XJ0200041

Письма в ЭЧАЯ. 2001. №5[108] Particles and Nuclei, Letters. 2001. No.5[108]

УДК 539.165.8

SOLAR NEUTRINO RESULTS FROM SAGE

V.N.Gavrin
For the SAGE collaboration[1]

The results of ten years of solar neutrino observation by the Russian–American gallium solar neutrino experiment (SAGE) are reported. The overall result of 70 runs during the measurement period from January 1990 to October 1999 is $75.4^{+7.0}_{-6.8}$ (stat.) $^{+3.5}_{-3.0}$ (syst.) SNU. This represents only slightly more than half of the predicted standard solar model rate of 129 SNU. The individual results on each run, and the results of combined analysis of all runs during each year, as well as the results of combined analysis of all runs during monthly and bimonthly periods are presented.

Приводятся результаты десятилетнего детектирования солнечных нейтрино в российско-американском галлиевом эксперименте SAGE. Общий результат по 70 сеансам наблюдения за период с января 1990 года по октябрь 1999 года составляет $75{,}4^{+7{,}0}_{-6{,}8}$ (стат.) $^{+3{,}5}_{-3{,}0}$ (сист.) SNU. Это немного больше половины величины скорости, предсказанной стандартной солнечной моделью. Представлены результаты по каждому сеансу наблюдения, результаты анализа по всем сеансам в течение каждого года, а также результатов комбинированных анализов всех сеансов в течение месячных и двухмесячных периодов наблюдения.

INTRODUCTION

The last several years have been an outstanding time for solar neutrino research. Two high-rate real-time experiments — Super-Kamiokande [1] and SNO [2] — began to present their data.

In spite of this great progress, the region of the solar neutrino spectrum [3] below ~ 2 MeV that contains the *pp* and CNO continua, as well as the ^{7}Be and *pep* lines, remains inaccessible to these new generation detectors. Presently, radiochemical gallium experiments are the only technique able to measure and monitor the low-energy part of the solar neutrino spectrum, since they are mainly sensitive to its principal component — the flux of *pp* neutrinos. It is very important that both SAGE [4,5] and GALLEX's successor GNO [6,7] continue their measurements to increase the accuracy of their results.

The Gallium Germanium Neutrino Telescope (GGNT) used in SAGE is situated in an underground laboratory at the Baksan neutrino observatory in the Northern Caucasus mountains in southern Russia. The SAGE laboratory, with an overhead shielding of 4700 meters of water equivalent, is the second deepest laboratory in the world. This great depth makes the background from cosmic rays in SAGE measurements practically negligible.

---

[1] The full author list of the collaboration is given at the end of the paper.

SAGE has been measuring the capture rate of solar neutrinos with ~ 50 tons of metallic gallium in the liquid state via the reaction $^{71}\mathrm{Ga}(\nu_e, e^-)^{71}\mathrm{Ge}$ [8] since 1990. The metallic gallium target has the advantage that its sensitivity to background from internal and external radioactivity is much less than in any other form. The $^{71}\mathrm{Ge}$ atoms are chemically extracted from the target at the end of each exposure period with typical duration of 1–1.5 months and their decay is observed in low background proportional counters typically for 5–6 months of counting. The experimental layout and all the experimental procedures, including extraction of germanium from gallium, counting of $^{71}\mathrm{Ge}$, and data analysis, are described in detail in the recent article by the SAGE collaboration in Physical Review C «Measurement of the Solar Neutrino Capture Rate with Gallium Metal» [5]. After publication of this article, which reported measurements from January 1990 through December 1997, it was found that a modification to the data acquisition program, necessitated by replacement of some obsolete electronics in the counting system, distorted the results of individual runs from June 1996 through December 1997, and slightly influenced the overall result. In present report we recalculate the results during this interval and give the results for the full period of SAGE measurements. We report also the results of the combined analysis of all runs in yearly, monthly and bimonthly periods with corrected data. A single run result has little significance because of its large uncertainty; nonetheless, we give here a corrected table of results for individual runs so others may use them for their own analysis. We refer the reader to [5] for a full description of experimental techniques and methods of analysis.

