Radiochemical Solar Neutrino Experiments
A little bit of history

Main characteristic and results of the Cl and Ga experiments

Recent results of the SAGE experiment
The neutrino flux from the sun is of the order of $10^{10}\text{cm}^{-2}\text{sec}^{-1}$. The neutrinos emitted by the sun, however, are not very energetic. The use of high intensity piles permits two possible strong neutrino sources.

The object of this note is to show that the experimental observation of an inverse process produced by neutrinos is not out of the question with the modern experimental facilities, and to suggest a method which might make an experimental observation feasible.

The neutrino flux from the sun is of the order of $10^{10}\text{cm}^{-2}\text{sec}^{-1}$. The neutrinos emitted by the sun, however, are not very energetic. The use of high intensity piles permits two possible strong neutrino sources.
$\nu_e + ^{37}\text{Cl} \rightarrow ^{37}\text{Ar} + e^-$

Homestake Gold Mine (Lead, South Dakota, USA) 1478 m deep, 4200 m.w.e. 

Steel tank, 6.1 m diameter, 14.6 m long (6x10$^5$ liters)

615 tons of tetrachloroethylene ($\text{C}_2\text{Cl}_4$), 2.16 x 10$^{30}$ atoms of $^{37}\text{Cl}$ (133 tons)

Energy threshold: $E_{\text{th}}^\text{Cl} = 0.814 \text{ MeV}$ => 8B, 7Be, pep, hep


$R_{\text{exp}}^{\text{Cl}} = 2.56 \pm 0.16 \pm 0.16 \text{ SNU} = 2.56 \pm 0.23 \text{ SNU}$

$R_{\text{SM}}^{\text{Cl}} = 7.6 \pm 1.3/-1.1 \text{ SNU}$
**Kamiokande II**

**Φ measured**

\[ R_{\text{KII}} = \Phi_{\text{measured}} = 0.54 \pm 0.08 / +0.10 -0.07 \]

**Φ predicted**

\[ R_{\text{Cl}}(^8\text{B} + ^7\text{Be}) - R_{\text{KII}}(^8\text{B}) \sim 0 \]

(\sim 15\%)

**Paradox:**

1986-1995

\[ \nu + e^- \rightarrow \nu + e^- \]
Vadim Kuzmin proposed a radiochemical gallium detector and artificial $^{51}\text{Cr}$ neutrino source for its calibration in 1965.
The Laboratory research to develop a gallium experiment began approximately in 1975. In the United States this work took place at Brookhaven National Laboratory under direction of Ray Davis with participation of J.Bahcall, B.Cleveland, C.Evans, G.Friedlander, K.Rowley, R.Stoener from Brookhaven, and W.Frati, K.Lande from the University of Pennsylvania, I.Dostrovsky from the Weizmann Institute.

Methods were tested to extract germanium from liquid gallium metal and from gallium chloride solution. This group within several years has achieved great success in development both of these methods.
Collaborative Program for the Measurement of the Solar Neutrino Flux with a $^{71}\text{Ga}$ Detector

List of Scientific Participants

1. Brookhaven National Laboratory:
   Raymond Davis Jr., Senior Chemist
   Bruce Cleveland, Senior Research Associate
   Gerhart Friedlander, Senior Chemist
   Seymour Katcoff, Senior Chemist
   J. Keith Rowley, Chemist
   Joseph Weneser, Senior Physicist

2. Max Planck Institut fur Kernphysik:
   Till Kirsten, Professor of Physics
   Wolfgang Hampel, Senior Scientist
   Oliver Schaeffer, Professor of Geochemistry
   Kurt Buchler, Diplomphysiker
   Reinhold Schlotz, Diplomphysiker
   Gerd Heusser, Senior Scientist

3. Institute for Advanced Study:
   John N. Bahcall,
   Professor of Theoretical Physics

4. University of Pennsylvania:
   Kenneth Lande, Professor of Physics
   William Frati, Research Specialist
   Richard Steinberg,
   Assistant Professor of Physics.

5. Weizmann Institute of Science:
   Israel Dostrovsky,
   Institute Professor of Physical Chemistry
   Yehuda Eyal, Senior Scientist

Proposal submitted to the
Max Planck Gesellschaft zur Forderung der Wissenschaften, e.V.
by Brookhaven National Laboratory, Upton, NY, USA
and Max Planck Institut fur Kernphysik, Heidelberg,
Federal Republic of Germany

September 1978
The full-scale 50-ton gallium experiment with calibration experiment was proposed to the Department of Energy in 1981. A high level review committee convened by DOE recommended strongly that the experiment be carried out.

