], assuming that they originate from an unknown but constant-rate background and the exponentially decaying rate of ^{71}Ge. A single run result has little significance because of its large statistical uncertainty; nonetheless, we give in Table 1 the results for all individual SAGE runs [2] so others may use them for their own analyses. The results of all runs of SAGE are also plotted in Fig. 1.

4. RESULTS

The global best fit capture rate for all data from January 1990 to December 2001 (92 runs and 158 separate counting sets) is $70.9^{+5.3}_{-5.2}$ SNU, where the uncertainty is statistical only. In the windows that define the L and K peaks there are 1740 counts with 407.3 assigned by time analysis to ^{71}Ge (the total counting live time is more than 30 years). If one considers the L-peak and K-peak data independently, the results are $65.3^{+8.5}_{-8.2}$ SNU and $74.3^{+6.9}_{-6.6}$ SNU, respectively. The agreement between the two peaks serves as a strong check on the robustness of the event selection criteria. The systematic effects fall into three main categories: those associated with extraction efficiency, with counting efficiency, and with backgrounds. For a complete description of these effects see [11]. Our overall result is $70.9^{+5.3+3.7}_{-5.2-3.2}$ SNU. For comparison, the latest result of the GNO experiment (including GALLEX) is $74.1^{+5.4+4.0}_{-5.4-4.2}$ SNU [17]. If we combine the SAGE statistical and systematic uncertainties in quadrature, the result is $70.9^{+6.5}_{-6.1}$ SNU.

4.1. Tests of ^{71}Ge extraction efficiency

The validity of this result relies on the ability to chemically remove with a well known efficiency a few atoms of ^{71}Ge produced by neutrino interactions from 5×10^{29} atoms of Ga. To measure this efficiency about 350 μg of stable Ge carrier is added to the Ga at the beginning of each exposure, but even after this addition, the separation factor of Ge from Ga is still 1 atom in 10^{11}. We have performed several auxiliary measurements which confirmed that the technology of our experiment has the capability to extract ^{71}Ge at this level.

A test of all the experimental procedures including the chemical extraction, counting, and the analysis technique was performed using a 19.1 PBq (517 kCi) ^{51}Cr neutrino source. The result, expressed as the ratio of the measured ^{71}Ge production rate to that expected due to the source strength, is 0.95 ± 0.12 [18]. This value provides strong verification that the experimental efficiencies are as claimed and validates the fundamental assumption in radiochemical experiments that the extraction efficiency of atoms produced by neutrino interactions is the same as that of the natural carrier.

4.2. Temporal combinations of data

Neutrino oscillations can give a seasonal variation of the capture rate for some values of the mass and mixing angle parameters. Other phenomena can also yield temporal variations (see, e.g., [19,20]). In Ref. [12] we have given the results of combining the SAGE runs in various ways, monthly, bimonthly, and yearly. There is no compelling evidence for a temporal variation in any of these data divisions. The yearly results are plotted in Fig. 2 which shows that the rate has been more or less constant during the data taking period. Considering only the statistical errors, a χ^2 test against the hypothesis of the constant rate of 70.9 SNU yields $\chi^2 = 6.6$, which, with 11 degrees of freedom, has a probability of 83%.

5. THE *pp* NEUTRINO FLUX

One of the main purposes of the Ga experiment is to provide information that leads to the experimental determination of the flux of *pp* neutrinos at the Earth. In this Section we indicate the present state of this measurement where we use only information from the various solar neutrino experiments and assume that their reduced capture rate compared to SSM predictions is due to neutrino oscillations.

By combining the results of SAGE, GALLEX, and GNO, the capture rate in the Ga experiment is approximately 72 ± 5 SNU. This rate is the sum of the rates from all the compo-

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[2] The careful reader may detect that the results for some runs in Table 1 are not the same as in prior publications. Such revisions are necessary whenever new experimental information becomes available, such as new efficiency measurements or new rise-time calibrations.

Table 1
Results of analysis of K-peak events and of combined analysis of K- and L-peak events for all runs that could be analyzed in both peaks for period January 1990 through December 2001. See [21] for the definition and interpretation of Nw^2. The accuracy of the Monte Carlo-determined goodness of fit probability is ∼1.5% for each individual run and ∼4% for the combination of all runs.