1. SOLAR DATA

The SAGE data span a ten-year period during which many improvements to the experiment were made. As a result, the data naturally are divided into three periods: SAGE I, SAGE II, and SAGE III, differentiated by experimental conditions. The time period, the number of runs, and the combined results for each SAGE exposure period are presented in Table 1.

Table 1. **Results of combined analysis of various segments of SAGE data. The uncertainty in the probability is 4 %**

Data segment	Exposure period	Number of runs	Best fit, SNU	68 % conf. level, SNU	Nw^2	Prob., %
SAGE I	Jan. 1990–May 1992	16	81	63–101	0.097	24
SAGE II	Sep. 1992–Dec. 1994	21	79	66–92	0.105	32
SAGE III	Mar. 1994–Oct. 1999	33	72	63–81	0.042	89
SAGE	Jan. 1990–Oct. 1999	70	75	69–82	0.051	75

The capture rate for each extraction of all runs of SAGE is plotted in Fig. 1 and is given in Table 2. These results are derived from the K peak plus L peak wherever possible, otherwise from the K peak alone.

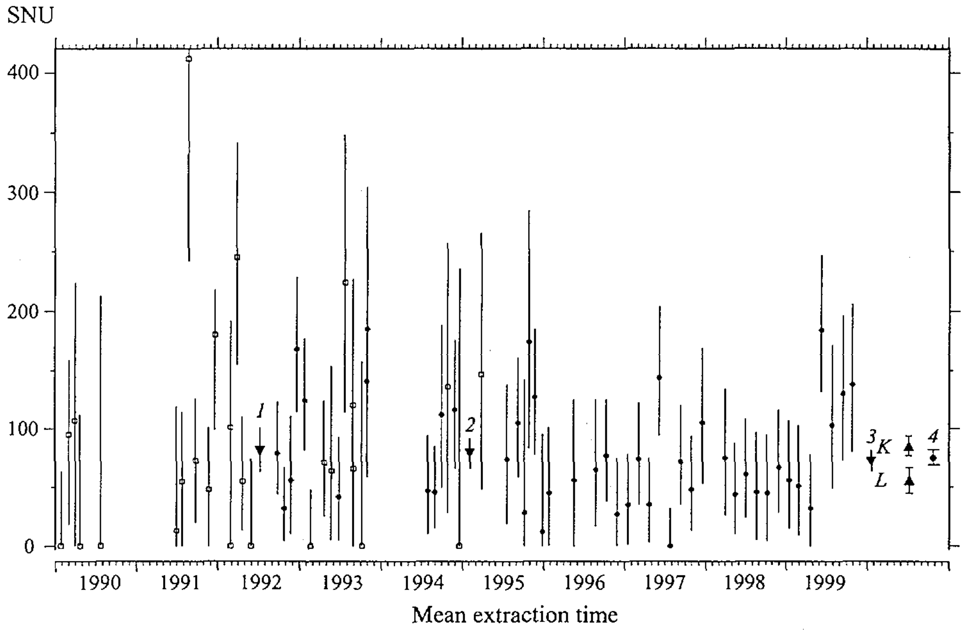

Fig. 1. Capture rate for each extraction as a function of time. All uncertainties are statistical. The symbols *1*, *2*, *3* and *4* indicate the combined result for SAGE I, II, III and the overall SAGE result, respectively. The symbols K and L indicate the combined result for the K and L peaks, respectively

Table 2: **Results of analysis of K-peak events and of combined analysis of K-peak and L-peak events for all runs that could be analyzed in both peaks**