But it was not funded.
A final effort to obtain DOE funding was submitted in 1985 by Brookhaven, Los Alamos, and a number of universities. It too was unsuccessful. About 15 years later Gerry Garvey said about this following comment: “This was largely due to the fact that there really is no federal agency with a clear charter for funding this kind of research (a genuine shortcoming in the U.S. system)”. A special subcommittee of the Nuclear Science Advisory Committee recommended at this time that those participants with long-term interest in the gallium experiment should associate themselves with groups in western Europe and/or the Soviet Union.
In 1984 after results of Kamiokande, the interest to gallium experiments increased more strong. In 1984 Max Plank Institute group under the leadership of Till Kirsten presented their own proposal and began to create the Western European countries Collaboration that got name GALLEX.
In the Soviet Union at the Institute for Nuclear Research we began a laboratory research to develop gallium experiment about the same time in 1975 using gallium chloride solution. But when we understood that our industry can not provide necessary purity in 50 tons of gallium chloride solution, and taking into account that metallic gallium is significantly less sensitive to radioactive impurities, we changed gallium solution for gallium metal. We used Davis’ idea and independently developed technology of extraction minute quantities of $^{71}\text{Ge}$ from many tons of metallic gallium.
The SAGE Collaboration
Measurement of the Solar Neutrino Capture Rate with gallium metal

J.N.Abdurashitov, V.N.Gavrin*, S.V.Girin, V.V.Gorbachev, P.P.Gurkina, T.V.Ibragimova, A.V.Kalikhov, N.G.Khairnasov, T.V. Knodel, I.N.Mirmov, A.A.Shikhin, E.P.Veretenkin, V.M.Vermul, V.E.Yants, and G.T.Zatsepin*

Institute for Nuclear Research, Russian Academy of Sciences, 117312 Moscow, Russia

M.L.Cherry
Louisiana State University, Baton Rouge, Louisiana 70803

T.J.Bowles*, W.A.Teasdale and D.L.Wark
Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

J.S.Nico
National Institute of Standards and Technology, Stop 8461, Gaithersburg, Maryland 20899, USA

B.T.Cleveland, S.R.Elliott, and J.F.Wilkerson*
University of Washington, Seattle, Washington 98195, USA

K.Lande, R.Davis, Jr., P.Wildenhain
Department of Physics and Astronomy, University of Pennsylvania Philadelphia, PA, 19104, USA

* - Principal Investigators
THE GNO COLLABORATION

E. Bellotti (spokesperson), C. Cattadori, L. Zanotti
*Dip. di Fisica, Universita' di Milano, Milano, Italy*

M. Balata, N. Ferrari, L. Ioannucci, M. Laubenstein, S. Nisi, L. Pandola
*INFN, Laboratori Nazionali del Gran Sasso, L'Aquila - Italy*

P. Belli, R. Bernabei, R. Cerulli, S. d'Angelo
*Dip. di Fisica, Universita' di Roma, Roma, Italy*

E. Burkert, W. Hampel, F.X. Hartmann, G. Heusser, J. Kiko, T. Kirsten, D. Motta, W. Rau, H. Richter
*Max Plank Institut fur Kernphysik, Heidelberg, Germany*

M. Altmann, F. von Feilitzsch, T. Lachenmaier, J. Lanfranchi, M. Weneser
*Technische Universitat Munchen, Munchen, Germany*

K. Ebert, E. Henrich
*Institut fur Technische Chemie, Karlsruhe, Germany*

M. Chiarini, G. Del Re, G. Veglio
*Universita' dell'Aquila, L'Aquila, Italy*
SAGE: Soviet-American Gallium Experiment
Baksan Neutrino Observatory, northern Caucasus, 3.5 km from entrance of horizontal adit
50 tons of metallic $^{71}\text{Ga}$, 2000 m deep, 4700 m.w.e. => $\Phi_{\mu} \sim 2.6 \text{ m}^{-2} \text{ day}^{-1}$
data taking: Jan 1990-Dec 2005, 145 runs, running
$$R_{\text{Ga}}^{\text{SAGE}} = 66.5^{+3.5}_{-3.4}^{+3.5}_{-3.2} \text{ SNU} = 66.5^{+4.9}_{-4.7} \text{ SNU}$$

GALLEX: GALLium EXperiment
Gran Sasso Underground Laboratory, Italy, overhead shielding: 3300 m.w.e.
30.3 tons of gallium in 101 tons of gallium chloride (GaCl$_3$–HCl) solution
data taking: May 1991-Jan 1997, 65 runs
$$R_{\text{Ga}}^{\text{GALLEX}} = 77.5 \pm 6.2^{+4.3}_{-4.7} \text{ SNU} = 77.5^{+7.6}_{-7.8} \text{ SNU}$$

GNO: Gallium Neutrino Observatory
Successor of GALLEX, GNO30: 30.3 tons of gallium
data taking: May 1998 - Sep 2003, 58 runs
$$R_{\text{Ga}}^{\text{GNO}} = 62.9^{+5.5}_{-5.3} \pm 2.5 \text{ SNU} = 62.9^{+6.0}_{-5.9} \text{ SNU}$$
$$\text{GALLEX} + \text{GNO} => R_{\text{Ga}}^{\text{GALLEX+GNO}} = 69.3 \pm 4.1 \pm 3.6 \text{ SNU} = 69.3 \pm 5.5 \text{ SNU}$$