Exp. date	Mean exposure date	Exposure time (days)	Ga mass (t)	Number of candidate events	Number fit to ^{71}Ge	Best fit (SNU)	68% conf. range (SNU)	Nw^2	Prob. (%)
Jan.90	1990.040	42.0	28.67	8	0.0	0	0– 64	0.367	5
Feb.90	1990.139	30.0	28.59	2	2.0	95	18– 159	0.164	23
Mar.90	1990.218	26.0	28.51	9	2.8	107	0– 224	0.053	65
Apr.90	1990.285	19.0	28.40	9	0.0	0	0– 112	0.104	41
July 90	1990.540	21.0	21.01	15	0.0	0	0– 213	0.142	25
June 91	1991.463	53.0	27.43	10	0.4	13	0– 119	0.211	13
July 91	1991.539	23.0	27.37	1	1.0	55	0– 115	0.159	25
Aug.91	1991.622	26.2	49.33	16	9.8	412	243– 577	0.036	83
Sep.91	1991.707	27.0	56.55	8	3.5	73	20– 126	0.041	80
Nov.91	1991.872	26.0	56.32	14	2.4	48	0– 102	0.095	32
Dec.91	1991.948	26.8	56.24	10	10.0	180	99– 217	0.063	79
Feb.92	1992.138	24.5	43.03	14	0.0	0	0– 43	0.057	75
Feb.92	1992.138	24.5	13.04	1	1.0	101	0– 192	0.085	88
Mar.92	1992.214	20.9	55.96	21	10.1	245	155– 342	0.043	71
Apr.92	1992.284	23.5	55.85	15	2.3	56	13– 111	0-143	16
May 92	1992.383	27.5	55.72	4	0.0	0	0– 74	0.134	34
Sep.92	1992.700	116.8	55.60	13	6.0	79	44– 123	0.097	27
Oct.92	1992.790	27.2	55.48	21	3.3	32	4– 67	0.105	23
Nov.92	1992.871	26.7	55.38	28	4.3	56	10– 111	0.047	69
Dec.92	1992.945	24.3	55.26	28	16.8	168	115– 229	0.057	56
Jan.93	1993.039	32.3	55.14	17	10.0	124	81– 177	0.089	34
Feb.93	1993.115	23.0	55.03	3	0.0	0	0– 48	0.116	39
Apr.93	1993.281	26.6	48.22	7	2.9	71	25– 124	0.041	81
May 93	1993.364	30.9	48.17	8	1.4	64	5– 153	0.073	53
June 93	1993.454	30.4	54.66	18	3.3	42	4– 92	0.557	0
July93	1993.537	27.9	40.44	28	7.6	225	114– 348	0.040	76
Aug.93	1993.631	34.0	40.36	4	2.5	67	20– 116	0.048	79
Aug.93	1993.628	63.8	14.09	1	1.0	120	0– 227	0.093	69
Oct.93	1993.749	13.0	14.06	0	0.0	0	0– 158	NA	NA
Oct.93	1993.800	34.7	14.10	4	3.0	142	60– 245	0.049	83
Oct.93	1993.812	24.6	14.02	7	4.0	185	80– 303	0.052	77
July 94	1994.551	31.3	50.60	22	3.4	47	9– 94	0.027	95
Aug.94	1994.634	31.0	50.55	27	3.9	46	15– 85	0.075	51
Sep.94	1994.722	33.2	37.21	30	6.5	112	50– 188	0.082	37
Oct.94	1994.799	28.8	50.45	44	4.8	136	27– 257	0.075	46
Nov.94	1994.886	31.0	50.40	23	8.0	116	66– 176	0.015	100
Dec.94	1994.951	21.0	13.14	9	0.0	0	0– 236	0.184	20
Mar.95	1995.209	42.5	24.03	23	3.7	147	47– 266	0.042	78
July 95	1995.538	19.9	50.06	33	5.0	74	19– 138	0.063	51

