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1. INTRODUCTION

SAGE (the Russian-American Gallium Experiment) is a radiochemical solar neutrino experiment using ⁷¹Ga as a target material. The low threshold (233 keV) for inverse beta decay on this common isotope (40% isotopic abundance of ⁷¹Ga) is well below the endpoint energy of the neutrino spectrum from proton-proton fusion. Thus gallium based experiments allow one to observe this low-energy branch of the solar neutrino spectrum. SAGE has been described in detail elsewhere (including these proceedings) and we direct the reader to the literature for details [1].

SAGE and the similar experiment GALLEX have been measuring the solar neutrino flux since the early 1990's. SAGE has observed a rate of 69 ± 10 , $+5$, -7 SNU [1] (1 SNU = 10^{-36} interactions/target atom/sec) and GALLEX has observed 77.1 ± 9.6 , -10.1 SNU [2]. Both of these results are well below solar model predictions of 137 ± 8 , -7 SNU [3] and 125 ± 5 SNU [4]. Taken together with other solar neutrino experimental results from the Cl experiment [5] and the Kamiokande experiment [6], a contradiction arises which cannot be accommodated by solar models [7-11].

The radiochemical experiments operate by chemically extracting and isolating a few atoms from many tons of target material (an isolation factor of about 10^{28} !). This impressively stringent requirement has raised skepticism

about how well the extraction efficiency is known. The extraction efficiency has been determined by a variety of chemical and volumetric measurements which rely on the introduction and subsequent extraction of a known amount of stable Ge carrier to the gallium target. Although auxiliary measurements have confirmed this procedure [1], the direct calibration of the experiment with a well-characterized neutrino source would lend significant credibility to the radiochemical technique. This paper describes such a study of SAGE.

2. THE SOURCE

The decay of ^{51}Cr to ^{51}V is via electron capture with a half life of 27.7 days and neutrino energies of 751 keV (90%) and 426 keV (10%) [12]. A 320-keV gamma ray accompanies the 10% branch. These neutrino energies are well matched to that of proton-proton and ^7Be solar neutrinos. The source we have fabricated is 513 gm of 92%-enriched, ^{50}Cr -metal rods encased in a tungsten shield which in turn is welded inside a stainless steel casing. The ^{50}Cr was irradiated and the source fabricated at the BN-350 fast breeder reactor at Aktau, Kazakhstan.

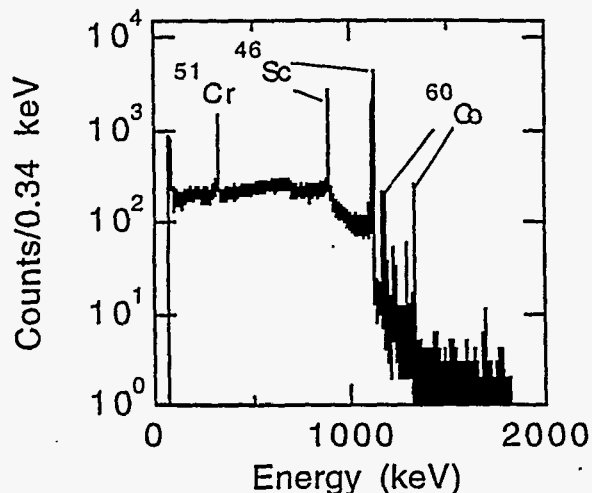


Figure 1. A Ge detector spectrum of the gamma rays emitted by the Cr source. Gamma lines are labeled by the isotope of origin. Other contaminants whose lines are not labeled include ^{59}Fe , ^{182}Ta and ^{209}Sb .

The source was irradiated from September 4 to December 18, 1994. It was then transported to the Baksan Neutrino Observatory and exposure of the gallium began at 18:00 on December 26, 1994. At this time the source had an estimated activity of 509 kCi.

Fig. 1 shows a gamma spectrum of the source. The 320 keV ^{51}Cr gamma is attenuated by a large factor by the tungsten shield but still shows a significant line in the spectrum. The higher energy lines of ^{46}Sc , ^{59}Fe , ^{60}Co , and ^{182}Ta have much smaller attenuations and thus produce lines even though they constitute far lower activity than the primary ^{51}Cr source. Limits on the level of contamination activity can be determined from this spectrum. The 1.5 Ci activity of ^{46}Sc is the largest single contribution and the total activity of all contaminants is estimated to be less than 2 Ci.

