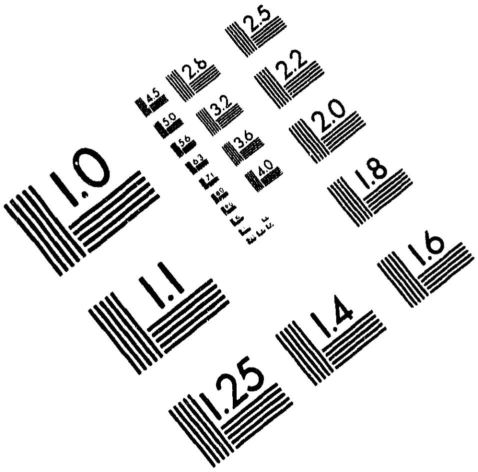

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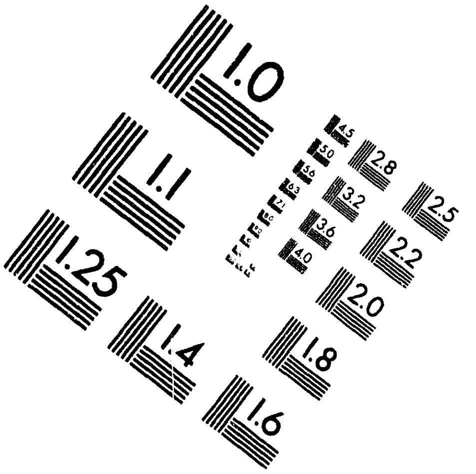

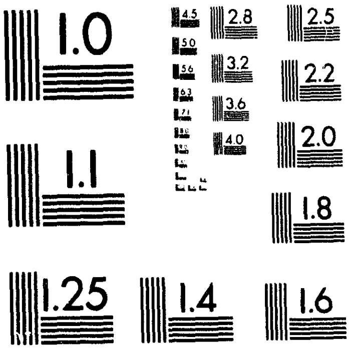

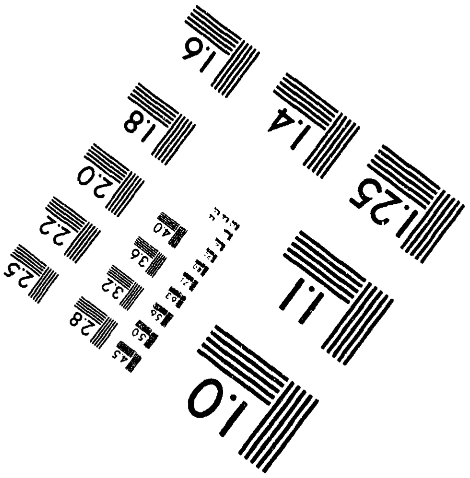

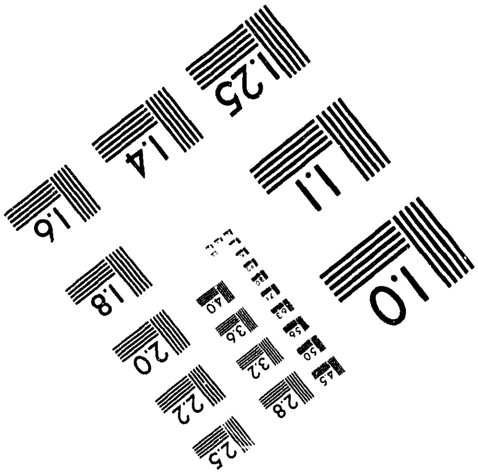

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TITLE:

FIRST RESULTS FROM SAGE II

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SUBMITTED TO:

Proceedings from the 5th Conference on the Intersections of Particle and Nuclear Physics, St. Petersurg, FL, May 31 - June 6, 1994.

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FIRST RESULTS FROM SAGE II

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ABSTRACT

The Russian-American Gallium solar neutrino Experiment (SAGE) began the second phase of operation (SAGE II) in September of 1992. Monthly measurements of the integral flux of solar neutrinos have been made with 55 tonnes of gallium. The K-peak results of the first five runs of SAGE II give a capture rate of 76^{+21}_{-18} (stat) $^{+5}_{-7}$ (sys) SNU. Combined with the SAGE I result, the capture rate is 74^{+13}_{-12} (stat) $^{+5}_{-7}$ (sys) SNU. This represents only 56%-60% of the capture rate predicted by different Standard Solar Models.