Exp. date	Mean exposure date	Exposure time (days)	Ga mass (t)	Number of candidate events	Number fit to ^{71}Ge	Best fit (SNU)	68% conf. range (SNU)	Nw^2	Prob. (%)
Aug.95	1995.658	46.7	50.00	24	7.4	106	60– 161	0.061	55
Sep.95	1995.742	28.8	49.95	33	1.2	28	0– 142	0.058	73
Oct.95	1995.807	18.7	49.83	25	6.9	174	84– 284	0.022	99
Nov.95	1995.875	25.8	49.76	32	10.2	127	78– 185	0.032	89
Dec.95	1995.962	32.7	41.47	40	0.5	13	0– 95	0.068	66
Jan.96	1996.045	29.7	49.64	35	3.5	45	0– 101	0.047	74
May 96	1996.347	49.9	49.47	16	3.7	56	0– 124	0.031	96
Aug.96	1996.615	45.0	49.26	21	4.2	65	17– 125	0.096	33
Oct.96	1996.749	45.8	49.15	21	5.4	77	37– 125	0.046	75
Nov.96	1996.882	48.7	49.09	28	1.9	27	0– 75	0.103	37
Jan.97	1997.019	49.8	49.04	24	2.6	35	1– 78	0.190	13
Mar.97	1997.151	44.9	48.93	23	6.2	74	35– 122	0.097	27
Apr.97	1997.277	42.9	48.83	22	2.7	35	3– 75	0.037	88
June 97	1997.403	45.6	48.78	27	10.4	144	94– 204	0.078	34
July 97	1997.537	45.9	48.67	22	0.0	0	0– 32	0.333	7
Sep.97	1997.671	46.4	48.56	15	4.6	72	35– 120	0.033	90
Oct.97	1997.803	45.0	48.45	26	3.4	48	12– 94	0.083	44
Dec.97	1997.940	47.0	48.34	24	6.2	105	53– 169	0.031	91
Apr.98	1998.225	44.9	48.05	39	5.4	75	26– 134	0.052	72
May 98	1998.347	30.0	51.17	23	3.4	44	10– 88	0.051	68
July 98	1998.477	45.6	51.06	22	4.8	61	24– 108	0.065	52
Aug.98	1998.611	45.7	50.93	33	3.6	46	5– 97	0.039	84
Oct.98	1998.745	45.8	50.81	40	3.8	45	4– 95	0.028	95
Nov.98	1998.883	45.8	50.68	32	5.9	67	28– 116	0.101	30
Jan.99	1999.014	44.7	50.54	21	4.5	56	15– 107	0.036	84
Feb.99	1999.130	38.7	50.43	16	1.6	24	0– 67	0.114	28
Apr.99	1999.279	51.7	50.29	10	1.8	38	5– 83	0.105	36
June 99	1999.417	46.7	50.17	14	12.9	172	123– 232	0.048	80
July 99	1999.551	45.7	50.06	17	5.5	103	49– 172	0.118	20
Sep.99	1999.685	45.7	49.91	20	7.1	93	43– 154	0.099	28
Oct.99	1999.801	38.7	49.78	16	10.0	138	80– 206	0.066	56
Jan.00	2000.035	28.8	49.59	24	5.4	63	23– 111	0.060	59
Feb.00	2000.127	30.7	49.48	21	9.1	107	63– 157	0.058	55
Mar.00	2000.207	28.8	49.42	19	10.1	117	78– 165	0.046	79
May 00	2000.359	30.7	49.24	15	0.0	0	0– 32	0.143	40
June 00	2000.451	33.7	49.18	17	1.4	23	0– 75	0.179	17
July 00	2000.540	32.0	49.12	29	6.4	69	33– 111	0.088	34
Aug.00	2000.626	31.3	49.06	14	5.2	74	39– 117	0.086	33
Sep.00	2000.704	27.7	49.00	30	9.2	111	64– 166	0.093	24
Oct.00	2000.796	30.7	48.90	14	3.0	37	8– 75	0.020	99
Nov.00	2000.876	28.7	48.84	25	2.9	32	0– 73	0.208	9
Dec.00	2000.958	30.7	48.78	27	7.6	81	43– 127	0.062	68
Feb.01	2001.122	29.8	41.11	21	6.3	79	43– 125	0.088	34
Mar.01	2001.214	33.4	48.53	18	3.8	44	14– 80	0.120	24

Exp. date	Mean exposure date	Exposure time (days)	Ga mass (t)	Number of candidate events	Number fit to ^{71}Ge	Best fit (SNU)	68% conf. range (SNU)	Nw^2	Prob. (%)
Apr.01	2001.290	22.7	48.43	17	6.7	76	43– 117	0.074	45
May 01	2001.373	31.7	48.37	21	11.9	127	90– 171	0.088	31
June 01	2001.469	31.7	48.27	20	9.4	93	57– 135	0.025	96
July 01	2001.547	23.7	48.17	9	2.0	24	0– 58	0.033	92
Aug.01	2001.624	28.7	48.11	21	5.4	90	38– 155	0.065	57
Sep.01	2001.701	27.7	48.06	10	2.1	22	0– 53	0.139	18
Oct.01	2001.793	30.7	47.96	12	8.1	79	51– 115	0.071	50
Nov.01	2001.887	34.8	47.91	19	4.2	37	12– 69	0.115	20
Dec.01	2001.955	22.8	47.86	21	4.0	46	19– 81	0.059	68
Combined				1740	407.3	71	66– 76	0.050	74