3. EXTRACTION SCHEDULE

The 55 tons of Ga employed at SAGE is distributed among 8 of 10 reactors with approximately 7 tons in each. All but one of these 10 reactors is equipped with the necessary mechanical equipment for the extraction process. The remaining reactor had the stirring mechanism removed permitting the storage of 13 tons of Ga. This reactor was used for the Cr experiment. To perform the extraction with the usual chemical procedures, the gallium was transferred by a Teflon membrane pump to two of the other reactors after a Cr exposure. Eight source measurement extractions were conducted between Jan. 1 and May 24, 1995. The lengths of the exposure periods for the first 5 measurements were chosen so each would have about equal statistical sensitivity. The final 3 extractions were done monthly.

4. SOURCE STRENGTH AND EXPECTED COUNT RATE

The decay of the ^{51}Cr deposits energy in the form of heat in the W/Cr cylinder. On average this energy is 35.51 ± 0.16 keV/decay [12]. Thus the generated heat provides a measure of the source activity by means of calorimetry. The Cr source is put inside a thermally isolated cavity inside the calorimeter. The temperature drop

across a thermistor bridge joining this cavity is measured after thermal equilibrium has been reached. This temperature is compared with a calibration curve determined by a known heat source at many values spanning the range of the various ^{51}Cr measurements. The Cr activity was measured after each extraction with an average value determined for the source activity normalized to the date the source was first installed in the Ga.

The resulting activity is $509 \pm 10 \pm 40$ kCi with the first (second) uncertainty being due to statistics (systematics). The large systematic uncertainty is an overly conservative estimate of a possible error due to ignored non-linearities in the calorimeter. In the final analysis, this uncertainty should be greatly reduced by further direct calibration of the calorimeter.

The production rate of ^{71}Ge in the Ga can be factored into two contributions:

$$\text{Rate} = \kappa \langle L \rangle \text{ (atoms produced/day/kCi).}$$

The first (κ) is due to the Ga density and neutrino interaction cross section. The second ($\langle L \rangle$) is the average neutrino path length through the gallium. Although the gallium nearly approximates a cylinder, the bottom of the Ga tank is dished and the value of $\langle L \rangle$ is determined by Monte Carlo integration using an accurate map of the reactor shape. It is found to be 72.6 ± 0.2 cm.

The value of κ is 0.398 ± 0.040 (neutrino captures/cm-day-MCi) where the dominant uncertainty arises due to the neutrino absorption cross section [13]. This uncertainty has been quoted at the 3σ level. This cross section has recently been revisited by Hata and Haxton [14] who have reexamined the contribution due to excited states. They conclude that the previous estimate of this contribution inferred from (p,n) reactions was unjustified and claim that the Cr source experiments themselves determine that contribution. We have not included this theoretical cross-section uncertainty in the neutrino capture cross section in our final uncertainty estimates.

Putting this all together gives an expected production rate on Dec. 26, 1994 at 18:00 of 14.7 ± 1.5 atoms/day. This is equivalent to about

3500 SNU. The rate of production in the neighboring reactors is negligible and is ignored.

5. WAVEFORM ANALYSIS

The quantity of ^{71}Ge extracted from the gallium is determined by observing its decay in a small proportional counter (PC). When ^{71}Ge undergoes electron capture decay, it emits x rays of either 10.4 keV (the K peak) or 1.2 keV (the L peak). The low energy of these x rays results in a recoil electron of short range. Thus the radial extent of such electron trajectories in the counter is very short resulting in a PC pulse waveform with a fast risetime. Background processes, such as minimum ionizing particles, may deposit a similar amount of energy in the counter gas but will have large path lengths and hence slow risetimes.

A digitizer has been used since late 1992 to record waveforms from the proportional counters. Each waveform is digitized at a gigahertz and fit to a functional form which describes pulses in terms of the radial extent of the trajectories in a PC [15]. The desired fast risetime events which would result from the ^{71}Ge x rays and Auger electrons will have a very small radial extent. Although this technique and the hardware risetime measurement technique [1] differ little for the large-amplitude K-peak waveforms, it is much more powerful in the low-amplitude L-peak region. In this region, offsets, noise, and nonlinearities of electronic modules dramatically decrease the hardware-based background rejection. The waveform analysis, however, overcomes these difficulties to provide a good separation between signal and background. The results here represent the first presentation of L-peak data from the SAGE experiment.

6. ANALYSIS

Each extraction has its candidate ^{71}Ge events chosen by selection in the energy-risetime plane. The time structure of these events is then analyzed with a maximum likelihood method [16] to separate the ^{71}Ge 11.4-day decay from a constant rate background. The only difference between this analysis and that done for the solar neutrino runs is that one

must account for the decay of the ^{51}Cr (as opposed to a constant solar flux), a "background" contribution from solar neutrinos, and a carryover correction arising from the ^{71}Ge that is not removed because of the approximately 15% inefficiency of the preceding chemical extraction.