Gallium Experiments: SAGE, GALLEX, GNO
Radiochemical experiments
$\nu_e + ^{71}\text{Ga} \rightarrow ^{71}\text{Ge} + e^-$
threshold $E_{\text{th}}^{\text{Ga}} = 0.233 \text{ MeV}$ => all $\nu$ fluxes ($pp$, $^7\text{Be}$, $^8\text{B}$, $\text{pep}$, $\text{hep}$, $^{13}\text{N}$, $^{15}\text{O}$, $^{17}\text{F}$)
$$\text{SAGE} + \text{GALLEX} + \text{GNO} => R_{\text{Ga}}^{\exp} = 67.7 \pm 3.6 \text{ SNU}$$
$$\text{Standard Solar Model} => R_{\text{Ga}}^{\text{SSM}} = 128^{+9}_{-7} \text{ SNU}$$
**GALLEX $^{51}$Cr source results**

**Source 1**
- Source activity: 1.17 +/- 0.04 MCi
- Expected rate: 11.7 +/- 0.2 $^{71}$Ge at/day
- Ratio R: 1.0 +/- 0.10

**Source 2**
- Source activity: 1.87 +/- 0.07 MCi
- Expected rate: 12.7 +/- 0.2 $^{71}$Ge at/day
- Ratio R: 0.84 +/- 0.11

**Joint Ratio R**: 0.93 +/- 0.08
SAGE $^{51}\text{Cr}$ source result

exposure time Dec 1994 – May 1995
source activity $0.517 \pm 0.007\ MCi$
expected rate $14.9 \pm 0.2\ 71\text{Ge at/day}$

Ratio $R$ $0.95 \pm 0.11 \pm 0.06$

$517\ kCi$ source of $^{51}\text{Cr}$
was produced by irradiation
$512.7\ g$ of 92.4%-enriched
$^{50}\text{Cr}$ in high-flux fast
neutron reactor.
**Ga (n, γ) experiment**

To test the possibility that atomic excitations might tie up $^{71}$Ge in a chemical form from which it would not be efficiently extracted, the radioactive isotopes $^{70}$Ge and $^{72}$Ga, which beta decay to $^{70}$Ge and $^{72}$Ge, were produced in liquid gallium by neutron irradiation.

The Ge isotopes were extracted from the Ga using our standard procedure. The number of Ge atoms was determined by mass spectroscopic measurements and was found to be consistent with the number expected based on the known neutron flux and capture cross section, thus suggesting that chemical traps are not present.

**GALLEX**

Any possible *hot chemistry* effect was ruled out in GALLEX by the extremely important $^{71}$As test, which proved the chemical efficiency to be $(100.0 \pm 1.2)\%$
The values of $\Delta m^2_{12}$ and $\theta_{12}$ for each component are calculated for three neutrino mixing with parameters

$\Delta m^2_{12} = (7.92 \pm 0.36) \times 10^{-5} \text{ eV}^2 \quad \theta_{12} = 34^{+1.7}_{-1.5} \quad \theta_{13} = 5.44^{+2.79}_{-5.44}$

From 268 solar neutrino extractions in the SAGE and GALLEX/GNO experiments:

\[ [pp+^7\text{Be}+\text{CNO}+\text{pep}+^8\text{B} | \text{Ga}] = 67.7 \pm 3.6 \text{ SNU} \]

\[ [^8\text{B} | \text{SNO}] = (1.68 \pm 0.11) \times 10^6 \nu_e/(\text{cm}^2\cdot\text{s}) \rightarrow [^8\text{B} | \text{Ga}] = 3.7 +1.2 -0.7 \text{ SNU} \]

\[ [pp+^7\text{Be}+\text{CNO}+\text{pep} | \text{Ga}] = 64.0 +3.7 -3.3 \text{ SNU} \]

\[ [^7\text{Be}+\text{CNO}+\text{pep}+^8\text{B} | \text{Cl}] = 2.56 \pm 0.23 \text{ SNU} \]

\[ [^8\text{B} | \text{Cl}] = 1.72 \pm 0.14 \text{ SNU} \rightarrow [^7\text{Be}+\text{CNO}+\text{pep} | \text{Cl}] = 0.84 \pm 0.27 \text{ SNU} \]

\[ [^7\text{Be}+\text{CNO}+\text{pep} | \text{Ga}] = [^7\text{Be}+\text{CNO}+\text{pep} | \text{Cl}] \times \sigma(\nu_\gamma, Ga)/\sigma(\nu_\gamma, Cl) = 25.1 +8.2 -8.1 \text{ SNU} \]

\[ [^7\text{Be}+\text{CNO}+\text{pep} | \text{Ga}] = 25.1 +8.6 -8.4 \text{ SNU} \]

\[ [pp | \text{Ga}] = [pp+^7\text{Be}+\text{CNO}+\text{pep} | \text{Ga}] - [^7\text{Be}+\text{CNO}+\text{pep} | \text{Ga}] = 38.1 +8.9 -9.1 \text{ SNU} \rightarrow \]

the measured electron neutrino pp flux at Earth of

\[ (3.23 +0.76 -0.78) \times 10^{10}/(\text{cm}^2\cdot\text{s}) \times \langle P_i^{pe} \rangle = 0.555 \]

\[ (5.94 \pm 0.06) \times 10^{10}/(\text{cm}^2\cdot\text{s}) \text{ (SSM)} \times \langle P_i^{pe} \rangle = (3.30 \pm 0.07) \times 10^{10}/(\text{cm}^2\cdot\text{s}) \]

Excellent agreement
90% C.L. exclusion plot in the frequency/amplitude plane from the analysis of GALLEX and GNO data

L. Pandola,
hep-ph/0406248
Vladimir,

It is very exciting to hear that you are planning a new throughput test of the Sage detection with a good 37Ar source. Congratulations! That is very exciting. I hope you can do the same thing on the GNO detector. I would be very honored if you dedicated the first 37Ar run to the Milano celebration.