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 of Davis et al.[1-3] has persisted for more than twenty years. The Kamiokande water Cerenkov experiment[4] observes only 50%-64% of the ^{8}B flux predicted by the SSMs. SAGE[5] and GALLEX[6] have measured rates of about 60% of the SSM predictions. Thus, all four operating solar neutrino experiments have reported significant deficits of the flux of solar neutrinos.

The ^{37}Cl and Kamiokande experiments are primarily sensitive to the high-energy ^{8}B solar neutrinos, whose production rate depends critically ($\propto T_c{}^{18}$) on the core temperature of the Sun. Numerous non-standard solar models[7,8] that reduce the core temperature have been suggested, but none have been able to reproduce the observed ^{8}B flux without running into difficulties accounting for other observed features of the Sun. New particle physics[7,8], such as neutrino matter oscillations, have

Table 1: Counting and background parameters for SAGE I and II. The data for SAGE I are the range of values from early and latter SAGE I measurements.

	SAGE I	SAGE II
K Peak Bkgd Rate (cts/d)	0.116 ± 0.019 - 0.064 ± 0.010	0.016 ± 0.005
L Peak Bkgd Rate (cts/d)	—	0.069 ± 0.017

been invoked to provide an explanation of the "solar neutrino problem". Analyses[9,10] of the consistency of the chlorine and Kamiokande II results conclude that the results are inconsistent with any astrophysical explanations and are better described by Mikheyev-Smirnov-Wolfenstein (MSW) neutrino oscillations. However, given the uncertainties in the SSMs, it does not seem possible to rule out an astrophysical origin of the solar neutrino problem[11].

The ^{71}Ga (ν_e, e^-)^{71}Ge reaction[12] provides the only feasible means at present to measure low-energy solar neutrinos. The SSM calculations show that the dominant contribution to the capture rate in ^{71}Ga arises from the p-p neutrinos (71 ± 4 SNU where 1 Solar Neutrino Unit = 10^{-36} captures/target atom/s), while the total predicted rate in the SSMs is 122.5 – 131.5 SNU.

The Baksan Gallium Experiment

The detector is situated in a specially built underground laboratory at the Baksan Neutrino Observatory in the Northern Caucasus Mountains. The experimental layout and the chemical and counting procedures have been described previously[5] and are not discussed here. The SAGE II counting system underwent several upgrades in the summer of 1992. These upgrades included replacing several components of the detector with ultrapure materials, use of a 1 GHz transient digitizer, and implementation of extensive noise suppression techniques. The signal to background in SAGE II improved substantially relative to SAGE I, as shown in Table 1. Eighteen additional solar neutrino runs have been made since September 1992, most of which include 1 GHz transient digitization of the pulse waveform. In the SAGE II data, we are able to measure both the ^{71}Ge K and L peaks.

The proportional counter containing the extraction sample is typically calibrated at one month intervals using an external ^{55}Fe source. The ^{71}Ge K-peak acceptance window is then determined by extrapolation from the ^{55}Fe peak. The extrapolation procedure was verified by filling a PC with ^{71}GeH$_4$ together with the standard counter gas. In SAGE II, we have also employed a Cd-Se fluorescence source which provides peaks at 11.2 keV (Se K-peak fluorescence), 6.9 keV (Xe escape peak), 6.4 keV (fluorescence from the Fe cathode), and 1.4 keV (Se L-peak fluorescence). We now also routinely measure the resolution integrated over the full counter volume using a Cd source in order to check the uniformity of the counter response.