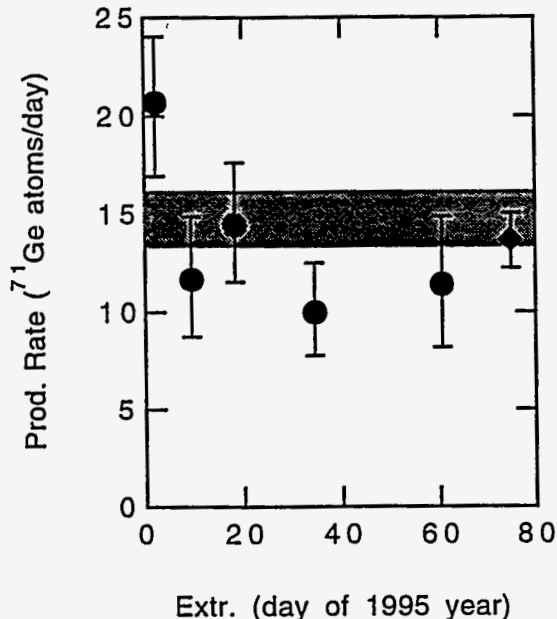


Figure 2. The 5 production rate measurements. The solid circles indicate the 5 measurements and the diamond the combined result. The shaded bar indicates the range of the expected production rate defined by its uncertainty.

Figure 2 shows the results of the first 5 exposure/extractions which are being presented here. The result of each run is normalized to the Cr activity production rate on Dec. 26 at 16:00. The combined fit of the 5 runs gives a production rate of $13.6 \pm 1.4 +0.9, -1.4$ atoms/day where the first uncertainty is statistical and the latter is systematic. A fit permitting the ^{71}Ge half life to vary gives 12.0 ± 1.5 days also consistent with its known half life of 11.4 days. The analysis of the final 3 runs will modestly decrease the statistical uncertainty. Figure 3 shows the energy spectrum of the fast events clearly indicating the K and L peaks.

Table 1 lists the preliminary estimates of the uncertainties associated with these measurements. For the most part they are

determined in a similar manner as the solar neutrino runs [1].

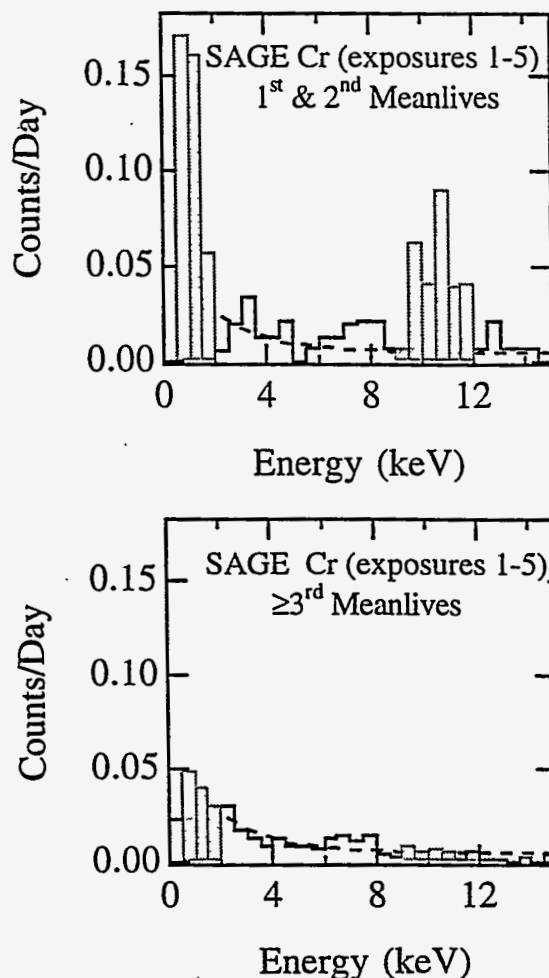


Figure 3. The top panel shows the energy spectrum of the fast risetime events observed during the 5 Cr exposure measurements during the first two meanlives of counting. The bottom panel show a similar spectrum but for counting after two meanlives. The ^{71}Ge K and L peaks are evident in the top panel.

Table 1. A summary of the contributions to the systematic uncertainty. The total is taken to be the quadrature sum of the contributions. The statistical uncertainty is $\pm 10\%$.