The difference in the rates of the gallium experiments in the two time periods is interesting but not compelling statistically, in my view. I think that the hypothesis of a statistical fluctuation is probably more likely than any time dependence in the flux. I do not know of any attractive scenarios that predict a significant time dependence in the observed \( \nu_e \) solar neutrino flux, particularly one that has such a large pp contribution. However, it is always good to continue to look. We have been surprised before by solar neutrino measurements and we may be surprised again. Nature is very imaginative.

Warmest personal regards,

John Bahcall

---

### Table: Gallium Rate (SNU) and \( \Delta m^2 \) Values

<table>
<thead>
<tr>
<th>Time period</th>
<th>05/14/91-01/23/97</th>
<th>05/20/98-04/09/03</th>
<th>05/14/91-4/09/03</th>
<th>Full data set 01/90-12/05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number runs</td>
<td>65</td>
<td>58</td>
<td>123</td>
<td></td>
</tr>
<tr>
<td><strong>GALLEX/GNO</strong></td>
<td>77.5 ± 6.2</td>
<td>62.9 ± 5.6</td>
<td>69.3 ± 4.1</td>
<td></td>
</tr>
<tr>
<td>Number runs</td>
<td>45</td>
<td>49</td>
<td>94</td>
<td>145</td>
</tr>
<tr>
<td><strong>SAGE</strong></td>
<td>79.4 ± 8.8</td>
<td>65.0 ± 5.1</td>
<td>68.9 ± 4.3</td>
<td>66.5 ± 3.5</td>
</tr>
<tr>
<td>Number runs</td>
<td>(110)</td>
<td>(107)</td>
<td>(217)</td>
<td>(268)</td>
</tr>
<tr>
<td><strong>SAGE+GALLEX/GNO</strong></td>
<td>78.3 ± 5.9</td>
<td>63.9 ± 4.2</td>
<td>69.1 ± 3.9</td>
<td>67.7 ± 3.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gallium Rate (SNU)</th>
<th>63.3 ± 3.6</th>
<th>68.1 ± 3.75</th>
<th>77.8 ± 5.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta m^2 ) (10^{-5} \text{ eV}^2) &amp; 8.2^{+0.3}<em>{-0.3} (+1.0) &amp; 8.2^{+0.3}</em>{-0.3} (+1.0) &amp; 8.2^{+0.3}_{-0.3} (+1.0)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \tan^2 \theta_{12} ) &amp; 0.39^{+0.05}<em>{-0.04} (+0.19) &amp; 0.39^{+0.05}</em>{-0.04} (+0.19) &amp; 0.38^{+0.05}_{-0.05} (+0.21)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( p-p ) &amp; 1.03^{+0.02}<em>{-0.02} (+0.05) &amp; 1.01^{+0.02}</em>{-0.02} (+0.06) &amp; 0.99^{+0.02}_{-0.02} (+0.07)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( ^8\text{B} ) &amp; 0.87^{+0.04}<em>{-0.04} (+0.09) &amp; 0.87^{+0.04}</em>{-0.04} (+0.09) &amp; 0.88^{+0.04}_{-0.04} (+0.09)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( ^7\text{Be} ) &amp; 0.25^{+0.85}<em>{-0.25} (+1.37) &amp; 1.03^{+0.24}</em>{-1.03} (+0.77) &amp; 1.29^{+0.26}_{-0.57} (+0.74)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Analysis of solar and reactor data assuming different values of the event rate in gallium solar neutrino experiments.
\[ \frac{L_{CNO}}{L_\odot} < 7.3\% (7.8\%) \text{ at } 3 \sigma \]

John N. Bahcall,  
M.C. Gonzalez-Garcia  
Carlos Pena-Garay,  
The BNO-LNGS joint measurement of the solar neutrino capture rate in $^{71}$Ga

arXiv:nucl-ex050931 v1 23 Sep 2005
Astroparticle Physics, volume 25, pages 349-354
The BNO@LNGS experiment:

J. N. Abdurashitov\textsuperscript{a}, T. J. Bowles\textsuperscript{c}, C. Cattadori\textsuperscript{b, e}, B. T. Cleveland\textsuperscript{g}, S. R. Elliott\textsuperscript{c}, N. Ferrari\textsuperscript{b}, V. N. Gavrin\textsuperscript{a}, S. V. Girin\textsuperscript{a}, V. V. Gorbachev\textsuperscript{a}, P. P. Gurkina\textsuperscript{a}, W. Hampel\textsuperscript{d}, T. V. Ibragimova\textsuperscript{a}, F. Kaether\textsuperscript{d}, A. V. Kalikhov\textsuperscript{a}, N. G. Khairnasov\textsuperscript{a}, T. V. Knodel\textsuperscript{a}, I. N. Mirmov\textsuperscript{a}, J. S. Nico\textsuperscript{c}, L. Pandola\textsuperscript{b}, H. Richter\textsuperscript{d}, A. A. Shikhin\textsuperscript{a}, W. A. Teasdale\textsuperscript{c}, E. P. Veretenkin\textsuperscript{a}, V. M. Vermul\textsuperscript{a}, J. F. Wilkerson\textsuperscript{g}, V. E. Yants\textsuperscript{a}, and G. T. Zatsepin\textsuperscript{a}