Exposure date	Ga mass, tons	Peak	Number of counts		Best fit, SNU	68 % conf. level, SNU	Nw^2	Good fit probability, %
			Total	^{71}Ge				
Jan. 90	28.7	K	8	0.0	0.0	0–64	0.367	4
Feb. 90	28.6	K	2	2.0	95.2	18–159	0.164	26
Mar. 90	28.5	K	9	2.8	107.1	0–224	0.053	66
Apr. 90	28.4	K	9	0.0	0.0	0–112	0.104	40
July 90	21.0	K	15	0.0	0.0	0–213	0.142	28
June 91	27.4	K	10	0.4	12.7	0–119	0.211	14
July 91	27.4	K	1	1.0	55.2	0–115	0.159	26
Aug. 91	49.3	K	16	9.8	412.1	243–577	0.036	83
Sep. 91	56.6	K	8	3.5	73.1	20–126	0.041	79
Nov. 91	56.3	K	14	2.4	48.4	0–102	0.095	30
Dec. 91	56.2	K	10	10.0	179.6	99–217	0.063	77
Feb. 92–1	43.0	K	14	0.0	0.0	0–43	0.057	74
Feb. 92–2	13.0	K	1	1.0	101.0	0–192	0.085	88
Mar. 92	56.0	K	21	10.1	245.2	155–342	0.043	72
Apr. 92	55.8	K	15	2.3	55.5	13–111	0.143	18
May 92	55.7	K	4	0.0	0.0	0–74	0.134	30

Table 2: (continuation)

Exposure date	Ga mass, tons	Peak	Number of counts		Best fit, SNU	68 % conf. level, SNU	Nw^2	Good fit probability, %
			Total	^{71}Ge				
Sep. 92	55.6	$K+L$	13	6.0	79.1	44–123	0.097	25
Oct. 92	55.5	$K+L$	21	3.3	32.1	4–67	0.105	26
Nov. 92	55.4	$K+L$	28	4.3	55.9	10–111	0.047	70
Dec. 92	55.3	$K+L$	28	16.8	168.4	115–229	0.057	53
Jan. 93	55.1	$K+L$	17	10.0	124.2	81–177	0.089	32
Feb. 93	55.0	K	3	0.0	0.0	0–48	0.116	41
Apr. 93	48.2	K	7	2.9	71.0	25–124	0.041	82
May 93	48.2	K	8	1.4	63.8	5–153	0.073	51
June 93	54.7	$K+L$	18	3.3	41.5	4–92	0.557	0
July 93	40.4	K	28	7.6	224.5	114–348	0.040	78
Aug. 93–1	40.4	K	4	2.5	66.5	20–116	0.048	79
Aug. 93–2	14.1	K	1	1.0	120.0	0 227	0.093	7
Oct. 93–1	14.1	K	0	0.0	0.0	0–158	NA	NA
Oct. 93–2	14.1	$K+L$	4	3.0	141.5	60–245	0.049	83
Oct. 93–3	14.0	$K+L$	7	4.0	184.9	80–303	0.052	77
July 94	50.6	$K+L$	22	3.4	47.0	9–94	0.027	5
Aug. 94	50.6	$K+L$	27	3.9	45.7	15–85	0.075	52
Sep. 94–1	37.2	$K+L$	30	6.5	112.3	50–188	0.082	39
Oct. 94	50.5	K	44	4.8	135.9	27–257	0.075	45
Nov. 94	50.4	$K+L$	23	8.0	116.2	66–176	0.015	100
Dec. 94	13.1	K	9	0.0	0.0	0–236	0.184	19
Mar. 95	24.0	K	23	3.7	146.9	47–266	0.042	77
July 95	50.1	$K+L$	33	5.0	73.6	19–138	0.063	55
Aug. 95	50.0	$K+L$	24	7.4	105.5	60–161	0.061	56
Sep. 95	50.0	$K+L$	33	1.2	28.0	0–142	0.058	73
Oct. 95	49.8	$K+L$	25	6.9	174.3	84–284	0.022	98
Nov. 95	49.8	$K+L$	32	10.2	126.9	78–185	0.032	88
Dec. 95–2	41.5	$K+L$	40	0.5	12.5	0–95	0.068	62
Jan. 96	49.6	$K+L$	35	3.5	45.0	0–101	0.047	76
May 96	49.5	$K+L$	16	3.7	55.6	0–124	0.031	95
Aug. 96	49.3	$K+L$	21	4.2	65.2	17–125	0.096	31
Oct. 96	49.2	$K+L$	21	5.4	76.7	37–125	0.046	74
Nov. 96	49.1	$K+L$	28	1.9	27.0	0–75	0.103	37
Jan. 97	49.0	$K+L$	24	2.6	34.8	1–78	0.190	13
Mar. 97	48.9	$K+L$	23	6.2	73.6	35–122	0.097	25
Apr. 97	48.8	$K+L$	22	2.7	35.1	3–75	0.037	86
June 97	48.8	$K+L$	27	10.4	143.9	94–204	0.078	34
July 97	48.7	$K+L$	22	0.0	0.0	0–32	0.333	7
Sep. 97	48.6	$K+L$	15	4.6	72.0	35–120	0.033	89
Oct. 97	48.5	$K+L$	26	3.4	47.7	12–94	0.083	49
Dec. 97	48.3	$K+L$	24	6.2	105.0	53–169	0.031	89
Apr. 98	48.1	$K+L$	39	5.4	74.6	26–134	0.052	72
May 98	51.2	$K+L$	23	3.4	44.3	10–88	0.051	68
July 98	51.1	$K+L$	22	4.8	61.2	24–108	0.065	52
Aug. 98	50.9	$K+L$	33	3.6	46.1	5–97	0.039	84