Chem. Extr. Efficiency	$\pm 5.5\%$
Counting Efficiency	$+2.9, -4.2\%$
Radon	-7.7%
Solar Neutrino Subtraction	$\pm 0.3\%$
Carryover Ge Subtraction	$\pm 1.6\%$
Total Systematic	$+6.4, -10.5\%$

8. DISCUSSION

The final result can be expressed as a ratio of the measured ^{71}Ge production to that expected due to the source strength. The result of $0.93 \pm 0.15, -0.17$ is consistent with 1.0 to first order. Although a finer level of precision will be determined as the final analysis is completed, the result indicates that the experimental efficiencies are as previously claimed [1]. One concludes therefore that the discrepancy between the SAGE measured solar neutrino flux and the solar model prediction cannot be explained by an experimental artifact.

The experimental efficiencies are known to a higher precision than can be tested by this method. Thus in an absolute sense, this measurement does not represent a direct calibration. A more precise description is that the Cr experiment is a systematic test of the experimental procedures. The solar flux measurement will not be scaled by the above ratio.

GALLEX has completed a ^{51}Cr calibration measurement with the result 0.97 ± 0.11 [17]. Both of these experiments give similar solar neutrino flux results and have verified their efficiencies even though they employ very different chemistries, indicating that it is very difficult to dismiss the experimental results and their striking disagreement with standard solar model predictions.

ACKNOWLEDGMENTS

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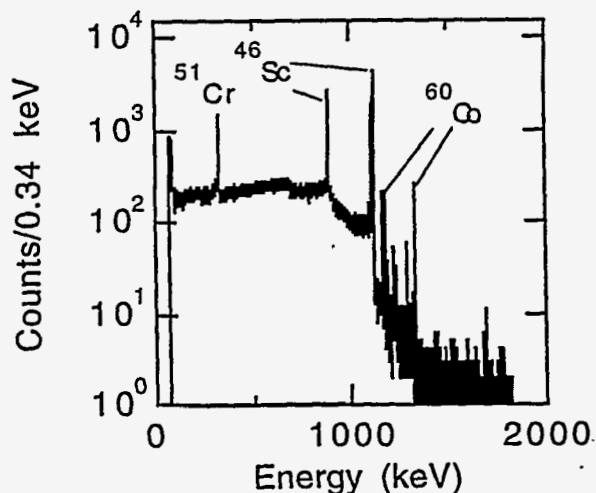


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A digitizer has been used since late 1992 to record waveforms from the proportional counters. Each waveform is digitized at a gigahertz and fit to a functional form which describes pulses in terms of the radial extent of the trajectories in a PC [15]. The desired fast risetime events which would result from the ^{71}Ge x rays and Auger electrons will have a very small radial extent. Although this technique and the hardware risetime measurement technique [1] differ little for the large-amplitude K-peak waveforms, it is much more powerful in the low-amplitude L-peak region. In this region, offsets, noise, and nonlinearities of electronic modules dramatically decrease the hardware-based background rejection. The waveform analysis, however, overcomes these difficulties to provide a good separation between signal and background. The results here represent the first presentation of L-peak data from the SAGE experiment.

6. ANALYSIS

Each extraction has its candidate ^{71}Ge events chosen by selection in the energy-risetime plane. The time structure of these events is then analyzed with a maximum likelihood method [16] to separate the ^{71}Ge 11.4-day decay from a constant rate background. The only difference between this analysis and that done for the solar neutrino runs is that one

must account for the decay of the ^{51}Cr (as opposed to a constant solar flux), a "background" contribution from solar neutrinos, and a carryover correction arising from the ^{71}Ge that is not removed because of the approximately 15% inefficiency of the preceding chemical extraction.

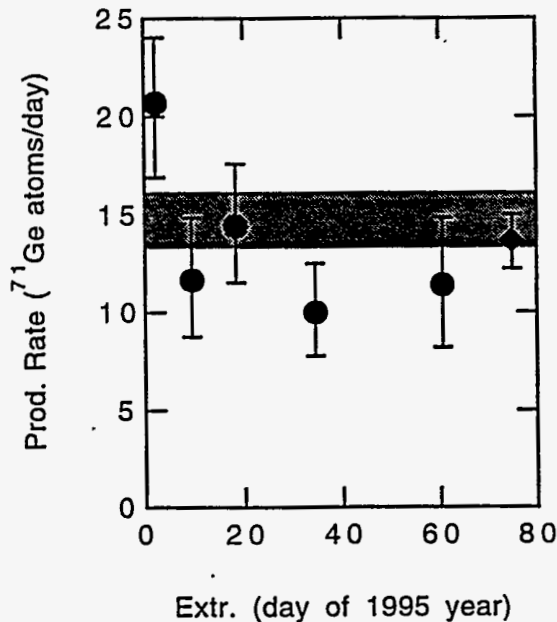


Figure 2. The 5 production rate measurements. The solid circles indicate the 5 measurements and the diamond the combined result. The shaded bar indicates the range of the expected production rate defined by its uncertainty.