\textsuperscript{a}Institute for Nuclear Research of the Russian Academy of Sciences, Moscow 117312, Russia
\textsuperscript{b}INFN, Laboratori Nazionali del Gran Sasso (LNGS), S.S.17/bis Km 18+910, I-67010 L’Aquila, Italy
\textsuperscript{c}Los Alamos National Laboratory, Los Alamos, NM 87545 USA
\textsuperscript{d}Max-Planck-Institut für Kernphysik (MPIK), Postfach 103980, D-69029 Heidelberg, Germany
\textsuperscript{e}National Institute of Standards and Technology, Gaithersburg, MD 20899 USA
\textsuperscript{f}Dipartimento di Fisica, Università di Milano ‘La Bicocca’ e INFN, Sezione di Milano, Via Emanueli, I-20126 Milano, Italy
\textsuperscript{g}Department of Physics, University of Washington, Seattle, WA 98195 USA
All the steps (and the extraction procedure) were done rapidly so that the total time from the end of solar neutrino exposure to the start of counting, including transport from Baksan to Gran Sasso, averaged 61.8 hours for the six extractions. The extraction samples were measured in GNO ultralow background counters which had previously been used to measure 11 of the last 13 GNO solar neutrino extractions.
SAGE

Full data set 01/90-12/05: 145 runs

66.5 ± 3.5 ± 3.4 SNU
Measurement of the response of a Ga solar neutrino experiment to neutrino from an $^{37}$Ar source

Physical Review C73, 045805 (2006)
### Extraction schedule and related parameters

The times of exposure are given in days of year 2004

<table>
<thead>
<tr>
<th>Extraction name</th>
<th>Extraction date (2004)</th>
<th>Source exposure</th>
<th>Solar neutrino exposure</th>
<th>Mass Ga (tones)</th>
<th>Carrier mass (mg)</th>
<th>Extraction efficiency from Ga into GeH4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar 1</td>
<td>6 May</td>
<td>121.17</td>
<td>118.48</td>
<td>13.085</td>
<td>0.0</td>
<td>0.93 (0.59)</td>
</tr>
<tr>
<td>Ar 2</td>
<td>14 May</td>
<td>128.42</td>
<td>125.38</td>
<td>13.084</td>
<td>2.15</td>
<td>0.96 (0.93)</td>
</tr>
<tr>
<td>Ar 3</td>
<td>29 May</td>
<td>136.42</td>
<td>133.51</td>
<td>13.063</td>
<td>2.11</td>
<td>0.93 (0.90)</td>
</tr>
<tr>
<td>Ar 3-2</td>
<td>30 May</td>
<td>136.42</td>
<td>150.91</td>
<td>13.049</td>
<td>2.74</td>
<td>0.93 (0.87)</td>
</tr>
<tr>
<td>Ar 4</td>
<td>13 Jun</td>
<td>151.42</td>
<td>147.47</td>
<td>13.055</td>
<td>2.08</td>
<td>0.97 (0.92)</td>
</tr>
<tr>
<td>Ar 5</td>
<td>28 Jun</td>
<td>166.40</td>
<td>162.47</td>
<td>13.018</td>
<td>2.10</td>
<td>0.98 (0.97)</td>
</tr>
<tr>
<td>Ar 6</td>
<td>13 Jul</td>
<td>181.42</td>
<td>173.57</td>
<td>13.025</td>
<td>2.19</td>
<td>0.98 (0.97)</td>
</tr>
<tr>
<td>Ar 7</td>
<td>28 Jul</td>
<td>196.42</td>
<td>193.49</td>
<td>12.974</td>
<td>2.15</td>
<td>0.98 (0.97)</td>
</tr>
<tr>
<td>Ar 8</td>
<td>12 Aug</td>
<td>211.42</td>
<td>208.48</td>
<td>12.997</td>
<td>2.09</td>
<td>0.98 (0.96)</td>
</tr>
<tr>
<td>Ar 9</td>
<td>27 Aug</td>
<td>226.42</td>
<td>223.47</td>
<td>12.945</td>
<td>2.14</td>
<td>0.98 (0.96)</td>
</tr>
<tr>
<td>Ar10</td>
<td>11 Sep</td>
<td>241.42</td>
<td>238.38</td>
<td>12.969</td>
<td>2.11</td>
<td>0.98 (0.96)</td>
</tr>
</tbody>
</table>

The first irradiation of Ga began at 04:00 on 30 April 2004 (reference time)
Results of analysis of L- and K-peak events. All production rates are referred to the time of the start of the first exposure. The parameter $Nw^2$ measures the goodness of fit of the sequence of event times. The probability was inferred from $Nw^2$ by simulation.

