Measurement of the response of a Ga solar neutrino experiment to neutrinos from an $^{37}$Ar source

J N Abdurashitov$^1$, V I Barsanov$^2$, T J Bowles$^3$, B T Cleveland$^4$, S R Elliott$^4$, V N Gavrin$^1$, S V Girin$^5$, V V Gorbachev$^5$, P P Gurkina$^1$, W C Haxton$^4$, T V Ibragimova$^6$, A A Janelidze$^2$, A V Kalikhov$^1$, A I Karpenko$^7$, N G Khairnasov$^1$, Yu S Khomyakov$^8$, T V Knodel$^1$, A V Korenkova$^2$, N A Kotelnikov$^5$, K Lande$^2$, V V Maltsev$^5$, S Yu Markov$^5$, V A Matveev$^1$, I N Mirmov$^1$, O V Mishin$^1$, J S Nico$^9$, N N Oshkanov$^5$, V M Poplavsky$^5$, A N Petrov, V V Popov$^5$, V V Selin$^9$, Z N Shakirov$^2$, A A Shikhin$^1$, A Suzuki$^{10}$, W A Teasdale$^3$, A M Tuchkov$^5$, B A Vasiliev$^9$, E P Veretenkin$^1$, V M Vermul$^1$, S A Voronov$^4$, J F Wilkerson$^4$, V E Yants$^1$, A A Zamyatina$^2$, G T Zatsepin$^1$ and S B Zlokazov$^2$

$^1$Institute for Nuclear Research of the Russian Academy of Sciences, Moscow 117312, Russia
$^2$Institute of Nuclear Materials, Zarechny 624250, Sverdlovsk region, Russia
$^3$Los Alamos National Laboratory, Los Alamos, NM 87545 USA
$^4$University of Washington, Seattle, WA 98195 USA
$^5$Beloyarsk Nuclear Power Plant, Zarechny 624250, Sverdlovsk region, Russia
$^6$Institute of Physics and Power Engineering, Obninsk 249020, Kaluga region, Russia
$^7$Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, PA 19104 USA
$^8$OKB Mechanical Engineering, Nizhny Novgorod 603074, Russia
$^9$National Institute of Standards and Technology, Gaithersburg, MD 20899 USA
$^{10}$Research Center for Neutrino Science, Tohoku University, Aramaki, Aoba, Sendai, Japan

E-mail: gavrin@dionis.iasnet.ru

Abstract. An intense source of $^{37}$Ar was produced by the $(n, \alpha)$ reaction on $^{40}$Ca by irradiating calcium oxide in the fast neutron breeder reactor at Zarechny, Russia. The $^{37}$Ar was released from the solid target, sealed into a small source, and was used to irradiate 13 tonnes of gallium metal in the Russian-American gallium solar neutrino experiment SAGE. The initial source strength was $409 \pm 2 \text{ kCi}$. The measured production rate of $^{71}$Ge on gallium metal was $11.0^{+1.0}_{-0.9} \text{ (stat)} \pm 0.6 \text{ (syst.) atoms per day, which is } 0.79^{+0.09}_{-0.10} \text{ of the theoretically calculated production rate.}$

1. Introduction

The major purposes of the work presented here were, first, to develop the technology of fabrication of a very intense $^{37}$Ar source [1, 2], then to test the technology by making a source prototype with a comparatively not very high intensity and, finally, to use the prototype for measurement of the response of Ga in SAGE to neutrinos from $^{71}$Ar [3]. The $^{37}$Ar source has several important advantages...
compared to a $^{51}$Cr source, the production technology of which was developed before. $^{51}$Cr sources were used in the SAGE [4] and GALLEX [5] experiments.

A major advantage is that an $^{37}$Ar source, in contrast to a $^{51}$Cr source, can be made practically free of radioactive impurities. Other advantages of $^{37}$Ar compared to $^{51}$Cr are that the half life is longer (35 d compared to 27 d), that the neutrino energy is greater (811 keV compared to 747 keV), that the decay is purely to the ground state (100% compared to 90%), thus giving a monoenergetic neutrino source, and that there are no accompanying $\gamma$ rays (except for inner bremsstrahlung), thus requiring little shielding and yielding a very compact source. Finally, since nearly 97% of Ca is $^{40}$Ca, no isotopic separation is required before irradiation. In contrast, to make a $^{51}$Cr source, the irradiated isotope $^{50}$Cr must be enriched as its content in natural Cr is only 4.3%.

2. Source production
Nineteen irradiation assemblies, each of which contained 17.3 kg of CaO (12.36 kg Ca), were placed in the blanket zone of the breeder reactor BN-600 at Zarechny, Russia. The total fast flux at this reactor is $2.3 \times 10^{15}$ neutrons/(cm$^2$s), of which $1.7 \times 10^{14}$ neutrons/(cm$^2$s) have energy above the 2-MeV threshold of the production reaction $^{40}$Ca($n$, $\alpha$)$^{37}$Ar. Irradiation began on 31 October 2003 and continued until 12 April 2004, the normal reactor operating cycle. After a cooling period of a week, the assemblies were removed from the reactor, the $^{37}$Ar was extracted and purified, and measurements of gas volume and isotopic composition were made.

As the last steps of source fabrication, the purified Ar was transferred to a pre-weighted source holder. The source holder was then weighed to determine the amount of $^{37}$Ar contained within. To complete the source, the source holder was placed within two concentric stainless steel vessels with a Pb shield between them. These two vessels were welded shut and the heat output of the finished source was measured with a calorimeter.

3. Measurement of source activity
The results of the six activity measurements are summarized in Table 1. Their weighted average is 409 ± 2 kCi. The two measurements with the calorimeter are each about 1.5 $\sigma$ above and below this average, but still for all measurements $\chi^2 = 7.2$, which with 5 DOF has a probability of 21%.

| Measurement method          | Activity (kCi $^{37}$Ar at 04:00 on April 2004) |
|------------------------------|-----------------------------------------------|
| Volume of gas                | 409.3 ± 5                                      |
| Mass of gas                  | 412.3 ± 3                                      |
| Calorimetry at Zarechny      | 401.3 ± 4                                      |
| Calorimetry at Baksan        | 422.5 ± 9                                      |
| Proportional counter         | 405.1 ± 4                                      |
| Isotopic solution            | 410.1 ± 5                                      |

4. Measured and predicted production rates
At the Baksan Neutrino Observatory ten exposures of 13 tons of gallium metal to the $^{37}$Ar source in SAGE were carried out. The $^{71}$Ge produced by the reaction $^{71}$Ga($\nu_e$, $e^{-}$)$^{71}$Ge was extracted, purified, and counted. The experimental procedures were basically the same as used with the SAGE Cr experiment in 1995 [4]. An outline of the extraction procedure is given in [6]. The same program for data analysis was used that we used to analyze runs with the $^{51}$Cr source and that we also use for analysis of solar neutrino data [7].

The measured production rate in the $K$ and $L$ peaks, including both statistical and systematic errors, is $p_{\text{measured}} = 11.0^{+1.0}_{-0.9}$ (stat) ± 0.6 (syst) atoms of $^{71}$Ge produced per day.
Based on the source activity of 409 +/- 2 kCi and on the cross section of $70.0^{+4.9}_{-2.1} \times 10^{-46}$ cm$^2$ [8], and combining the uncertainty terms in quadrature, the predicted production rate is $P_{\text{predicted}} = 13.9^{+1.0}_{-0.4}$ atoms of $^{71}$Ge produced per day.

5. Summary
The ratio of measured to predicted production rate is

$$\frac{P_{\text{measured}}}{P_{\text{predicted}}} = \frac{11.0^{+0.9}_{-0.9} (\text{stat}) \pm 0.6 (\text{syst.})}{13.9^{+1.0}_{-0.4}} = 0.79^{+0.09}_{-0.10}$$

where the statistical and systematic uncertainties have been combined in quadrature. This result is nearly 2.5 $\sigma$ less than unity which has a probability of slightly more than 1%. The results of the four neutrino source experiments with Ga are shown graphically in Fig.1. The weighted average value of the ratio of measured to predicted $^{71}$Ge production rates is $0.88 \pm 0.05$, more than two standard deviations less than unity. Although not statistically conclusive, the combination of these experiments suggests that the predicted rates may be overestimated.

![Figure 1. Results of all neutrino source experiments with Ga. The dashed region is the weighted average of all four experiments.](image)

The $^{37}$Ar source used in this experiment was made as a prototype for the production of a much more intense source. Based on the experience gained in making this source, the reactor engineers for BN-600 conclude that sources in the range of 2.0–2.5 M Ci could be made if the Ca-containing modules were placed in the core of the reactor, rather than in the blanket zone, as was done here.

Acknowledgements
We thank Alexander Rumyantsev and Lev Ryabev (Federal Agency of Atomic Energy, Russia) and Valery Rubakov (Institute for Nuclear Research RAS, Russia) for their vigorous and continuous support for the $^{37}$Ar project. This work was partially funded by grants from the USA, Japan, and Russia and carried out under the auspices of the International Science and Technology Center (project no. 1431).

References
[1] Haxton W C 1988 Phys. Rev. C 38 2474
[2] Gavrin V N, Kochetkov A L, Kornoukhov V N, Kosarev A A and Yants V E 1992 Institute for Nuclear Research of the Russian Academy of Sciences Report No. P-777
[3] Abdurashitov J N et al 2005 Proc. of the Eleventh Int. Workshop on Neutrino Telescopes (Venezia, 22-25 February 2005) ed Milla Baldo Ceolin p 187
[4] Abdurashitov J N et al 1999 Phys. Rev. C 59 2246 (Preprint hep-ph/9803418)
[5] Hampel W et al 1998 Phys. Lett. B 420 114
[6] Abdurashitov J N et al (SAGE Collaboration) 1999 Phys. Rev. C 60 055801 (Preprint astro-ph/9907113)
[7] Cleveland B T 1983 Nucl. Instrum. Methods Phys. Res. A 214 451
[8] Bahcall J N 1997 Phys. Rev. C 56 3391 (Preprint hep-ph/ 9710491)