Figure 2 shows the results of the first 5 exposure/extractions which are being presented here. The result of each run is normalized to the Cr activity production rate on Dec. 26 at 16:00. The combined fit of the 5 runs gives a production rate of $13.6 \pm 1.4 +0.9, -1.4$ atoms/day where the first uncertainty is statistical and the latter is systematic. A fit permitting the ^{71}Ge half life to vary gives 12.0 ± 1.5 days also consistent with its known half life of 11.4 days. The analysis of the final 3 runs will modestly decrease the statistical uncertainty. Figure 3 shows the energy spectrum of the fast events clearly indicating the K and L peaks.

Table 1 lists the preliminary estimates of the uncertainties associated with these measurements. For the most part they are

determined in a similar manner as the solar neutrino runs [1].

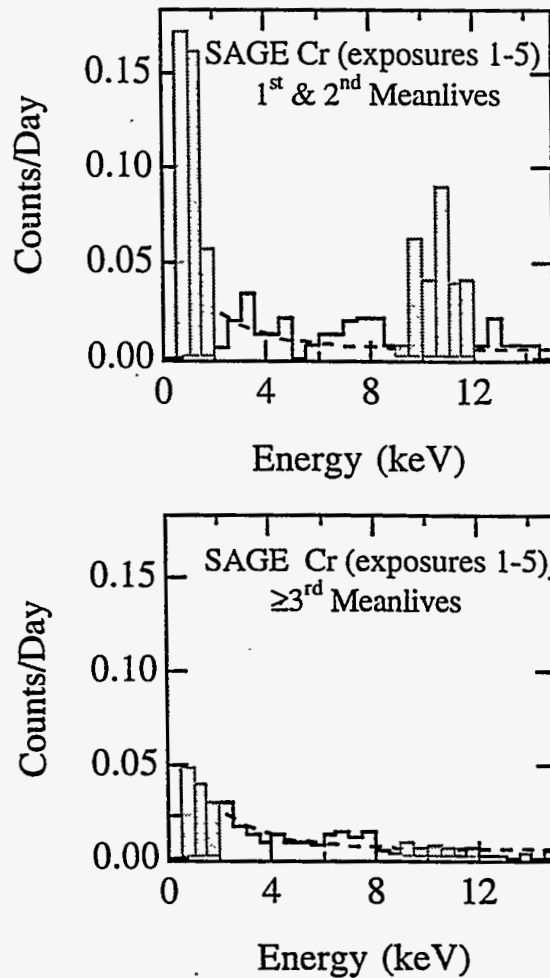


Figure 3. The top panel shows the energy spectrum of the fast risetime events observed during the 5 Cr exposure measurements during the first two meanlives of counting. The bottom panel shows a similar spectrum but for counting after two meanlives. The ^{71}Ge K and L peaks are evident in the top panel.

Table 1. A summary of the contributions to the systematic uncertainty. The total is taken to be the quadrature sum of the contributions. The statistical uncertainty is $\pm 10\%$.

Chem. Extr. Efficiency	$\pm 5.5\%$
Counting Efficiency	$+2.9, -4.2\%$
Radon	-7.7%
Solar Neutrino Subtraction	$\pm 0.3\%$
Carryover Ge Subtraction	$\pm 1.6\%$
Total Systematic	$+6.4, -10.5\%$

8. DISCUSSION

The final result can be expressed as a ratio of the measured ^{71}Ge production to that expected due to the source strength. The result of 0.93 ± 0.15 is consistent with 1.0 to first order. Although a finer level of precision will be determined as the final analysis is completed, the result indicates that the experimental efficiencies are as previously claimed [1]. One concludes therefore that the discrepancy between the SAGE measured solar neutrino flux and the solar model prediction cannot be explained by an experimental artifact.

The experimental efficiencies are known to a higher precision than can be tested by this method. Thus in an absolute sense, this measurement does not represent a direct calibration. A more precise description is that the Cr experiment is a systematic test of the experimental procedures. The solar flux measurement will not be scaled by the above ratio.

GALLEX has completed a ^{51}Cr calibration measurement with the result 0.97 ± 0.11 [17]. Both of these experiments give similar solar neutrino flux results and have verified their efficiencies even though they employ very different chemistries, indicating that it is very difficult to dismiss the experimental results and their striking disagreement with standard solar model predictions.

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