Table 2: (continuation)

Exposure date	Ga mass, tons	Peak	Number of counts		Best fit, SNU	68 % conf. level, SNU	Nw^2	Good fit probability, %
			Total	^{71}Ge				
Oct. 98	50.8	$K+L$	40	3.8	45.3	4–95	0.028	95
Nov. 98	50.7	$K+L$	32	5.9	67.3	28–116	0.101	30
Jan. 99	50.5	$K+L$	21	4.5	56.2	15–107	0.036	84
Feb. 99	50.4	$K+L$	21	3.4	51.3	9–104	0.113	22
Apr. 99	50.3	$K+L$	11	1.5	32.4	0–78	0.076	54
June 99	50.2	$K+L$	15	13.8	184.4	132–247	0.058	73
July 99	50.1	$K+L$	17	5.5	102.9	49–172	0.118	20
Sep. 99	49.9	$K+L$	22	10.0	130.0	73–196	0.127	16
Oct. 99	49.8	$K+L$	16	10.0	138.3	80–206	0.066	48
Combined (114 data sets)			1325	288.6	75.4	69–82	0.051	75

2. SYSTEMATIC EFFECTS

During the last two years, a detailed study of all known systematic effects that may affect the solar neutrino production rate has significantly decreased the systematic error. In particular, significant success was achieved in the investigation of the contribution of internal radon, that was a substantial part of the total uncertainty (for details see Ref. 5).

The systematic effects fall into three main categories and are summarized in Table 3.

Table 3. **A summary of systematic effects and their uncertainties in SNU**

Extraction efficiency	
Ge carrier mass	±1.4
Extracted Ge mass	±1.7
Residual carrier Ge	±0.5
Ga mass	±1.4
Counting efficiency	
Counter effect	±1.9
Gain shifts	−2.1
Resolution	$^{+0.5}_{-0.3}$
Rise time limits	±0.7
Lead and exposure times	±0.7
Backgrounds	
Neutrons, U, Th, muons	−1.0
Other Ge isotopes	−0.6
External radon	0.0
Internal radon	−0.2
Total	$^{+3.5}_{-3.0}$

3. RESULTS

The global best fit capture rate for the 70 SAGE runs (114 data sets: 70 from the K peak and 44 from the L peak) is $75.4^{+7.0}_{-6.8}$ SNU, where the uncertainty is statistical only. In the windows that define the L and K peaks, there are 1325 counts with 288.6 assigned to ^{71}Ge (the total counting lifetime is 22.31 y). The total systematic uncertainty is determined by adding in quadrature all the contributions given in Table 3 and is $^{+3.5}_{-3.0}$ SNU. Our overall result is thus $75.4^{+7.0}_{-6.8}$ (stat.) $^{+3.5}_{-3.0}$ (syst.). If we combine the statistical and systematic uncertainties in quadrature, the result is $75.4^{+7.8}_{-7.4}$ SNU.