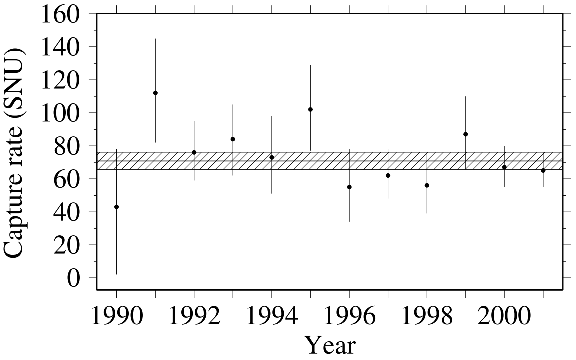

Figure 2. Combined SAGE results for each year. Shaded band is the combined best fit and its uncertainty for all years. Error bars are statistical with 68% confidence.

nents of the solar neutrino flux, which we denote by [*pp*+^{7}Be+CNO+*pep*+^{8}B|Ga,exp], where "exp" indicates that this is a measured rate. (We ignore the *hep* contribution, as it is a negligible 0.05% of the total in the SSM calculation [7].)

The only one of these flux components that is known is the ^{8}B flux, measured by SNO to be [^{8}B|SNO,exp] = $(1.75 \pm 0.15) \times 10^6$ electron neutrinos/(cm^2 s) [14]. Since the shape of the ^{8}B spectrum in SNO and SuperKamiokande is very close to that of the SSM above 5 MeV and the cross section for Ga rises steeply with energy, we can use the SNO flux and the cross section for ^{8}B neutrinos with SSM shape ($2.40^{+0.77}_{-0.36} \times 10^{-42}$ cm^2 [see [22] for the cross sections used here]) to conclude that the ^{8}B contribution to the Ga experiment is [^{8}B|Ga,exp] = $4.2^{+1.4}_{-0.7}$ SNU. Subtracting this measured value from the total Ga rate gives [*pp*+^{7}Be+CNO+*pep*|Ga,exp] = $67.8^{+5.1}_{-5.2}$ SNU.

The measured capture rate in the Cl experiment is [^{7}Be+^{8}B+CNO+*pep*|Cl,exp] = 2.56 ± 0.23 SNU [9]. (The *hep* contribution will again be neglected as it is only 0.5% of the total in the SSM.) Since the cross section in Cl is dominated by neutrinos above 5 MeV, we can again use the SNO flux and the cross section calculated for the SSM ($1.14^{+0.04}_{-0.04} \times 10^{-42}$ cm^2), and deduce that the contribution of ^{8}B to the Cl experiment is [^{8}B|Cl,exp] = 2.00 ± 0.18 SNU. Subtracting this component from the total leaves [^{7}Be+CNO+*pep*|Cl,exp] = 0.56 ± 0.29 SNU, all of which is due to neutrinos of medium energy.

Neutrino oscillations have the effect of introducing an energy-dependent survival factor to the fluxes predicted by the SSM. For the medium-energy neutrinos this factor for the Cl experiment can be approximated by the ratio of the measured rate to the SSM prediction of [^{7}Be+CNO+*pep*|Cl,SSM] = 1.79 ± 0.23 SNU. If we assume that the survival factor varies slowly with energy, we find it to be given by [^{7}Be+CNO+*pep*|Cl,exp]/[^{7}Be+CNO+*pep*|Cl,SSM] = 0.31 ± 0.17. Since the ^{7}Be contribution dominates, and it is at a single energy, the error in this factor due to the assumption that it is the same for all of these flux components can be estimated by considering the contribution of the non-^{7}Be components to the total in the SSM, which is 36%. We thus increase the error from 0.17 to $0.17 + 0.31 \times 0.36 = 0.28$.

The relative contributions to the capture rate of the medium-energy neutrinos are about the same in Ga as in Cl (75% from ^{7}Be in Ga compared to 64% in Cl). Thus it is reasonable to apply the survival factor determined for Cl to the Ga experiment, i.e., [^{7}Be+CNO+*pep*|Ga,exp] = (0.31 ± 0.28)× [^{7}Be+CNO+*pep*|Ga,SSM] = 14.4 ± 13.0 SNU. We subtract this contribution from the rate above and get the result for the measured *pp* rate in the Ga experiment [*pp*|Ga,exp] = [*pp*+^{7}Be+CNO+*pep*|Ga,exp] - [^{7}Be+CNO+*pep*|Ga,exp] = 53 ± 14 SNU.

Since the cross section does not change appreciably over the narrow range of Ga response to the *pp* neutrinos, (0.23–0.42) MeV, we divide the capture rate by the SSM cross section for electron neutrinos of $11.7^{+0.3}_{-0.3} \times 10^{-46}$ cm^2 and obtain the measured electron neutrino *pp* flux at Earth of $(4.6 \pm 1.2) \times 10^{10}/(\text{cm}^2\ \text{s})$. So far as we are aware, this is the first model-independent determination of the *pp* flux from the Sun. Note that, in contrast to other methods of analysis (see, e.g., [23]), we have only used experimental data in this calculation and have not imposed the very restrictive luminosity constraint [24] or any particular model for the probability of neutrino survival as a function of energy.

Alternatively, if we divide the capture rate by the cross section multiplied by the survival probability for *pp* neutrinos, which is 60% for the favored LMA solution assuming no transitions to sterile neutrino flavors, we receive the rate of *pp* neutrino emission in the solar fusion reaction of $(7.6 \pm 2.0) \times 10^{10}/(\text{cm}^2\ \text{s})$, in agreement with the SSM calculation of $(5.95 \pm 0.06) \times 10^{10}/(\text{cm}^2\ \text{s})$ [7]. The major component of the error in the *pp* flux measurement is due to the poor knowledge of the energy-dependent survival factor.

Several approximations were made in arriving at this value, whose nature cannot be easily quantified, so perhaps the error given here is somewhat underestimated. Nonetheless, it will be possible to reduce the error in this flux greatly when the region of mass and mixing angle parameters is better determined, as should be done by the KamLAND experiment, and when the ^{7}Be flux is directly measured, as anticipated by Borexino. The dominant error should eventually be due to the inaccuracy of the Ga measurement itself, and hence we are seeking to reduce our statistical and systematic errors.

As a side remark, it is sometimes claimed that the *pp* flux from the Sun can be determined solely from the measured photon luminosity. We wish to point out that, although the flux and the luminosity are related, a solar model is essential to extract the flux. This is because ^{3}He in the Sun can either be consumed through $^3\text{He}(^3\text{He},2p)^4\text{He}$, the termination of the *pp*I branch, or can lead on to the *pp*II or *pp*III branches via $^3\text{He}(^4\text{He},\gamma)^7\text{Be}$. The relative rates of these reactions depend on the solar conditions (temperature, density, composition, etc.) and can only be determined by a solar model.

6. SUMMARY AND CONCLUSIONS

The methods and analysis of the SAGE experiment have been summarized and results for 92 extractions during 12 years of operation from January 1990 through December 2001 have been presented. The measured capture rate is $70.9^{+5.3}_{-5.2}$ SNU where the uncertainty is statistical only. Analysis of all known systematic effects indicates that the total systematic uncertainty is $^{+3.7}_{-3.2}$ SNU, less than the statistical error.

The SAGE result of 70.9 SNU represents 55% of SSM predictions [7]. Given the extensive systematic checks and auxiliary measurements that have been performed, especially the ^{51}Cr neutrino source experiment [18], this 6.0σ reduction of the solar neutrino capture rate compared to SSM predictions is very strong evidence that the solar neutrino spectrum below 2 MeV is significantly depleted, as has been proven for the ^{8}B flux by the Cl, Kamiokande, and SNO experiments. The SAGE result is even somewhat below the astrophysical minimum capture rate of $79.5^{+2.3}_{-2.0}$ SNU [22].

Many recent phenomenology papers (see, e.g., [23,25,26]) discuss the combined fit of all solar neutrino experiments. Their conclusion is that the electron neutrino oscillates into other species and the best fit is to the LMA region of Mikheyev-Smirnov-Wolfenstein (MSW) oscillations. To more precisely determine the oscillation parameters in the solar sector will require additional data, especially from experiments sensitive to the low-energy neutrinos. In this vein, SAGE continues to perform regular solar neutrino extractions every four weeks with ~50 t of Ga and will continue to reduce its statistical and systematic uncertainties.