Solar Neutrino Flux Measurements

A standard analysis procedure for event selection was developed with two

Table 2: Statistical analysis of runs

Exposure Date	Ga Mass (tonnes)	^{71}Ge Events	K Peak Events	Best Fit SNU	68% CL (SNU)	Nw^2	Probability (%)
Jan 90	28.672	0.0	8	0	0 - 60	0.366	5
Feb 90	28.592	2.0	2	86	17-145	0.164	23
Mar 90	28.508	2.8	9	100	0-210	0.053	64
Apr 90	28.402	0.0	9	0	0-101	0.104	41
Jul 90	21.011	0.0	15	0	0-199	0.142	24
Jun 91	27.429	0.4	10	11	0-107	0.211	12
Jul 91	27.373	1.0	1	49	0-103	0.158	26
Aug 91	49.335	9.8	16	350	207-492	0.036	82
Sept 91	56.551	3.5	8	64	18-113	0.041	79
Nov 91	56.322	2.4	14	44	0-93	0.095	35
Dec 91	56.238	10.0	10	159	88-193	0.063	77
Feb 92a	43.030	0.0	14	0	0-39	0.057	76
Feb 92b	13.040	1.0	1	90	0-173	0.085	85
Mar 92	55.960	10.1	21	222	141-311	0.043	71
Apr 92	55.848	2.3	15	49	12-98	0.143	17
May 92	55.716	0.0	4	0	0-67	0.134	31
Sept 92	55.600	1.9	3	43	12-83	0.134	27
Oct 92	55.482	2.2	4	39	12-71	0.060	62
Nov 92	55.377	5.0	5	102	56-150	0.077	69
Dec 92	55.263	4.9	10	83	40-132	0.061	51
Jan 93	55.136	7.4	9	125	65-172	0.126	30

primary goals in mind: minimizing the efficiency uncertainty over the course of counting and keeping the background rate constant. This standard analysis is a slightly modified version of that used to analyze our first reported results[13]. Specifically, the data was corrected for gain variations on an event-by-event basis, the energy window we use was widened, and a 1 hour cut of the K-peak data following an opening of the passive shield was instituted.

Gain variations in the PCs were observed in some of the runs with an average variation of 3.3% (the largest being 10%). As these shifts were usually monotonic, we accounted for them by linearly interpolating in time between ^{55}Fe calibrations bracketing the event. The frequency of calibrations was increased in later runs to minimize any uncertainty due to gain variations. In the SAGE II data presented here, the gain shifts averaged 2.2% (with a maximum shift of 5.8%).

After correcting for any gain variations, several cuts are made on the data. First, a cut is made to eliminate periods of noise bursts in the data. This results in the exclusion of a small fraction of a percent of the counting time. Second, cuts are made on energy and inverse rise time that accept 2 FWHM (98.15% acceptance) in energy centered symmetrically around the ^{55}Fe peak, and 95% of the inverse rise time distribution, with 1% being cut on fast rise time pulses (i.e., noise) and 4% cut on slow rise time pulses (i.e., background). Third, any event that has associated NaI activity is eliminated. Fourth, a cut was made to eliminate possible backgrounds

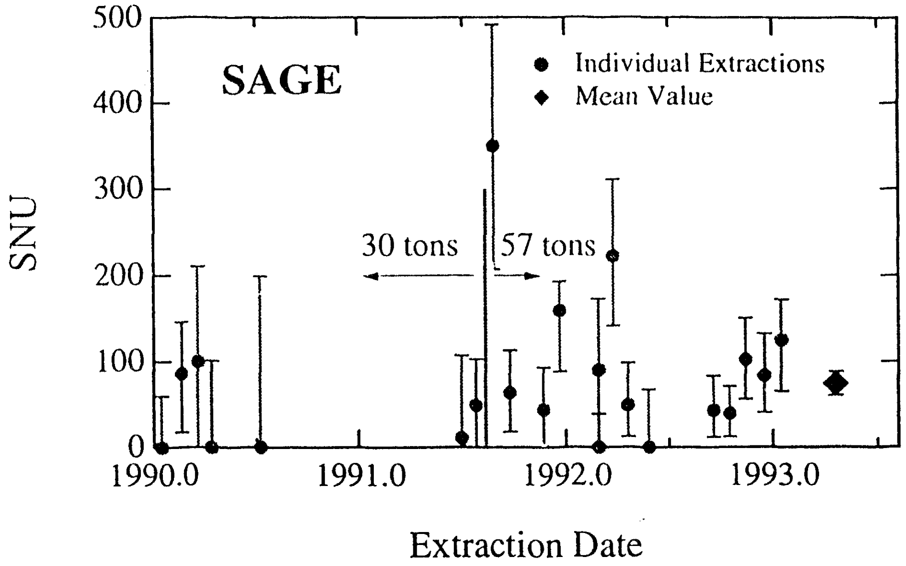

Figure 1: Best fit values and 1-σ uncertainties for each of the runs, together with the best fit value and 1-σ uncertainty for the combined 1990-92 data.

from Rn daughters on the external surfaces of the PCs. Removing all data within 1.0 hour of a shield opening eliminates any observable excess of such events in the K-peak acceptance window.

A maximum likelihood analysis[14] is carried out on the remaining events by fitting the time distribution to a ^{71}Ge exponential decay (11.43 day half life) plus a constant rate background. The results of the maximum likelihood analysis for each of the runs are given in Table 2. We note that the number of ^{71}Ge events obtained by summing the individual runs (66.7 events) differs slightly from that (62.0 events) obtained by an analysis of the combined data. This is due to the constraint in the combined fit that all runs yield a common value of the capture rate. The good agreement is an indication of the consistency of the individual runs with the final result.

Figure 1 shows the individual run results along with the combined result. The 20 solar neutrinos runs were compared with the predicted statistical distribution of signals from 1000 Monte Carlo simulations of each extraction using the combined fit parameters and the constants of each data set. The two distributions are quite similar and the data are distributed according to Poisson statistics, as expected. The half-life for the decay measured from the combined data sets is $9.7^{+4.8}_{-2.9}$d, in good agreement with the known ^{71}Ge half-life of 11.4 days. In addition, Figure 2 shows the SAGE II energy spectrum as a function of the ^{71}Ge meanlife.

It is important to test the assumption that the extraction efficiency for ^{71}Ge atoms produced by solar neutrinos is the same as for the carrier. To check this, several tests have been carried out. First, Ge carrier doped with a known number of ^{71}Ge atoms was added to a reactor holding 7 tonnes of Ga. Three successive

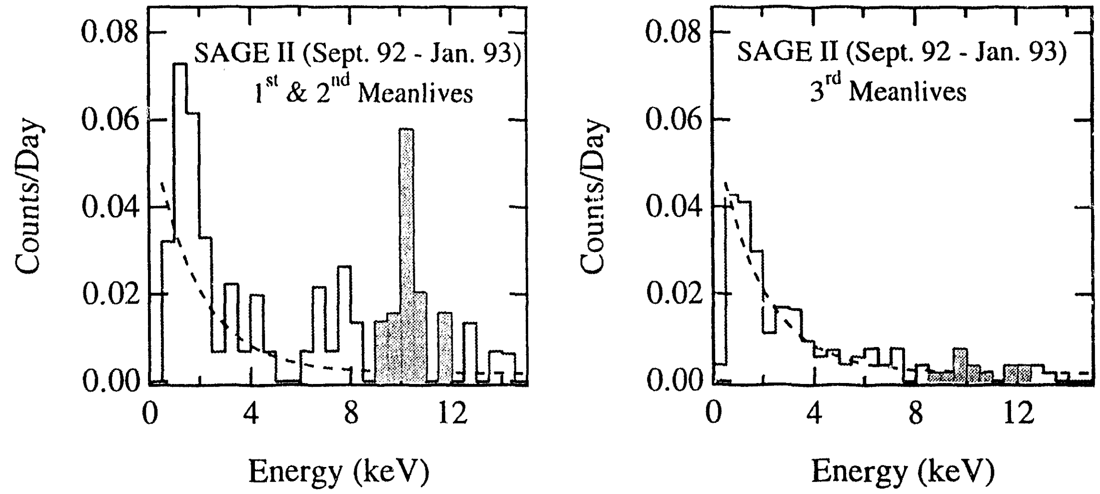

Figure 2: The data for the SAGE II runs are shown as a function of ^{71}Ge mean lifetime. (See Ref. 5 for the SAGE I data.) The count rate versus energy for a period covering the first two mean lifetimes of ^{71}Ge is shown on the left, while the count rate from all times greater than or equal to 3 mean lifetimes of ^{71}Ge is shown on the right. The hatched area indicates the expected position of the K peak. The dashed line is an exponential fit of energy spectrum for all times greater than or equal to 3 mean lifetimes of ^{71}Ge .

extractions were carried out, and the number of ^{71}Ge atoms in each extraction was determined by counting. The chemical extraction efficiency was $101 \pm 5\%$ and the ^{71}Ge extraction efficiency was $99^{+6}_{-8}\%$. A second set of measurements was made by observing the beta decay of radioactive Ga isotopes in liquid Ga. The extraction efficiencies were $98 \pm 10\%$ and $92 \pm 10\%$ for ^{70}Ge and ^{72}Ge produced by the beta decay of ^{70}Ga and ^{72}Ga , respectively.

Finally, an experiment using a neutrino source is planned in order to test the overall extraction efficiency in situ. A suitable neutrino calibration source can be made using ^{51}Cr , which decays by electron capture, emitting monoenergetic neutrinos of 751 keV and 426 keV. Preparations are underway to carry out a full-scale experiment with a 1-MCi ^{51}Cr source in 1994.

Results and Conclusions

The best fit value for the capture rate and the uncertainties for the combined 1990-93 solar neutrino data are

$$^{71}\text{Ga Rate} = 74^{+13}_{-12}\ \text{(stat)}\ ^{+5}_{-7}\ \text{(syst) SNU.}$$

This assumes that the extraction efficiency for ^{71}Ge atoms produced by solar neutrinos is the same as that measured using natural Ge carrier. The result corresponds to 62.0 counts assigned to ^{71}Ge decay, compared to the Bahcall-Pinsonneault and Turck-Chieze and Lopes SSM prediction of 106.9 and 99.6 counts, respectively. The contributions to the systematic error are summarized in Table 3.

Table 3: Systematic uncertainties (1-σ) for the combined 1990-93 data sets.

Systematic	Contribution (SNU)
Chemical Extraction Efficiency	± 2.5
Counting Efficiency	$+2.9/-2.1$
K-Peak Acceptance	$+3.5/-0.7$
Backgrounds	-3.5
Radon	-5.9
Total	$+5.2/-6.9$

The best fit values and uncertainties for the solar neutrino runs by year (shown in Figure 3) are

$$(1990)\ \ 40^{+31}_{-38}\ \text{(stat)}\ ^{+5}_{-7}\ \text{(syst) SNU}$$

$$(1991)\ \ 100^{+30}_{-26}\ \text{(stat)}\ ^{+5}_{-7}\ \text{(syst) SNU}$$

$$(1992)\ \ 62^{+29}_{-27}\ \text{(stat)}\ ^{+5}_{-7}\ \text{(syst) SNU}$$

$$(\text{SAGE II})\ \ 76^{+21}_{-18}\ \text{(stat)}\ ^{+5}_{-7}\ \text{(syst) SNU.}$$

The change in the 1990 value from that previously reported[13] is due to a combination of revised counter efficiencies, the incorporation of the Earth-Sun distance correction, and the wider energy window used in the new standard analysis[5].

The measurements made by SAGE from January 1990 through January 1993 have observed fewer ^{71}Ge atoms than predicted by the SSMs. From the 1990-93 data, SAGE observes only 56% and 60% of the predicted Bahcall-Pinsonneault and Turck-Chieze rates, respectively. Taken alone, the SAGE result appears to favor a non-astrophysical solution of the solar neutrino problem, but cannot rule out an astrophysical solution. Taken together with the other operating solar neutrino experiments, it seems that astrophysical solutions are improbable, as discussed by a number of authors[9,10,15,16].

The solar neutrino experiments are consistent with two possible MSW solutions, as shown in Figure 4. The "non-adiabatic" solution ($\Delta m^2 \approx 6 \times 10^{-6} eV^2$ and $sin^2 2\theta \approx 7 \times 10^{-3}$) is the favored solution and represents a strong suppression of ^{7}Be neutrinos, a significant suppression of ^{8}B neutrinos, and essentially no suppression for the p-p neutrinos. Alternately, for the large-mixing angle solution ($\Delta m^2 \approx 10^{-5} eV^2$ and $sin^2 2\theta \approx 0.8$), it may be that all solar neutrinos are suppressed approximately the same, roughly independent of energy. With the improved precision from the combined 1990-93 SAGE data, SAGE is seeing approximately the rate predicted for the p-p neutrinos alone. With the ability to count both the K and L peaks with 55 tonnes of gallium, SAGE expects to reach a precision within the next two years that should provide a strong test for astrophysical solutions to the "solar neutrino problem".

The SAGE collaboration wishes to thank A.E. Chudakov, G.T. Garvey, M.A. Markov, V.A. Matveev, J.M. Moss, S.P. Rosen, V.A. Rubakov, and A.N. Tavkhe-

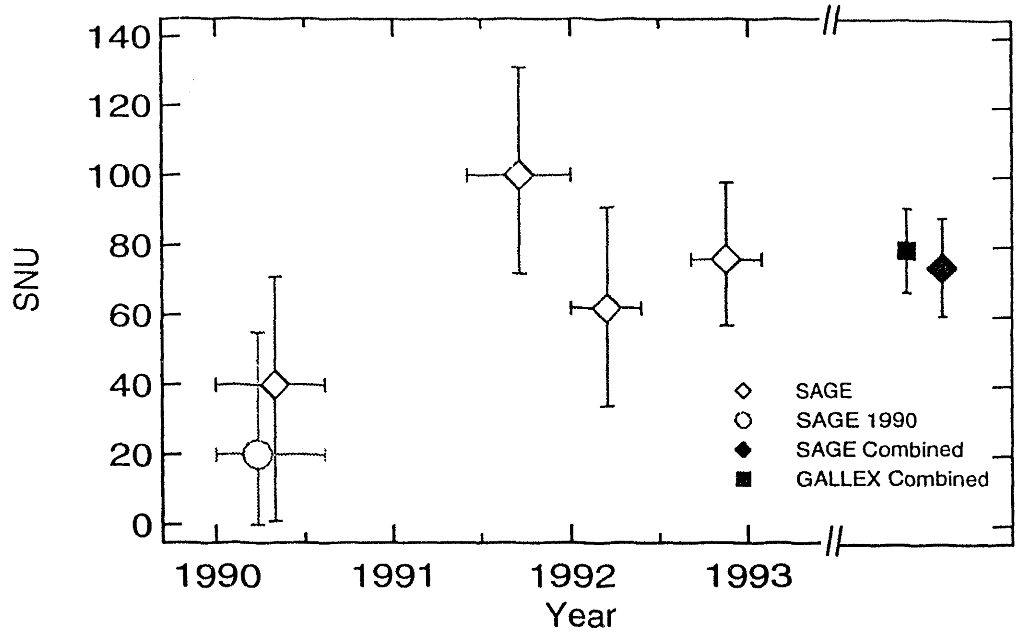

Figure 3: Results from SAGE for measurements from 1990 - 1993. Also shown are the current SAGE and GALLEX[6] results from all runs reported. The errors shown are derived by adding the quoted statistical and systematic uncertainties in quadrature.

lidze for their continued interest in our work and for stimulating discussions. We are also grateful to J.N. Bahcall, R.G.H. Robertson, A. Yu. Smirnov, and many members of the GALLEX collaboration for useful discussions and to N. Hata and P. Langacker for the MSW plot. We acknowledge the support of the Russian Academy of Sciences, the Institute for Nuclear Research of the Russian Academy of Sciences, the Russian Ministry of Science and Technology, the Russian Foundation of Fundamental Research, the Division of Nuclear Physics of the Department of Energy, the National Science Foundation, Los Alamos National Laboratory, and the University of Pennsylvania.

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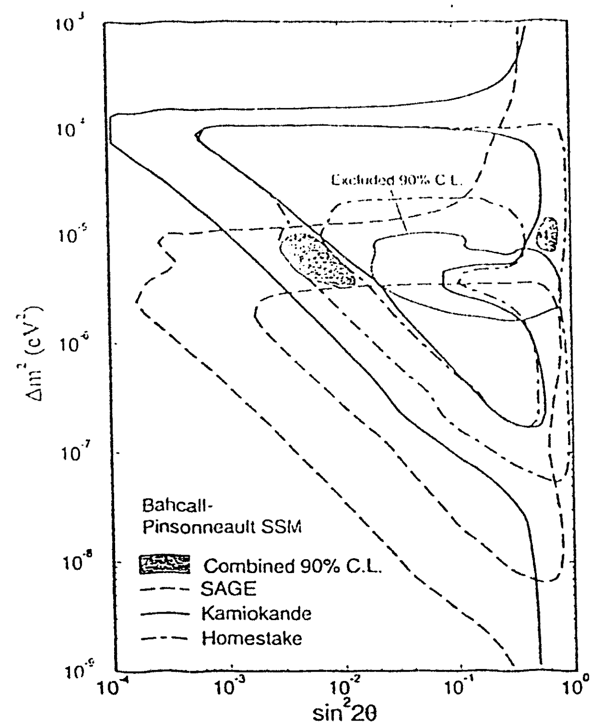

Figure 4: The allowed regions in the $sin^2 2\theta - \Delta m^2$ plane for the chlorine, Kamiokande, and SAGE data (dashed. The shaded areas for the allowed regions (90% CL) and dotted region for the excluded area (90% CL) are from the combined fit to all three experiments.

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