The validity of this result was confirmed by a rigorous check of the integrity of the experiment using a 19.1 PBq (517 kCi) ^{51}Cr neutrino source. The final result of the source experiment, expressed as the ratio of the measured ^{71}Ge production rate to that expected due to the source strength, is 0.95 ± 0.12 [9], which provides considerable evidence for the reliability of the solar neutrino measurement.

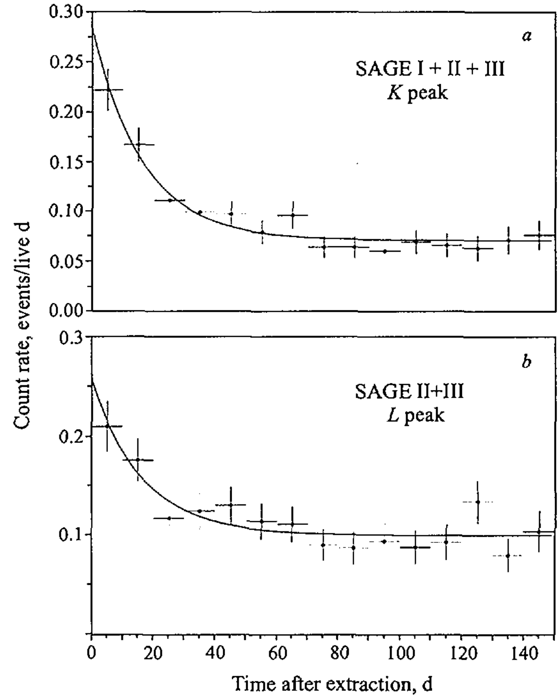

Fig. 2. Count rate for all runs in L and K peaks. The solid line is a fit to the data points with the 11.4-day half-life of ^{71}Ge plus a constant background. The vertical error bar on each point is proportional to the square root of the number of counts. The horizontal error bar is ±5 days

4. TESTS OF ANALYSIS HYPOTHESES

A major analysis hypothesis is that the time sequence of observed events for each run consists of the superposition of events from the decay of a fixed number of ^{71}Ge atoms plus background events which occur at a constant rate. The quantity Nw^2 and the goodness of fit probability inferred from it provide a quantitative measure of how well the data fit this hypothesis [10]. These numbers are evaluated for each single run as well as for each data set and are given in Tables 1, 2, and 3. There are some runs with rather low probability but no more than these expected due to normal statistical variation.

This method can also be used to determine the goodness of fit of the time sequence for any combination of runs. These numbers are given in Tables 1 and 2. For the combined time sequence of all L plus K events from all runs, this test yields $Nw^2 = 0.051$, with a goodness of fit probability of $(75 \pm 4)\,\%$.

A visual indication of the quality of this fit is provided in Fig. 2, which shows the count rate for all events in the L and K peaks vs. time after extraction. As is apparent, the observed rate fits the hypothesis quite well.

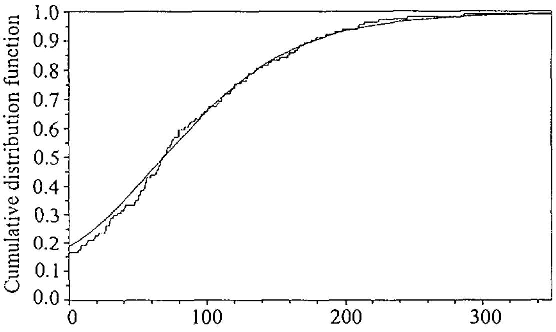

Fig. 3. Measured capture rate for all SAGE data sets (jagged curve) and the expected distribution derived by 1000 Monte-Carlo simulations of each set (smooth curve). The capture rate in the simulations was assumed to be 75.4 SNU

Another analysis hypothesis is that the rate of ^{71}Ge production is constant in time. It is apparent from Fig. 1 that there is no substantial long-term deviation from constancy. One way to consider this question quantitatively is to use the cumulative distribution function of the production rate $C(p)$, defined as the fraction of data sets whose production rate is less than p. Figure 3 shows this distribution for all data sets and the expected distribution from simulation, assuming a constant production rate of 75 SNU. The two curves are parallel to each other closely and can be compared by calculating the Nw^2 test statistic [10]. This gives $Nw^2 = 0.301$, whose probability is 14 %.