<table>
<thead>
<tr>
<th>Extraction name</th>
<th>Number of candidate events</th>
<th>Number fit to $^{71}$Ge</th>
<th>Number of events assigned to $^{37}$Ar source production</th>
<th>Solar $\nu$ production</th>
<th>$^{71}$Ge production rate by $^{37}$Ar source (atoms/day)</th>
<th>$Nw^2$</th>
<th>Probability (percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar 1</td>
<td>28</td>
<td>20.1</td>
<td>19.4</td>
<td>0.7</td>
<td>$10.3^{+3.2}_{-2.8}$</td>
<td>0.065</td>
<td>60</td>
</tr>
<tr>
<td>Ar 2</td>
<td>48</td>
<td>29.9</td>
<td>28.7</td>
<td>1.2</td>
<td>$10.5^{+3.3}_{-2.5}$</td>
<td>0.048</td>
<td>73</td>
</tr>
<tr>
<td>Ar 3</td>
<td>69</td>
<td>52.9</td>
<td>51.3</td>
<td>1.6</td>
<td>$14.5^{+4.3}_{-2.1}$</td>
<td>0.110</td>
<td>35</td>
</tr>
<tr>
<td>Ar 3-2</td>
<td>13</td>
<td>2.4</td>
<td>2.3</td>
<td>0.1</td>
<td>$0.8^{+0.9}_{-0.8}$</td>
<td>0.273</td>
<td>7</td>
</tr>
<tr>
<td>Ar 4</td>
<td>45</td>
<td>25.4</td>
<td>23.8</td>
<td>1.6</td>
<td>$9.5^{+2.3}_{-2.2}$</td>
<td>0.142</td>
<td>13</td>
</tr>
<tr>
<td>Ar 5</td>
<td>38</td>
<td>25.6</td>
<td>23.8</td>
<td>1.8</td>
<td>$11.5^{+3.1}_{-2.5}$</td>
<td>0.108</td>
<td>29</td>
</tr>
<tr>
<td>Ar 6</td>
<td>34</td>
<td>11.6</td>
<td>9.7</td>
<td>1.9</td>
<td>$6.5^{+2.2}_{-1.7}$</td>
<td>0.042</td>
<td>81</td>
</tr>
<tr>
<td>Ar 7</td>
<td>18</td>
<td>8.4</td>
<td>6.7</td>
<td>1.7</td>
<td>$6.1^{+3.3}_{-2.7}$</td>
<td>0.079</td>
<td>43</td>
</tr>
<tr>
<td>Ar 8</td>
<td>29</td>
<td>12.8</td>
<td>11.2</td>
<td>1.6</td>
<td>$14.5^{+2.7}_{-2.3}$</td>
<td>0.055</td>
<td>68</td>
</tr>
<tr>
<td>Ar 9</td>
<td>20</td>
<td>9.0</td>
<td>7.3</td>
<td>1.7</td>
<td>$12.1^{+0.8}_{-0.5}$</td>
<td>0.068</td>
<td>58</td>
</tr>
<tr>
<td>Ar10</td>
<td>34</td>
<td>6.7</td>
<td>5.1</td>
<td>1.6</td>
<td>$12.0^{+2.6}_{-0.9}$</td>
<td>0.293</td>
<td>3</td>
</tr>
<tr>
<td>Combined</td>
<td>363</td>
<td>203.4</td>
<td>188.0</td>
<td>15.4</td>
<td>$11.0^{+1.0}_{-0.9}$</td>
<td>0.063</td>
<td>55</td>
</tr>
</tbody>
</table>

For all runs combined the best fit rate is $11.0^{+1.0/-0.9}$ atoms of $^{71}$Ge produced by the source at the reference time. The uncertainty is purely statistical and is given with 68% confidence.
Summary of the contributions to the systematic uncertainty in the measured neutrino capture rate.

The quadratic combination of all these systematic uncertainties is +5.2/-5.4%. The measured production rate in the $K$ and $L$ peaks, including both statistical and systematic errors, is thus

$$p_{\text{measured}} = 11.0 +1.0/-0.9 \text{ (stat)} \pm 0.6 \text{ (syst)}$$
37Ar as a calibration source for solar neutrino detectors

W. Haxton
Institute for Nuclear Theory, Department of Physics, FM-15, University of Washington, Seattle Washington 98195
(Received 18 July 1988; revised manuscript received 12 September 1988)

I discuss the possibility that a high-intensity 811-keV $^{37}$Ar neutrino source, produced by neutron capture on separated $^{36}$Ar, could be used to calibrate the $^7$Be solar neutrino capture cross sections of $^{71}$Ga, $^{127}$I, and other detectors...

The advantages of a $^{37}$Ar source compared to a $^{51}$Cr source

1. Practically free of radioactive impurities.
2. Half-life longer (35 d compared to 27 d).
3. The neutrino energy is greater (811 keV compared to 747 keV).
4. The decay is purely to the ground state (100% compared to 90%).
The total fast flux at this reactor is $2.3 \cdot 10^{15}$ neutrons/(cm$^2 \cdot$ s), of which $1.7 \cdot 10^{14}$ neutrons/(cm$^2 \cdot$ s) have energy above the 2 MeV threshold of the production reaction $^{40}\text{Ca}$(n, alpha) $^{37}\text{Ar}$.
Project:
“Calibration and testing of the technology for the preparation of an intense neutrino source based on $^{37}$Ar isotope as well as for the calibration of gallium detector of solar neutrinos”
Nineteen irradiation assemblies, each of which contained 17.3 kg of CaO (12.36 kg Ca), were placed in the blanket zone of the reactor.