Acknowledgments

We thank J. N. Bahcall, M. Baldo-Ceolin, G. T. Garvey, W. Haxton, V. A. Kuzmin, V. V. Kuzminov, V. A. Matveev, L. B. Okun, R. G. H. Robertson, V. A. Rubakov, A. Yu. Smirnov, A. N. Tavkhelidze, and many members of GALLEX and GNO for their continued interest and for stimulating discussions. We appreciate the support of the Russian Foundation for Fundamental Research under grants 96-02-18399 and 99-02-16110, the Division of Nuclear Physics of the U.S. Department of Energy under grant DEFG03-97ER41020, and the U.S. Civilian Research and Development Foundation under awards RP2-159 and RP2-2253.

REFERENCES

1. SAGE Coll., V. N. Gavrin *et al.,* Nucl. Phys. B (Proc. Suppl.) 19 (1991) 84.
2. SAGE Coll., J. S. Nico *et al.,* Proc. Int. Conf. Pan. XIII Particles and Nuclei, Italy, (1994) 747.
3. SAGE Coll., S. R. Elliott *et al.,* Proc. XXXth Rencontres de Moriond, Les Arcs, France, (1995) 439.
4. SAGE Coll., T. J. Bowles *et al.,* Proc. 4th Int. Solar Neutrino Conf., Heidelberg, Germany, (1997) 109.
5. SAGE Coll., E. P. Veretenkin *et al.,* Proc. the 4th Int. Solar Neutrino Conf., Heidelberg, Germany, (1997) 126.
6. V. N. Gavrin, Nucl. Phys. B (Proc. Suppl.) 91 (2000) 36.
7. J. N. Bahcall, M. H. Pinsonneault, and S. Basu, astro-ph/0010346, Astrophys. J. **555** (2001) 990.
8. A. S. Brun, S. Turck-Chièze, and P. Morel, astro-ph/9806272, Astrophys. J. 506 (1998) 913.
9. B. T. Cleveland, T. J. Daily, R. Davis, Jr., J. R. Distel, K. Lande, C. K. Lee, and P. S. Wildenhain, Astrophys. J. 496, (1998) 505.
10. Y. Fukuda *et al.,* Phys. Rev. Lett. 77 (1996) 1683.
11. SAGE Coll., J. N. Abdurashitov *et al.,* astro-ph/9907113, Phys. Rev. C 60 (1999) 055801.
12. SAGE Coll., J. N. Abdurashitov *et al.,* arXiv:astro-ph/0204245 v1, Zh. Eksp. Teor. Fiz. 122 (2002) 1 (in Russian).
13. S. Fukuda *et al.,* hep-ex/0103032, Phys. Rev. Lett. 86 (2001) 5651; hep-ex/0103033, Phys. Rev. Lett. 86 (2001) 5656.
14. Q. R. Ahmad *et al.,*, nucl-ph/0106015, Phys. Rev. Lett. 87 (2001) 071301.
15. V. A. Kuzmin, Zh. Eksp. Teor. Fiz. 49 (1965) 1532 (Sov. Phys. JETP 22 (1966) 1051.)
16. B. T. Cleveland, Nucl. Instrum. Methods Phys. Res. 214 (1983) 451.
17. GNO Coll., M. Altmann *et al.,* hep-ex/0006034, Phys. Lett. B490 (2000) 16.
18. SAGE Coll., J. N. Abdurashitov *et al.,* hep-ph/9803418, Phys. Rev. C. 59 (1999) 2246.
19. J. Pulido and E. Kh. Akhmedov, hep-ph/9907399, Astropart. Phys. 13 (2000) 227.
20. P. A. Sturrock and J. D. Scargle, astro-ph/0011228, Astrophys. J. 550 (2001) L101.
21. B. T. Cleveland, Nucl. Instrum. Methods Phys. Res. A 416 (1998) 405.
22. J. N. Bahcall, hep-ph/9710491, Phys. Rev. C 56, (1997) 3391.
23. J. N. Bahcall, M. C. Gonzalez-Garcia, and C. Peña-Garay, hep-ph/0106258, JHEP 0108 (2001) 014.
24. J. N. Bahcall, hep-ph/0108148, Phys. Rev. C 65 (2002) 025801.
25. P. I. Krastev and A. Yu. Smirnov, hep-ph/0108177, Phys. Rev. D 65 (2002) 073022.
26. M.C. Gonzalez-Garcia, M. Maltoni, and C. Peña-Garay, hep-ph/0108073.