5. TEMPORAL COMBINATIONS OF DATA

Although the statistical tests are consistent with a constant production rate, they cannot exclude the possibility of a cyclic time variation whose magnitude is comparable with the statistical uncertainty. We thus give in Table 4 the capture rate results for several of the possible temporal combinations of SAGE data. The variation due to the change in the Earth–Sun distance has been removed from our reported capture rate.

6. SUMMARY AND CONCLUSIONS

Ten years of measurements of the solar neutrino flux give the capture rate result $75.4^{+7.0}_{-6.8}$ SNU, where the uncertainty is statistical. Analysis of all known systematic effect indicates that the total systematic uncertainty is $^{+3.5}_{-3.0}$ SNU, considerably smaller than the statistical uncertainty. The SAGE result of 75.4 SNU corresponds to 58 % [11] or 59 % [3] of SSM predictions. Given the extensive systematic checks and auxiliary measurements that have been performed, especially the ^{51}Cr neutrino source experiment [9], this low value of the solar neutrino flux compared to SSM predictions is a very strong evidence that the solar neutrino spectrum below 2 MeV is significantly depleted, as was previously shown for the ^{8}B flux by the chlorine [12] and Kamiokande experiments [1].

There are now very strong indications that the solar neutrino deficit has a particle physics explanation [13] and is a consequence of neutrino mass. Possible credible explanations for the solar neutrino deficit involve either matter-enhanced Mikheev–Smirnov–Wolfenstein neutrino

Table 4. **Capture rate results for yearly, monthly and bimonthly combinations of SAGE data. Runs are assigned to each time period by their mean exposure time**

Exposure period	Number of data series	Best fit, SNU	68 % range, SNU	Exposure period	Number of data series	Best fit, SNU	68 % conf. level, SNU
1990	5	43	2–78	Jan. + Feb.	17	51	36–67
1991	6	112	82–145	Mar. + Apr.	12	71	51–92
1992	13	76	59–95	May + June	15	81	62–102
1993	15	84	65–105	July + Aug.	22	68	53–84
1994	10	73	51–98	Sep. + Oct.	29	80	66–95
1995	13	101	77–128	Nov. + Dec.	19	99	82–117
1996	10	56	34–79	Feb. + Mar.	13	73	54–93
1997	16	62	8–78	Apr. + May	15	58	42–75
1998	12	56	39–75	June + July	18	69	51–88
1999	14	101	79–124	Aug. + Sep.	27	77	64–91
Jan.	9	56	33–82	Oct. + Nov.	24	81	66–98
Feb.	8	47	27–69	Dec. + Jan.	17	92	75–111
Mar.	5	140	100–186	Feb. + Nov.	19	64	49–79
Apr.	7	44	25–65	Mar. + Oct.	18	102	81–124
May	8	74	51–101	Apr. + Sep.	23	65	51–79
June	7	92	60–126	May + Aug.	19	76	60–93
July	11	57	37–80				
Aug.	11	77	57–99				
Sep.	16	77	60–95				
Oct.	13	86	62–112				
Nov.	11	78	58–99				
Dec.	8	134	104–164				

oscillations, in which the solar ν_e oscillates into other flavor neutrinos or sterile neutrinos [14], or vacuum oscillations [14–16].

To fully unreveal the solar neutrino story, however, will require more experiments, especially those with sensitivity to low-energy neutrinos or to neutrino flavor (like SNO). SAGE continues to perform regular solar neutrino extractions every four weeks with approximately 50 tons of gallium and will continue to reduce its statistical and systematic uncertainties, thus further limiting possible solutions to the solar neutrino problem.

Acknowledgements. We acknowledge the support of the Russian Academy of Sciences, the Russian Ministry of Science and Technology, the Russian Foundation of Basic Research under grants 96-02-18399 and 99-02-16110, the Division of Nuclear Physics of the U.S. Department of Energy, the International Science Foundation under grants M7F000 and M7F300, and the U.S. Civilian Research and Development Foundation under grant RP2-159.