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 and moved to a hot cell of BNPP where ampoules with irradiated target were taken out from assemblies and moved to extraction facility of the Institute of Nuclear Materials, where each ampoule was cut open in a vacuum system and the CaO dissolved in nitric acid.


37Ar was extracted from acid solution by a He purge and then stored on charcoal at LN2 temperature.

When the extractions from all the assemblies had been completed, the 37Ar was purified by flowing over zeolite at room temperature, followed by two Ti absorbers, operating at 400-450°C and 900-950°C. The purified 37Ar, whose volume was ~ 2.5 l, was then adsorbed on another charcoal trap 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-weighed source holder, which consisted of a stainless steel vessel with a volume of ~180 ml. Inside this vessel was 40 g of activated charcoal onto which the purified $^{37}\text{Ar}$ was cryopumped. When essentially all the $^{37}\text{Ar}$ had been adsorbed, the vessel was closed by compressing three separate knife-edge seals, two onto copper gaskets and one onto a lead gasket. The source holder was then weighed to determine the amount of $^{37}\text{Ar}$ 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. These procedures were completed on 29 April and the source was immediately flown by chartered plane to the Mineral Water airport, close to the experimental facility at the Baksan Neutrino Observatory in the northern Caucasus mountains.
Measurement of source activity

Summary of source strength measurements

Summary of different activity measurements. The stated uncertainty includes all known systematics.

<table>
<thead>
<tr>
<th>Measurement method</th>
<th>Activity (kCi $^{37}$Ar at 04:00 on 30 April 2004)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume of gas</td>
<td>$409 \pm 6$</td>
</tr>
<tr>
<td>Mass of gas</td>
<td>$412 \pm 4$</td>
</tr>
<tr>
<td>Calorimetry at Zarechny</td>
<td>$401 \pm 4$</td>
</tr>
<tr>
<td>Calorimetry at Baksan</td>
<td>$422 \pm 9$</td>
</tr>
<tr>
<td>Proportional counter</td>
<td>$405 \pm 4$</td>
</tr>
<tr>
<td>Isotopic dilution</td>
<td>$410 \pm 5$</td>
</tr>
</tbody>
</table>

The six completed activity measurements are given in the Table. These measurements are adopted in the weighted average, $409 \pm 2$ kCi.
**Predicted production rate**

\[ p = AD\langle L\rangle\sigma, \quad \langle L\rangle = \frac{1}{4\pi V_S} \int_{\text{absorber}} dV_A \int_{\text{source}} \frac{dV_S}{r_{SA}^2} \]

Values and uncertainties of the terms that enter the calculation of the predicted production rate. All uncertainties are symmetric except for the cross section.

<table>
<thead>
<tr>
<th>Term</th>
<th>Value</th>
<th>Uncertainty Magnitude</th>
<th>Uncertainty Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic density ( D = \rho N_0 f I / M )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \rho ) (g Ga/cm(^3)) [16]</td>
<td>6.095</td>
<td>0.002</td>
<td>0.033</td>
</tr>
<tr>
<td>Avogadro’s number ( N_0 ) (10(^{23}) atoms Ga/mol)</td>
<td>6.0221</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>(^{71})Ga isotopic abundance ( f_I ) (atoms (^{71})Ga/100 atoms Ga)[17]</td>
<td>39.8921</td>
<td>0.0062</td>
<td>0.016</td>
</tr>
<tr>
<td>( M ) (g Ga/mol) [17]</td>
<td>69.72307</td>
<td>0.00013</td>
<td>0.0002</td>
</tr>
<tr>
<td>Atomic density ( D ) (10(^{22}) atoms (^{71})Ga/cm(^3))</td>
<td>2.1001</td>
<td>0.0008</td>
<td>0.037</td>
</tr>
<tr>
<td>Source activity at reference time ( A ) (10(^{16}) (^{37})Ar decays/s)</td>
<td>1.513</td>
<td>0.011</td>
<td>0.7</td>
</tr>
<tr>
<td>Cross section ( \sigma ) [10^{-46} \text{cm}^2/(^{71}\text{Ga atom} (^{37})\text{Ar decay})] [6]</td>
<td>70.0</td>
<td>+4.9, -2.1</td>
<td>+7.0, -3.0</td>
</tr>
<tr>
<td>Path length in Ga ( \langle L\rangle ) (cm)</td>
<td>72.6</td>
<td>0.2</td>
<td>0.28</td>
</tr>
<tr>
<td>Predicted production rate ( ^{71}\text{Ge atoms/d} )</td>
<td>13.9</td>
<td>+1.0, -0.4</td>
<td>+7.0, -3.1</td>
</tr>
</tbody>
</table>

Assuming a source activity of 409 ± 2 kCi, and combining the uncertainty terms in quadrature, the predicted production rate is thus

\[ p_{\text{predicted}} = 13.9 \, +1.0/\ -0.4 \, \text{atoms of} \, ^{71}\text{Ge produced per day}. \]
Upper panel: comparison of measured total production rate for each extraction with predicted rate.

Lower panel: measured rates from the $^{37}$Ar source extrapolated back to the start of the first extraction. The combined results for events in the the $L$- and $K$- peaks and for all events are shown separately at the right and compared to the predicted rate.

\[
\frac{P_{\text{measured}}}{P_{\text{predicted}}} = \frac{11.0^{+1.0}_{-0.9} \text{ (stat)} \pm 0.6 \text{ (syst)}}{13.9^{+1.0}_{-0.4}} = 0.79^{+0.09}_{-0.10}
\]
Comparison of source experiments with Ga

<table>
<thead>
<tr>
<th>Item</th>
<th>GALLEX Cr1[2, 3]</th>
<th>GALLEX Cr2 [2,3]</th>
<th>SAGE $^{51}$Cr [1]</th>
<th>SAGE $^{37}$Ar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source production</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass of reactor target (kg)</td>
<td>35.5</td>
<td>35.6</td>
<td>0.512</td>
<td>330</td>
</tr>
<tr>
<td>Target isotopic purity</td>
<td>38.6% $^{50}$Cr</td>
<td>38.6% $^{50}$Cr</td>
<td>92.4% $^{50}$Cr</td>
<td>96.94% $^{40}$Ca</td>
</tr>
<tr>
<td>Source activity (kCi)</td>
<td>1714 $^{+30/-43}$</td>
<td>1868 $^{+89/-57}$</td>
<td>516.6 $^{±6.0}$</td>
<td>409 $^{±2}$</td>
</tr>
<tr>
<td>Specific activity (kCi/g)</td>
<td>0.048</td>
<td>0.052</td>
<td>1.01</td>
<td>92.7</td>
</tr>
<tr>
<td>Gallium exposure</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gallium mass (tones)</td>
<td>30.4 (GaCl$_3$:HCl)</td>
<td>30.4 (GaCl$_3$:HCl)</td>
<td>13.1 (Ga metal)</td>
<td>13.1 (Ga metal)</td>
</tr>
<tr>
<td>Gallium density ($10^{21}$ 71Ga/cm$^3$)</td>
<td>1.946</td>
<td>1.946</td>
<td>21.001</td>
<td>21.001</td>
</tr>
<tr>
<td>Measured production rate $\rho$ ($^{71}$Ge/d)</td>
<td>11.9 $^{±1.1}$ $±0.7$</td>
<td>10.7 $^{±1.2}$ $±0.7$</td>
<td>14.0 $^{±1.5}$ $±0.8$</td>
<td>11.0 $^{±1.0}$ $^{±0.9}$ $±0.6$</td>
</tr>
<tr>
<td>$R$ = $P$(measured)/$P$(predicted)</td>
<td>1.00 $^{+0.11/-0.10}$</td>
<td>0.81 $±0.10$</td>
<td>0.95 $±0.12$</td>
<td>0.79 $^{±0.09/-0.10}$</td>
</tr>
</tbody>
</table>

The weighted average value of $R$, the ratio of measured to predicted $^{71}$Ge production rates, is $0.88 \pm 0.05$, more than two standard deviations less than unity.
Conclusions

■ Prototype $^{37}\text{Ar}$ neutrino source with strength of $409 \pm 2$ kCi was produced by irradiating 330 kg of CaO in the fast neutron breeder reactor BN-600 (Zarechny, Russia).

■ It is shown that $^{37}\text{Ar}$ source with strength of 2.0 – 2.5 Mci can be produced in BN-600 reactor.

■ Several techniques for source intensity measurement were developed.

■ Ten irradiations of 13 tonnes of gallium metal were made

\[ R = \frac{P(\text{measured})}{P(\text{predicted})} = 0.79 \pm 0.09/-0.10 \]

Since other our experiments have given us great confidence in our knowledge of the various efficiencies in the SAGE detector, we conclude: the source experiments with Ga should be considered to be a determination of the neutrino capture cross section.
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 of engineers for BN-600 conclude that sources in the range 2.0–2.5 MCi 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.
Zatsepin has chosen a mountain Andyrchi in Baksan Valley in the Northern Caucasus. It was the cheapest way that best of all fit to build the laboratory.
Grigori Domogatskiy is a Head of Baikal Neutrino Observatory.

Olga Ryazhskaya is now a leader of a well-known Italian-Russian LVD program.

Ludmila Volkova
Cosmic ray muons and atmospheric neutrinos

Stanislav Mikheev

Alexey Smirnov

\[ ^{71}\text{Ga} + \nu \rightarrow ^{71}\text{Ge} + e^- \]
Vadim Kouzmine, 1965

- 427 KeV $\nu$ (9.0%)
- 432 KeV $\nu$ (0.9%)
- 320 KeV $\gamma$
- 747 KeV $\nu$ (81.6%)
- 752 KeV $\nu$ (8.5%)
- $^{51}\text{Cr}$ (27.7 days)

EC

M S W effect