REFERENCES

1. *Suzuki Y. (Super-Kamiokande collab.)* // Proc. of XVIII Intern. Conf. on Neutrino Physics and Astrophysics, Takayama, Japan / Ed. by Y. Suzuki, Y. Totsuka. Elsevier, 1999. P.35.

2. *McDonald A. (SNO collab.)* // Proc. of XIX Intern. Conf. on Neutrino Physics and Astrophysics, Sudbury, Canada, 2000 (in print).

3. *Bahcall J.N., Basu S., Pinsonnealt M.H.* // Phys. Lett. B. 1998. V.433. P.1.

4. *Gavrin V.N. (SAGE collab.)* // Proc. of XVIII Intern. Conf. on Neutrino Physics and Astrophysics, Takayama, Japan / Ed. by Y.Suzuki, Y.Totsuka. Elsevier, 1999. P.20.
   Bowles T.J. (SAGE collab.) // Proc. of IV Intern. Solar Neutrino Conf. / Ed. by W. Hampel. MPI Kernphysik. Heidelberg, Germany, 1997. P.109.
   Nico J.S. (SAGE collab.) // Proc. of Intern. School on Particles and Cosmology, Baksan Valley, Kabardino–Balkaria / Ed. by E.N.Alexeev et al. 1999. P.63.

5. *Abdurashitov J.N. et al. (SAGE collab.)* // Phys. Rev. C. 1999. V.60. P.055801.

6. *Kirsten T.A. (GALLEX and GNO collab.)* // Proc. of XVIII Intern. Conf. on Neutrino Physics and Astrophysics, Takayama, Japan / Ed. by Y.Suzuki, Y.Totsuka. Elsevier, 1999. P.26.

7. *Bellotti E. (GNO collab.)* // Proc. of XIX Intern. Conf. on Neutrino Physics and Astrophysics, Sudbury, Canada, 2000 (to be published).

8. *Kuz'min V.A.* // Zh. Eksp. Teor. Fiz. 1965. V.49. P.1532.

9. *Abdurashitov J.N. et al. (SAGE collab.)* // Phys. Rev. Lett. 1996. V.77. P.4708.
   Abdurashitov J.N. et al. (SAGE collab.) // Phys. Rev. C. 1999. V.59. P.2246.

10. *Cleveland B.T.* // Nucl. Instr. Meth. In Phys. Res. 1983. V.214. P.451.

11. *Bruns A.S., Turck-Chieze S., Morel P.* // Astrophys. J. 1998. V.506. P.913.

12. *Cleveland B.T. et al.* // Astrophys. J. 1998. V.496. P.505.

13. *Berezinsky V., Fiorentini G., Lissia M.* // Phys. Lett. B. 1996. V.365. P.185.

14. *Bahcall J.N., Krastev P.I., Smirnov A.Yu.* // Phys. Rev. D. 1998. V.53. P.096016.

15. *Krastev P.I., Petkov S.T.* // Phys. Rev. D. 1996. V.53. P.1665.

16. *Abdurashitov J.N. et al. (SAGE collab.)* // Phys. Rev. Lett. 1999. V.83. P.4686.

The SAGE collaboration includes: J.N.Abdurashitov[a], T.J.Bowles[b], M.L.Cherry[c], B.T.Cleveland[d], R.Davis Jr.[d], S.R.Elliott[e], V.N.Gavrin[a], S.V.Girin[a], V.V.Gorbachev[a], T.V.Ibragimova[a], A.V.Kalikhov[a], N.G.Khairnasov[a], T.V.Knodel[a], K.Lande[d], I.N.Mirmov[a], J.S.Nico[f], A.A.Shikhin[a], W.A.Teasdale[b], E.P.Veretenkin[a], V.M.Vermul[a], D.L.Wark[b], P.S.Wildenhain[d], J.F.Wilkerson[e], V.E.Yants[a], G.T.Zatsepin[a]

[a] Institute for Nuclear Research, Russian Academy of Sciences, 117312, Moscow, Russia
[b] Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
[c] Louisiana State University, Baton Rouge, Louisiana 70803, USA
[d] University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
[e] University of Washington, Seattle, Washington 98195, USA
[f] National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA