BNO INR RAS
V.N. Gavrin

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**

Бруно Понтекорво

available, so that the requirement is of importance in a neutrino experiment.

5. The background, (i.e., the production of element Z ± 1 by other causes than the inverse β process), must be as small as possible.

An Example

“ 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 $10^{10} cm^{-2} sec^{-1}$. The neutrinos emitted by the sun, however, are not very energetic. The use of high intensity piles permits two possible strong neutrino sources.”

B. PO

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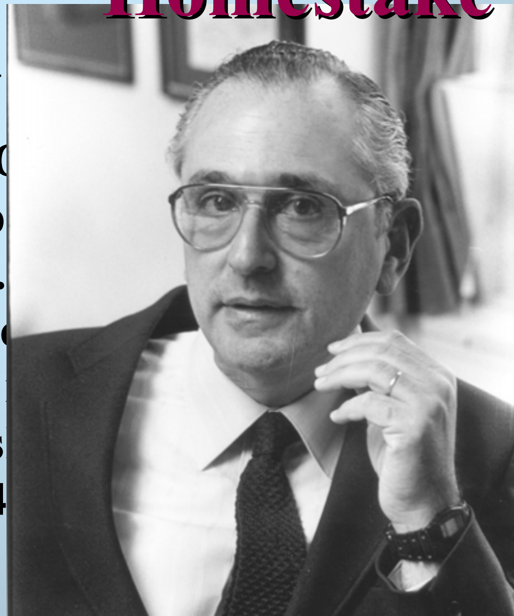
background, is fulfilled.

Causes other than inverse β processes capable of producing the radio element looked for are:

(a) (np) processes and Nuclear Explosions. The production of background by (np) process against the nucleus bombarded is zero, if the particular inverse β process selected involves the

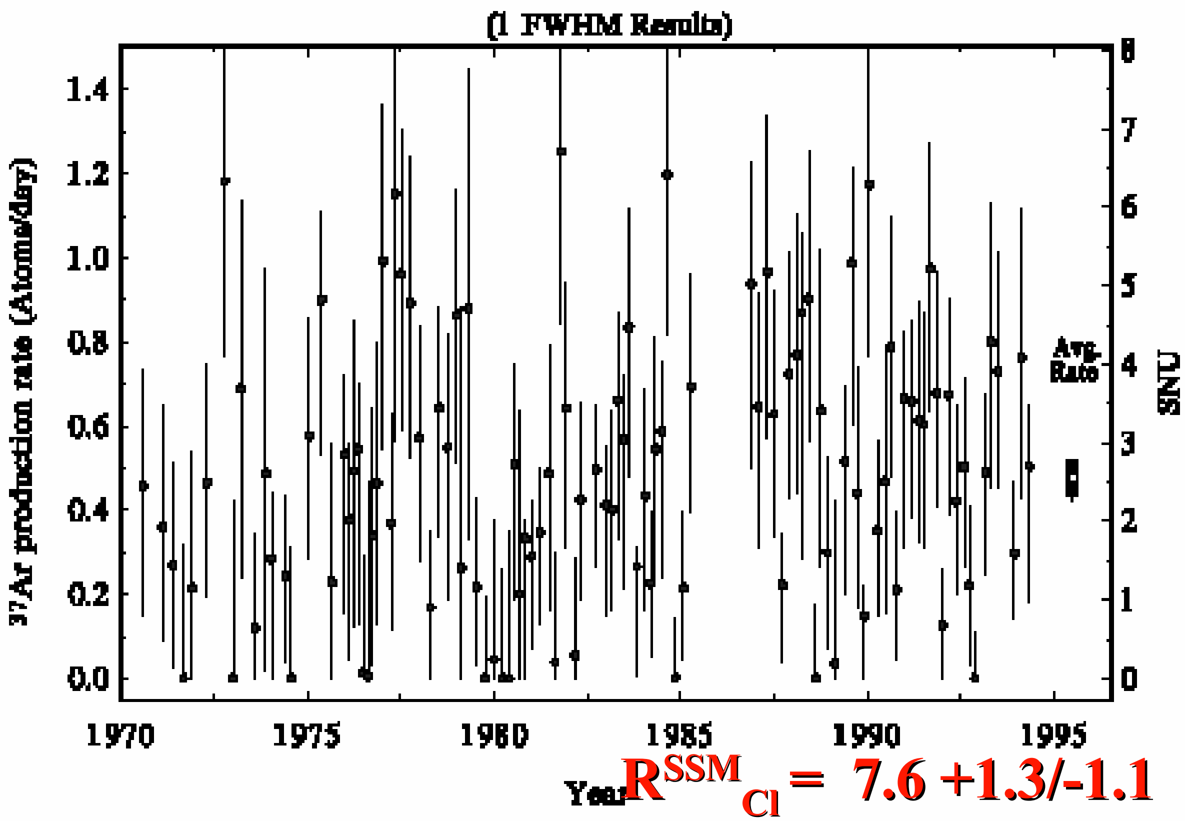
Homestake Radiochemical experiment

$\nu_e + {}^{37}Cl$ ->

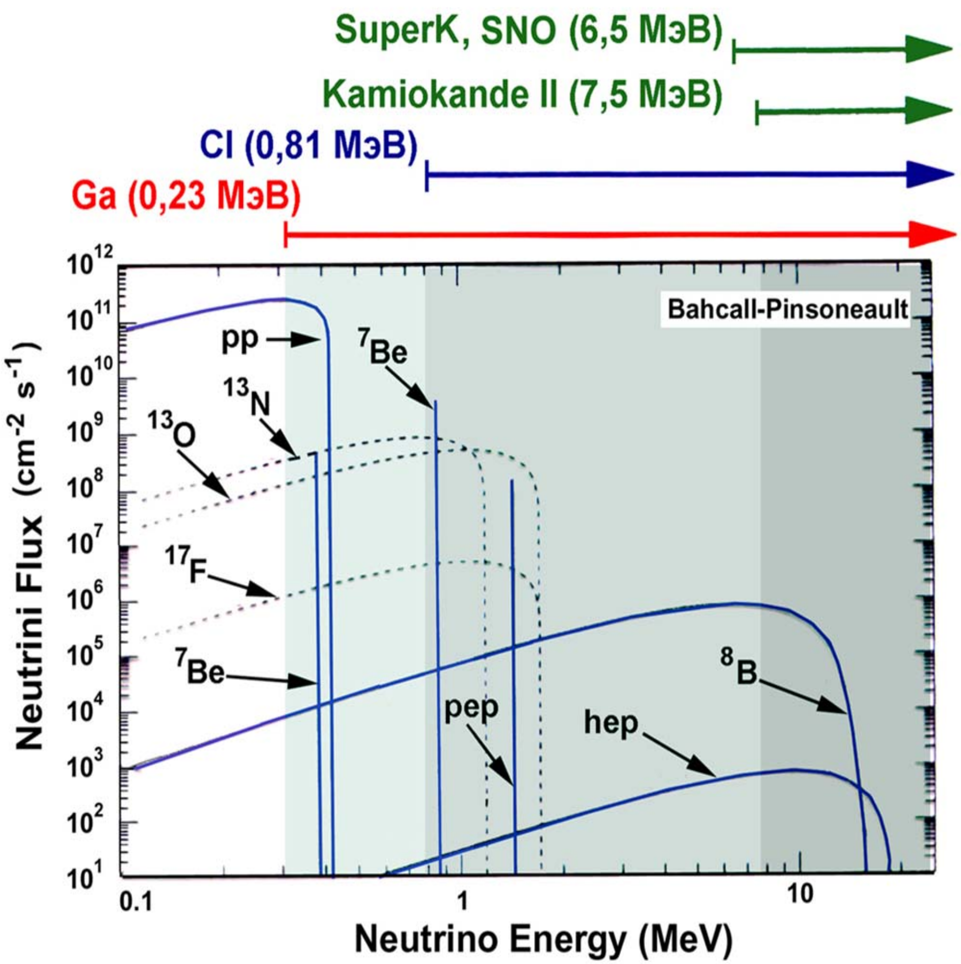


Homestake ... Dakota, USA)
1478 m deep ... m^{-2} day^{-1}
steel tank, 6. ... g ($6x10^5$ liters)
615 tons of t...
(C_2Cl_4), 2.16 ... tons)
energy thres...
E^{Cl}_{th} = 0.814 ...
data taking: ... s

R^{exp}_{Cl} = 2.56 ± 0.16 ± 0.16 SNU = 2.56 ± 0.23 SNU



R^{SSM}_{Cl} = 7.6 +1.3/-1.1 SNU



- 1 SNU = 1 interaction/sec in a target that contains 10^{36} atoms of the neutrino absorbing isotope.

1986-1995

$\nu + e^- \rightarrow \nu + e^-$

Kamiokande II

$$R_{KII} = \frac{\Phi\ \text{measured}}{\Phi\ \text{predicted}} = 0.54 \pm 0.08/^{+0.10}_{-0.07}$$

Paradox: $R_{Cl}(^8B + ^7Be) - R_{KII}(^8B) \sim 0$ (~15%)

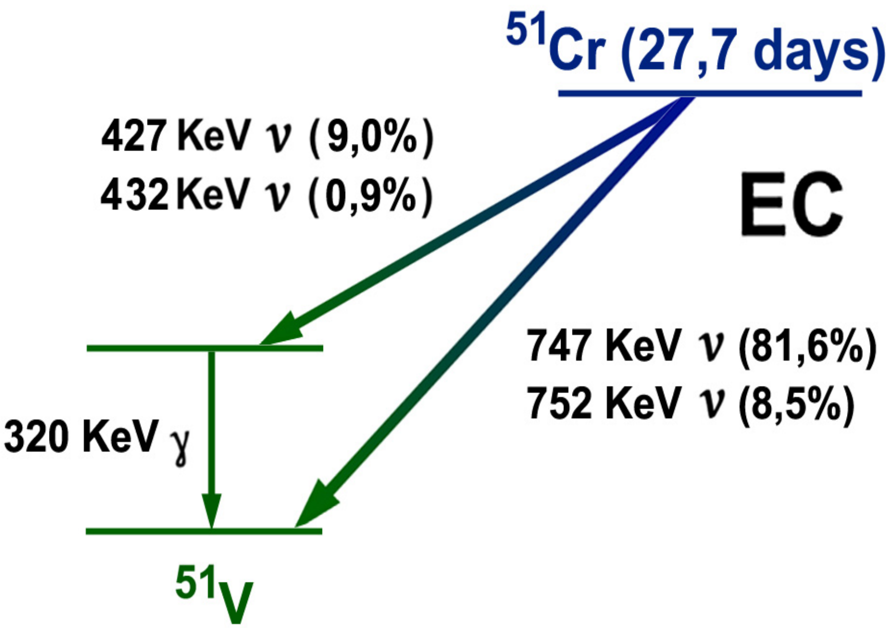
$$^{71}Ga + \nu \rightarrow {}^{71}Ge + e^-$$

Q = 233,2 keV

$T_{1/2}$ = 11,43 d

Vadim Kuzmin

Decay Scheme of Cr-51



Vadim Kuzmin proposed a radio-chemical gallium detector and artificial ^{51}Cr neutrino source for it's 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}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.

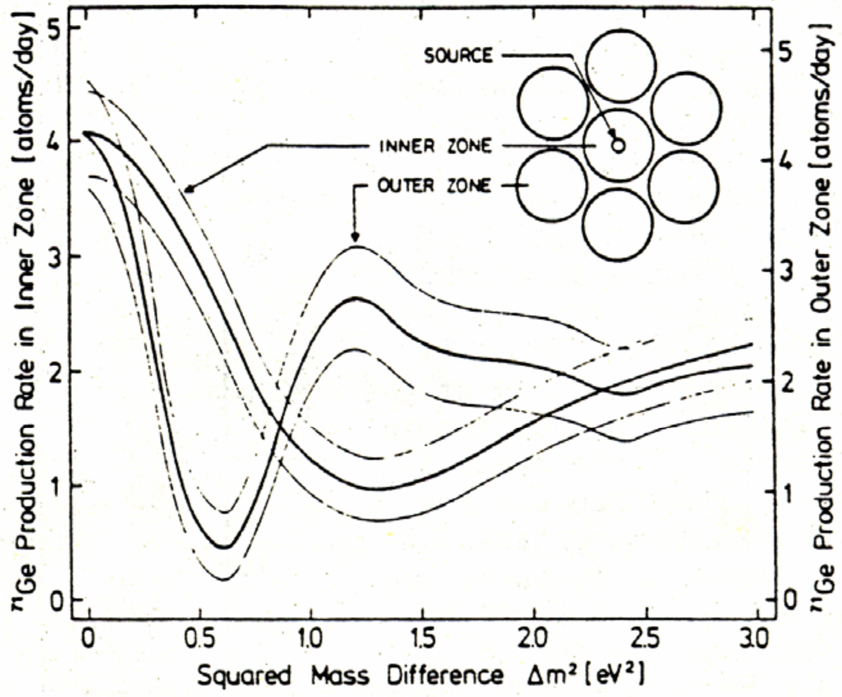
5. Weizmann Institute of Science:

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*

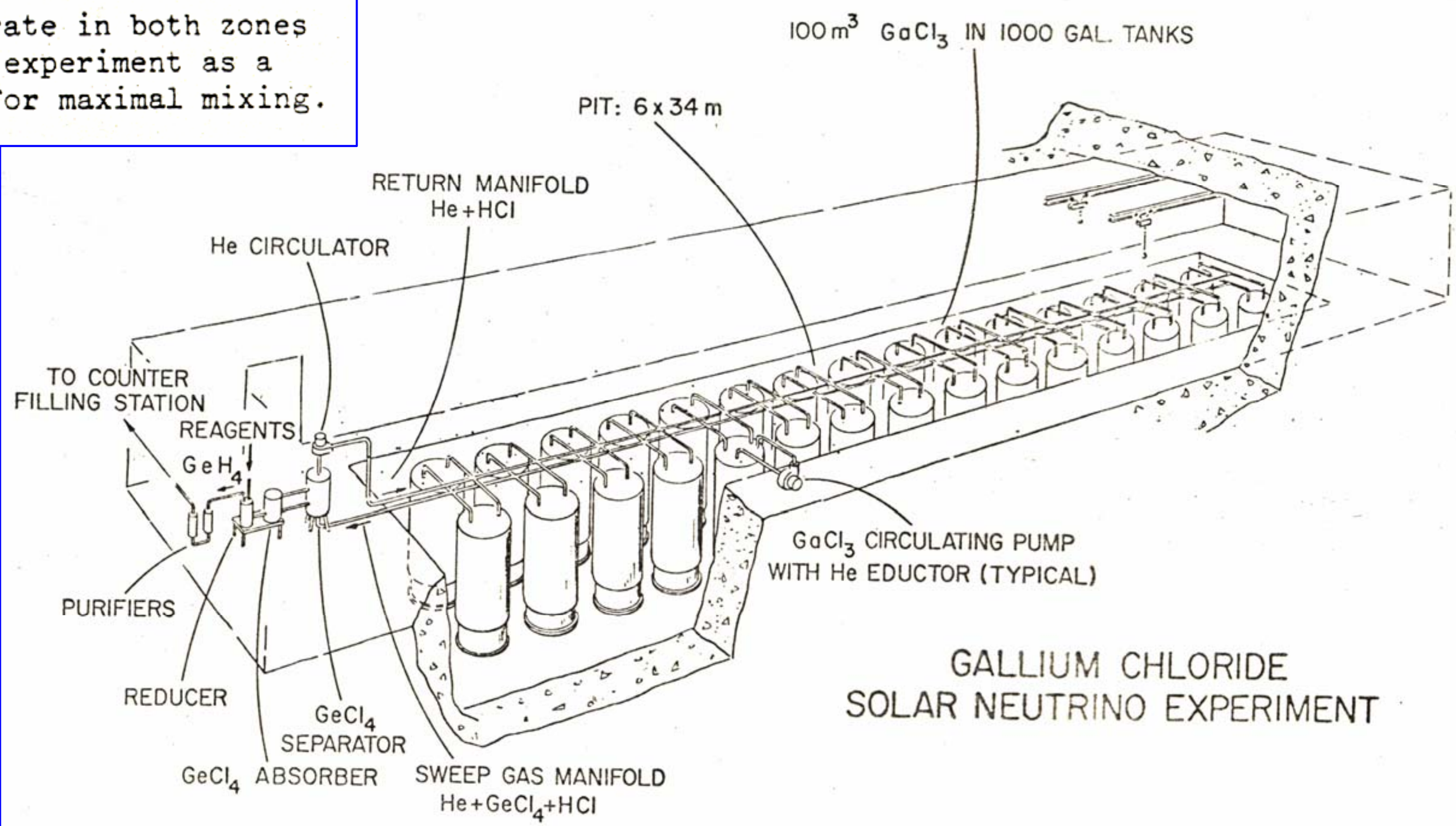
September 1978



^{71}Ge production rate in both zones of a ^{51}Cr source experiment as a function of Δm^2 for maximal mixing.

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}Ge from many tons of metallic gallium.

The SAGE Collaboration

Measurement of the Solar Neutrino Capture Rate with gallium metal

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SAGE: Soviet-American Gallium Experiment

Baksan Neutrino Observatory, northern Caucasus, 3.5 km from entrance of horizontal adit
50 tons of metallic ^{71}Ga, 2000 m deep, 4700 m.w.e. => $\Phi\mu \sim 2.6\ m^{-2}\ day^{-1}$
data taking: Jan 1990-Dec 2005, 145 runs, running

$R^{SAGE}_{Ga} = 66.5^{+3.5}_{-3.4}\ ^{+3.5}_{-3.2}$ SNU $= 66.5\ ^{+4.9}_{-4.7}$ 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

$R^{GALLEX}_{Ga} = 77.5 \pm 6.2\ ^{+4.3}_{-4.7}$ SNU $= 77.5\ ^{+7.6}_{-7.8}$ SNU

GNO: Gallium Neutrino Observatory

Successor of GALLEX, GNO30: 30.3 tons of gallium
data taking: May 1998 - Sep 2003, 58 runs

$R^{GNO}_{Ga} = 62.9\ ^{+5.5}/_{-5.3} \pm 2.5$ SNU $= 62.9\ ^{+6.0}_{-5.9}$ SNU

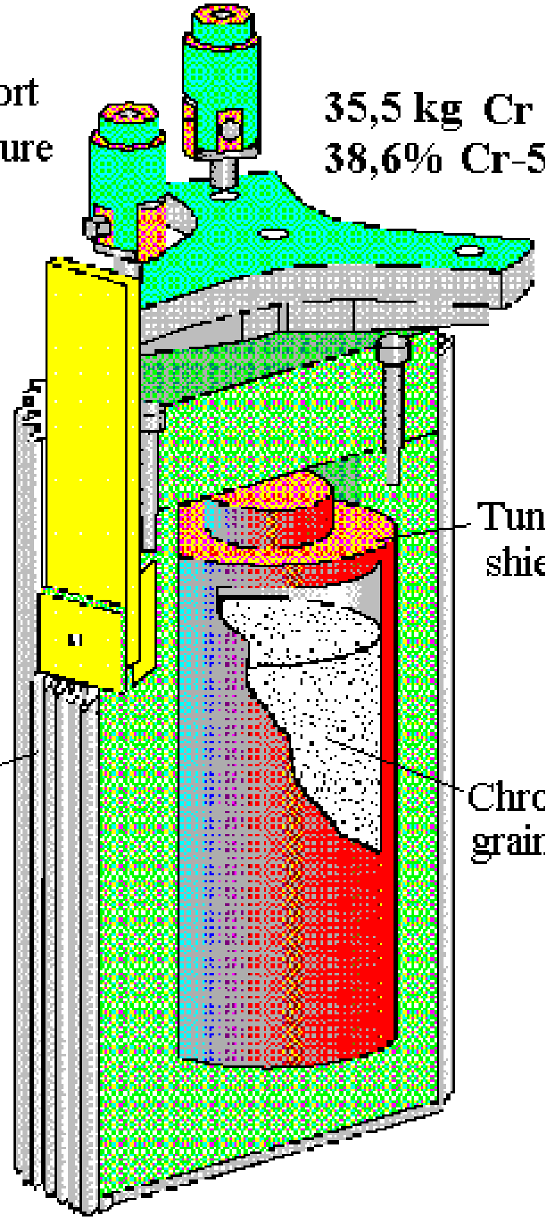
GALLEX + GNO => $R^{GALLEX+GNO}_{Ga} = 69.3 \pm 4.1 \pm 3.6$ SNU $= 69.3 \pm 5.5$ SNU

Gallium Experiments: SAGE, GALLEX, GNO

Radiochemical experiments
$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$
threshold $E^{Ga}_{th} = 0.233$ MeV => all ν fluxes (*pp*, ^{7}Be, ^{8}B, *pep, hep,* ^{13}N, ^{15}O, ^{17}F)

SAGE + GALLEX + GNO => $R^{exp}_{Ga} = 67.7 \pm 3.6$ SNU

Standard Solar Model => $R^{SSM}_{Ga} = 128\ ^{+9}_{-7}$ SNU



GALLEX ^{51}Cr source results

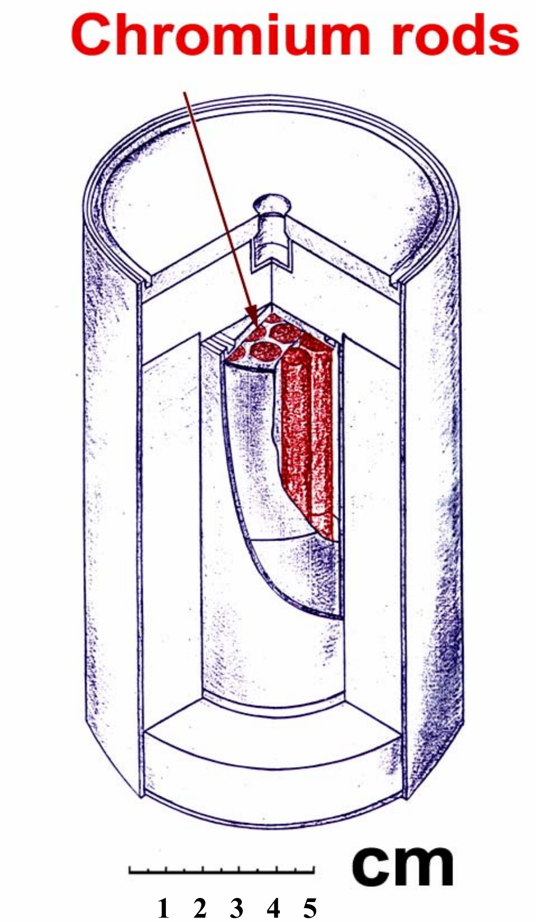
Source 1

exposure time	Jun 1994 – Oct 1994
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

exposure time	Oct 1995 – Feb 1996
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



517 kCi source of ^{51}Cr was produced by irradiation **512.7 g** of 92,4%-enriched ^{50}Cr in high-flux fast neutron reactor.

SAGE ^{51}Cr source result

exposure time	Dec 1994 – May 1995
source activity	0.517 +/- 0.007 MCi
expected rate	14.9 +/- 0.2 ^{71}Ge at/day

Ratio R $0.95^{+0.11}_{-0.10}{}^{+0,06}_{-0,05}$

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 ○1.2)%

THE *pp* NEUTRINO FLUX

$$R = \int_{E_{threshold}}^{\infty} \sigma(E)\Phi^{\odot}(E)dE$$ **- total capture rate in radiochemical experiment**

$$\Phi^{\odot}(E) = \sum_i \phi_i^{\odot} S_i^{\odot}(E)$$ **- total flux of electron neutrinos at the Earth**

i refers to the ***pp***, **^{7}Be**, ***pep***, **CNO**, **^{8}B** and ***hep***

$\phi_i^{\odot}$ - amplitude of flux component ***i*** at the Earth

$S_i^{\odot}$ - spectrum of the ***i***-th neutrino component at the Earth

$$\int_0^{\infty} S_i^{\odot}(E)(E)dE = 1 \qquad S_i^{\odot}(E) = A_i S_i^{\odot}(E) P_i^{ee}(E) \rightarrow A_i = 1/\left\langle P_i^{ee} \right\rangle \qquad P_i^{ee}$$ - survival factor

$$\left\langle P_i^{ee} \right\rangle = \int_0^{\infty} S_i^{\odot}(E) P_i^{ee}(E)dE$$ - spectrum-weighted average of P_i^{ee}

$$R_i = \frac{\phi_i^{\odot}\left\langle \sigma_i \right\rangle}{\left\langle P_i^{ee} \right\rangle} \qquad \left\langle \sigma_i \right\rangle = \int_{E_{threshold}}^{\infty} \sigma(E) S_i^{\odot}(E) P_i^{ee}(E)dE$$

The values of $\left\langle P_i^{ee} \right\rangle$ and $\left\langle \sigma_i \right\rangle$ for each component are calculated for three neutrino mixing with parameters

$\Delta m_{12}^2 = (7.92 \pm 0.36) \times 10^{-5}$ eV^2 $\quad \theta_{12} = 34^{+1.7}_{-1..5} \quad \theta_{13} = 5.44^{+2.79}_{-5.44}$

G. L. Fogli at al Prog. in Part. and Nucl. Phys. (in press) [arXiv: hep-ph/0506083].

Exp.	Spectrum component	$\langle P_i^{ee}\rangle$	$\langle\sigma_i^{\odot}\rangle$ (10^{-46} cm^2)	Percent uncertainty in $\langle\sigma_i^{\odot}\rangle$ due to σ	Δm^2_{12}	θ_{12}	θ_{13}	Total unc. in $\langle\sigma_i^{\odot}\rangle$ (%)
^{71}Ga	*pp*	0.555	11.76	+ 2.3,- 2.2	+ 0.0,- 0.0	+ 0.0,- 0.0	+ 0.0,- 0.0	+ 2.3,- 2.2
	pep	0.517	204.0	+17 ,- 7.0	+ 0.0,- 0.0	+ 0.0,- 0.0	+ 0.0,- 0.0	+17 ,- 7.0
	^{7}Be	0.537	71.87	+ 7.5,- 3.1	+ 0.0,- 0.0	+ 0.0,- 0.0	+ 0.0,- 0.0	+ 7.5,- 3.1
	^{13}N	0.539	59.84	+ 8.1,- 3.0	+ 0.0,- 0.0	+ 0.1,- 0.0	+ 0.0,- 0.0	+ 8.1,- 3.0
	^{15}O	0.531	112.2	+13 ,- 4.1	+ 0.1,- 0.1	+ 0.1,- 0.1	+ 0.0,- 0.0	+13 ,- 4.1
	^{17}F	0.531	112.9	+13 ,- 4.2	+ 0.1,- 0.1	+ 0.1,- 0.1	+ 0.0,- 0.0	+13 ,- 4.2
	^{8}B	0.374	21800	+32 ,-15	+ 0.3,- 0.2	+ 2.5,- 2.5	+ 0.0,- 0.1	+32 ,-16
	hep	0.347	66970	+33 ,-16	+ 0.3,- 0.3	+ 1.6,- 1.7	+ 0.1,- 0.1	+33 ,-16
^{37}Cl	*pep*	0.517	16.00	+ 2.0,- 2.0	+ 0.0,- 0.0	+ 0.0,- 0.0	+ 0.0,- 0.0	+ 2.0,- 2.0
	^{7}Be	0.535	2.400	+ 2.0,- 2.0	+ 0.0,- 0.0	+ 0.0,- 0.0	+ 0.0,- 0.0	+ 2.0,- 2.0
	^{13}N	0.539	1.651	+ 2.0,- 2.0	+ 0.1,- 0.1	+ 0.2,- 0.1	+ 0.0,- 0.0	+ 2.0,- 2.0
	^{15}O	0.531	6.665	+ 2.0,- 2.0	+ 0.1,- 0.1	+ 0.2,- 0.1	+ 0.0,- 0.0	+ 2.0,- 2.0
	^{17}F	0.531	6.716	+ 2.0,- 2.0	+ 0.1,- 0.1	+ 0.2,- 0.1	+ 0.0,- 0.0	+ 2.0,- 2.0
	^{8}B	0.374	10230	+ 3.7,- 3.7	+ 0.3,- 0.3	+ 2.8,- 2.8	+ 0.1,- 0.1	+ 4.6,- 4.6
	hep	0.347	41110	+ 3.7,- 3.7	+ 0.3,- 0.3	+ 1.8,- 1.8	+ 0.1,- 0.1	+ 4.1,- 4.1

[*pp*+^{7}Be+CNO+*pep*+^{8}B|Ga] = ***67.7 ± 3.6 SNU***

from **268** solar neutrino extractions in the SAGE and GALLEX/GNO experiments

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

[*pp*+^{7}Be+CNO+*pep*|Ga] = $64.0^{+3.7}_{-3.3}$ SNU

[^{7}Be+CNO+*pep*+^{8}B|Cl] = 2.56 ± 0.23 SNU [^{8}B|Cl] = 1.72 ± 0.14 SNU →

[^{7}Be+CNO+*pep*|Cl] = 0.84 ± 0.27 SNU

[^{7}Be+CNO+*pep*|Ga] = [^{7}Be+CNO+*pep*|Cl] × $\sigma(\nu_{^7Be},Ga)/\sigma(\nu_{^7Be},Cl)$ = $25.1^{+8.2}_{-8.1}$ SNU

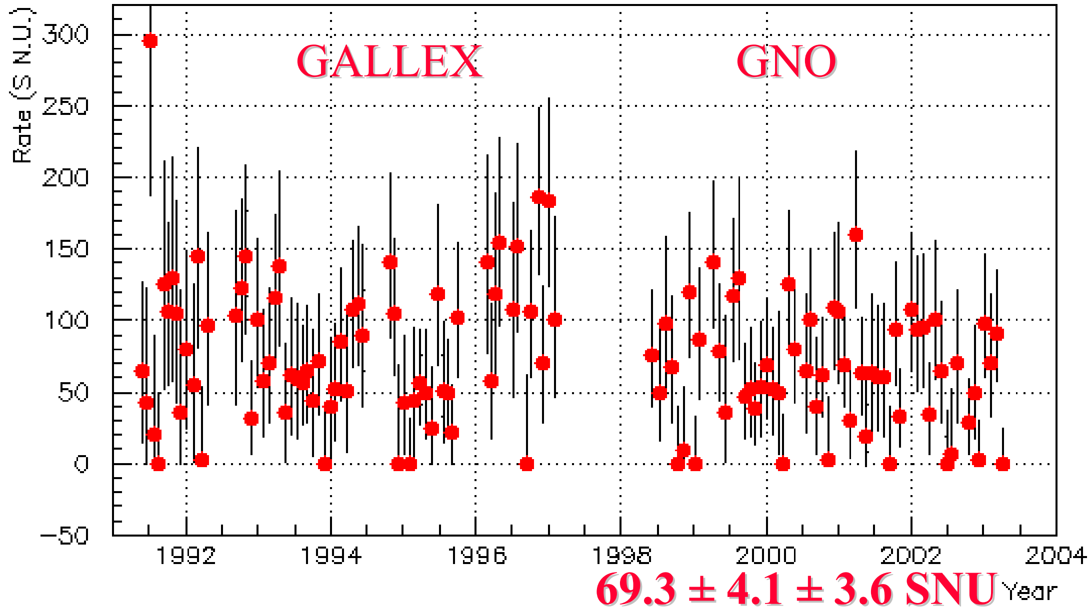
[^{7}Be+CNO+*pep*|Ga] = $25.1^{+8.6}_{-8.4}$ SNU

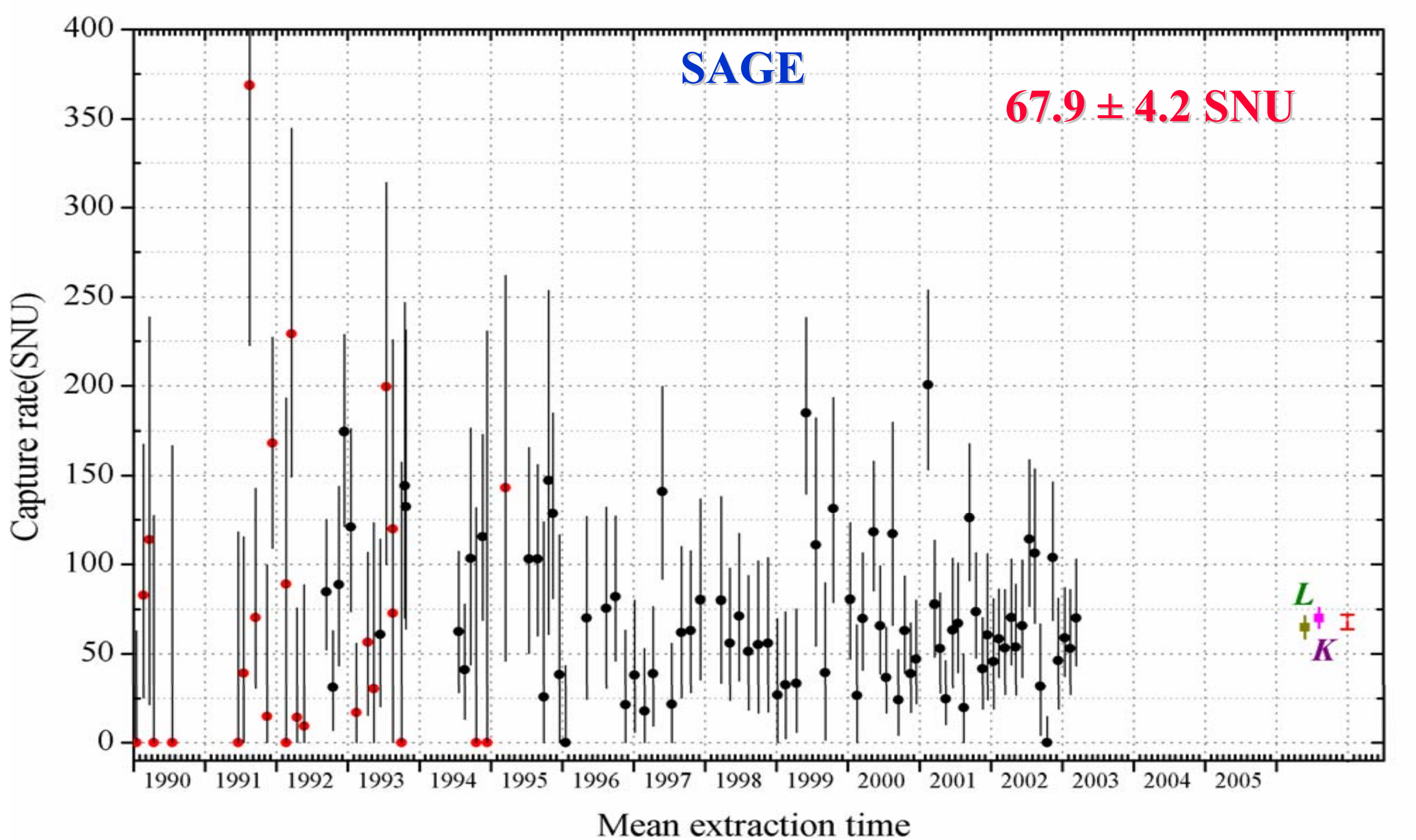
[*pp*|Ga] = [*pp*+^{7}Be+CNO+*pep*|Ga] - [^{7}Be+CNO+*pep*|Ga] = $38.1^{+8.9}_{-9.1}$ SNU →

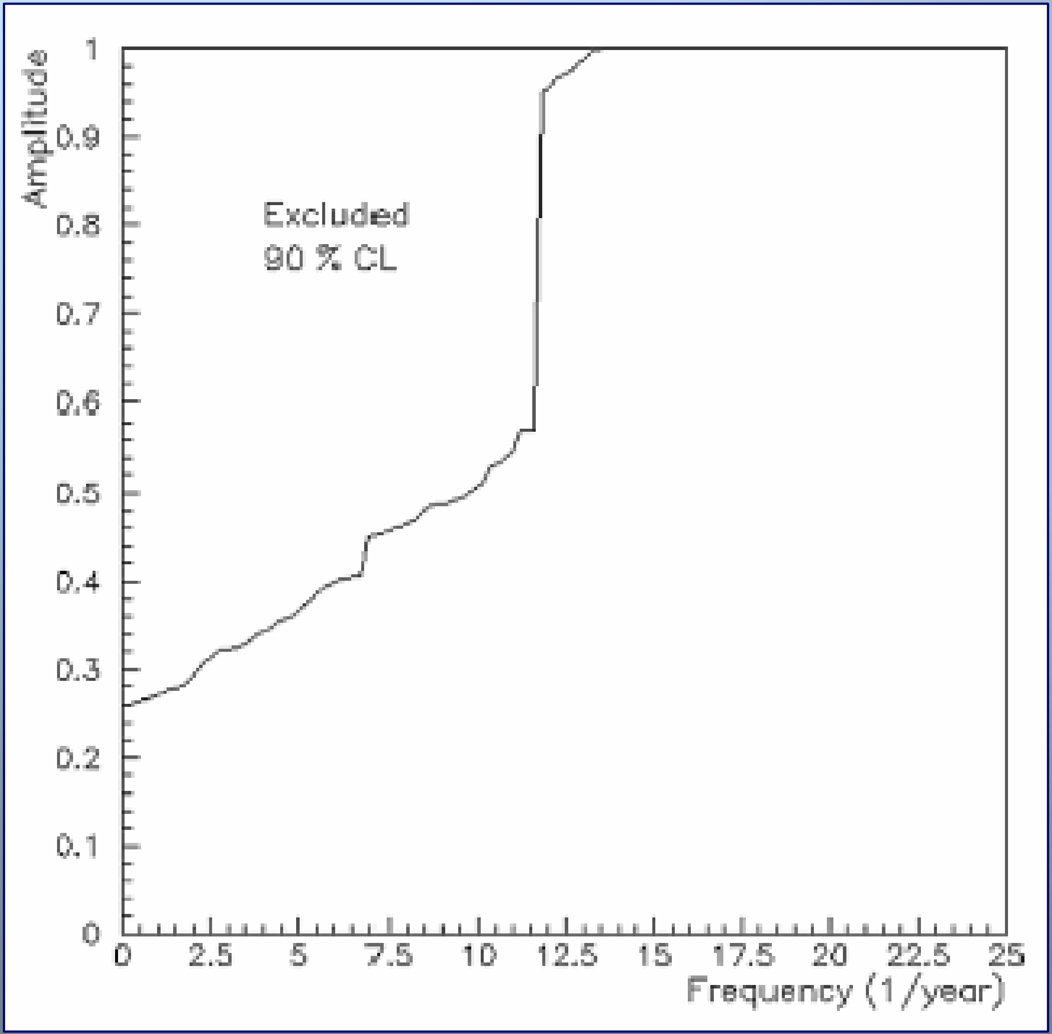
the measured electron neutrino ***pp*** flux at Earth of $(3.23^{+0.76}_{-0.78}) \times 10^{10}/(\text{cm}^2\text{-s})$

$(5.94 \pm 0.06) \times 10^{10}/(\text{cm}^2\text{-s})$ (SSM) $\times(\langle P_i^{ee}\rangle = \mathbf{0.555})$ = $(3.30 \pm 0.07) \times 10^{10}/(\text{cm}^2\text{-s})$

Excellent agreement

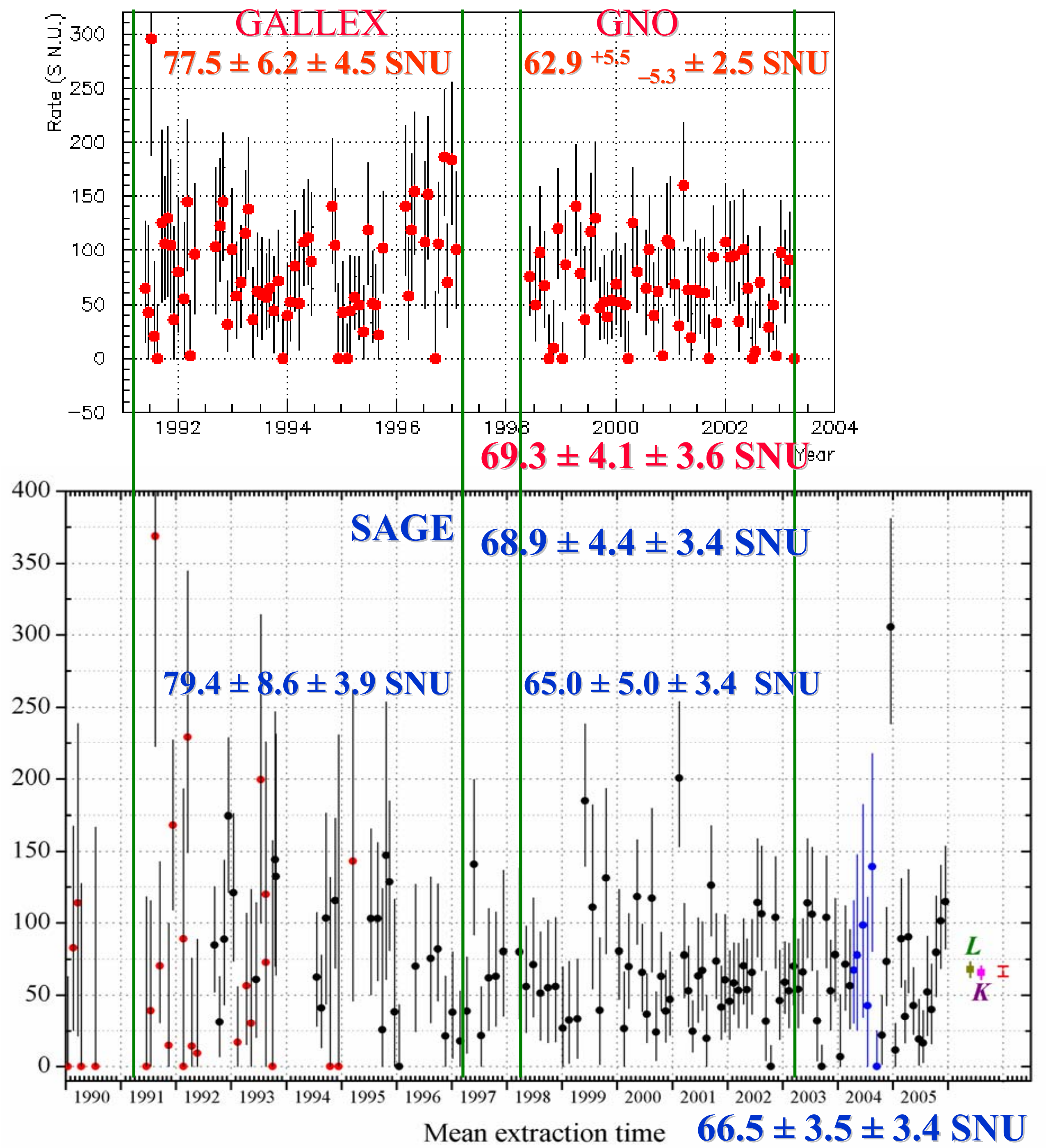

GALLEX
GNO
Rate (S N.U.)
Year
69.3 ± 4.1 ± 3.6 SNU


SAGE
67.9 ± 4.2 SNU
Capture rate(SNU)
Mean extraction time
L
K



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

L. Pandola,
hep-ph/0406248

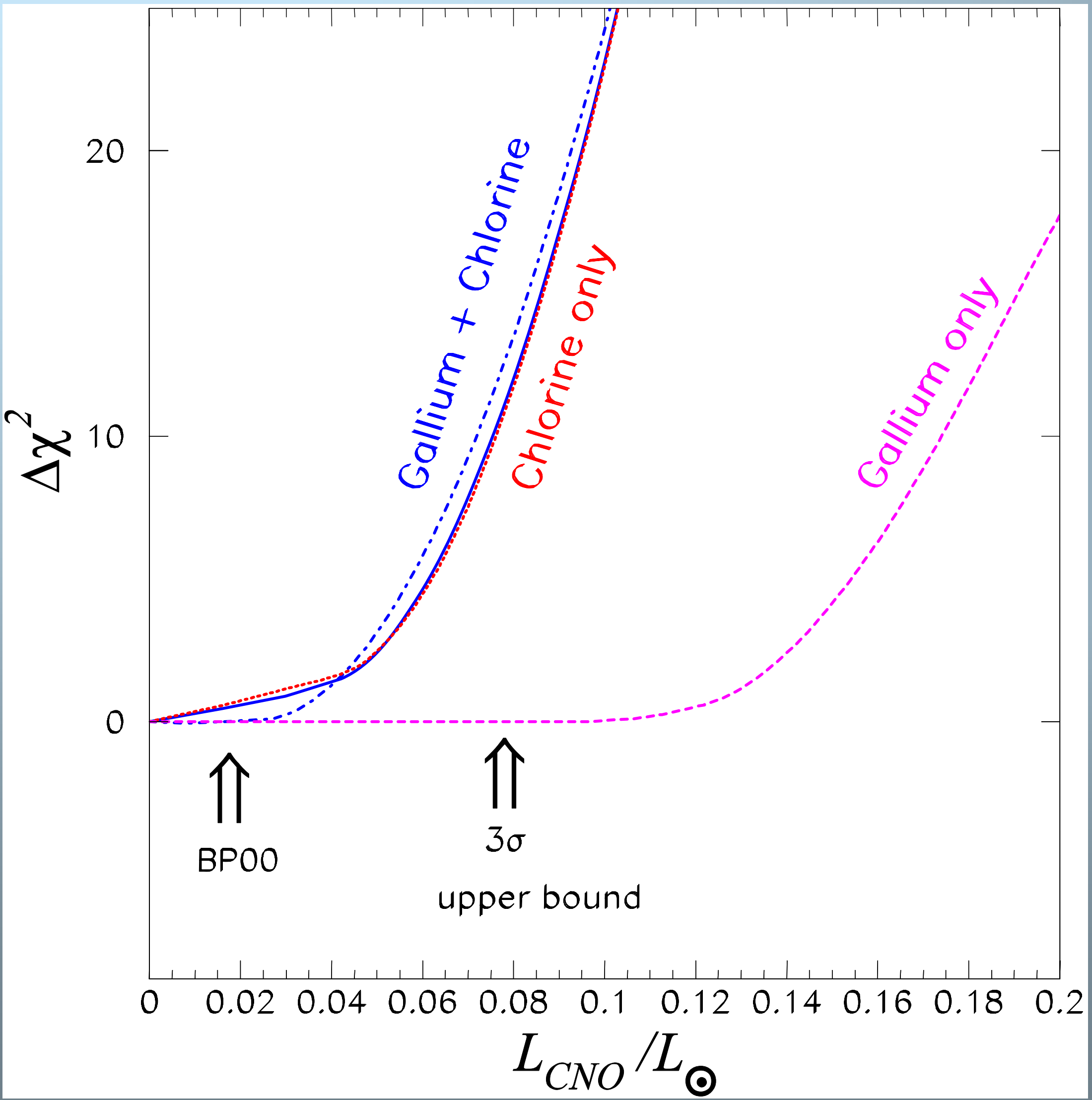


GALLEX
77.5 ± 6.2 ± 4.5 SNU
GNO
62.9 +5.5 −5.3 ± 2.5 SNU
Rate (S.N.U.)
Year
69.3 ± 4.1 ± 3.6 SNU
SAGE
68.9 ± 4.4 ± 3.4 SNU
79.4 ± 8.6 ± 3.9 SNU
65.0 ± 5.0 ± 3.4 SNU
L
K
Mean extraction time
66.5 ± 3.5 ± 3.4 SNU

Time period	05/14/91-01/23/97	05/20/98-04/09/03	05/14/91- 4/09/03	Full data set 01/90-12/05
Number runs	65	58	123	
GALLEX/GNO	$77.5 \pm 6.2\ ^{+4.3}_{-4.7}$	$62.9\ ^{+5.5}_{-5.3} \pm 2.5$	$69.3 \pm 4.1 \pm 3.6$	–
	$77.5\ ^{+7.6}_{-7.8}$	$62.9\ ^{+6.0}_{-5.9}$	69.3 ± 5.5	
Number runs	45	49	94	145
SAGE	$79.4\ ^{+8.8}_{-8.4} \pm 3.9$	$65.0\ ^{+5.1}_{-4.9} \pm 3.4$	$68.9\ ^{+4.5}_{-4.3} \pm 3.4$	$66.5\ ^{+3.5}_{-3.4}\ ^{+3.5}_{-3.2}$
	$79.4\ ^{+9.6}_{-9.3}$	$65.0\ ^{+6.1}_{-6.0}$	$68.9\ ^{+5.6}_{-5.5}$	$66.5\ ^{+4.9}_{-4.7}$
Number runs	(110)	(107)	(217)	(268)
SAGE+GALLEX/GNO	78.3 ± 5.9	63.9 ± 4.2	69.1 ± 3.9	67.7 ± 3.6

Gallium Rate (SNU)	63.3 ± 3.6	68.1 ± 3.75	77.8 ± 5.0
$\Delta m^2_{21} (10^{-5}\ \mathrm{eV}^2)$	$8.2^{+0.3}_{-0.3}\ (^{+1.0}_{-0.8})$	$8.2^{+0.3}_{-0.3}\ (^{+1.0}_{-0.8})$	$8.2^{+0.3}_{-0.3}\ (^{+1.0}_{-0.8})$
$\tan^2\theta_{12}$	$0.39^{+0.05}_{-0.04}\ (^{+0.19}_{-0.11})$	$0.39^{+0.05}_{-0.04}\ (^{+0.19}_{-0.11})$	$0.38^{+0.05}_{-0.05}\ (^{+0.21}_{-0.11})$
$p-p$	$1.03^{+0.02}_{-0.02}\ (^{+0.05}_{-0.07})$	$1.01^{+0.02}_{-0.02}\ (^{+0.06}_{-0.06})$	$0.99^{+0.02}_{-0.02}\ (^{+0.07}_{-0.06})$
^{8}B	$0.87^{+0.04}_{-0.04}\ (^{+0.09}_{-0.11})$	$0.87^{+0.04}_{-0.04}\ (^{+0.09}_{-0.11})$	$0.88^{+0.04}_{-0.04}\ (^{+0.09}_{-0.12})$
^{7}Be	$0.25^{+0.85}_{-0.25}\ (^{+1.37}_{-0.25})$	$1.03^{+0.24}_{-1.03}\ (^{+0.77}_{-1.03})$	$1.29^{+0.26}_{-0.57}\ (^{+0.74}_{-1.29})$

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,
Phys. Rev. Let. V90(13),2003

BNO INR RAS
V.N. Gavrin

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

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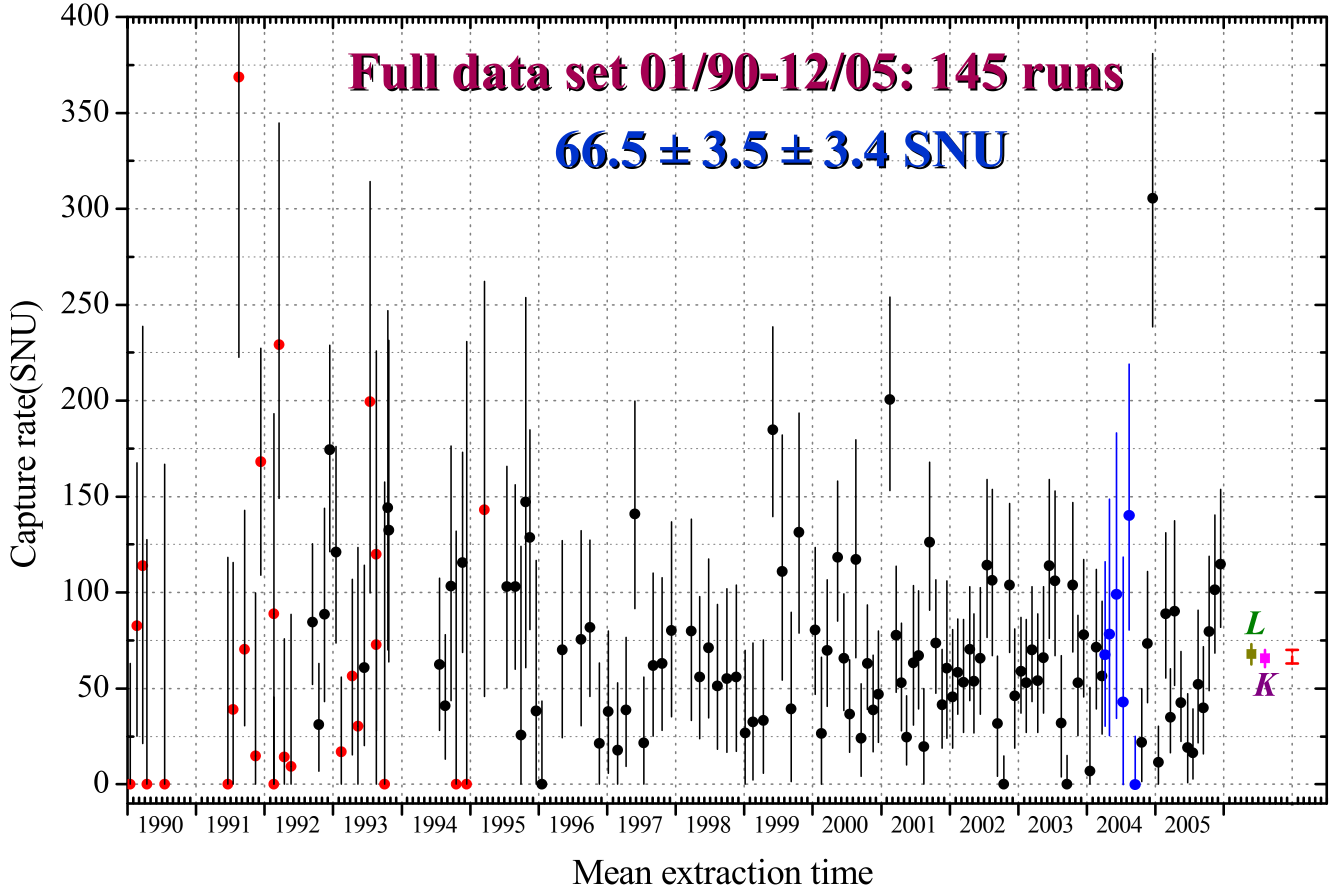
[c]Los Alamos National Laboratory, Los Alamos, NM 87545 USA
[d]Max-Planck-Institut f ̈ur Kernphysik (MPIK), Postfach 103980, D-69029 Heidelberg, Germany
[e]National Institute of Standards and Technology, Gaithersburg, MD 20899 USA
[f]Dipartimento di Fisica, Universit`a di Milano 'La Bicocca' e INFN, Sezione di Milano, Via Emanueli, I-20126 Milano, Italy
[g]Department of Physics, University of Washington, Seattle, WA 98195 USA

Extraction name	Extraction date (2004)	Exposure time Begin	Exposure time End	Mass Ga (tonnes)	^{76}Ge carrier mass (mkmol)	Added nat. Ge std.sol. (mkmol)	Extraction eff. extr.	Extraction eff. GeH_4
7R1044=S001	22 Apr	90.16	113.76	48.287	3.50	7.95	0.65	0.63
3R1054=S002	16 May	114.18	137.58	22.028	3.62	7.95	0.92	0.88
3R1064=S003	24 Jun	137.89	176.39	22.001	3.74	7.68	0.92	0.89
3R1074=S004	25 Jul	182.46	207.36	21.953	3.50	7.68	0.98	0.96
3R1084=S005	23 Aug	207.53	236.83	21.929	3.55	7.68	1.01	0.91
7R1094=S006	25 Sep	236.95	269.85	42.420	8.07	3.29	0.76	0.75

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.

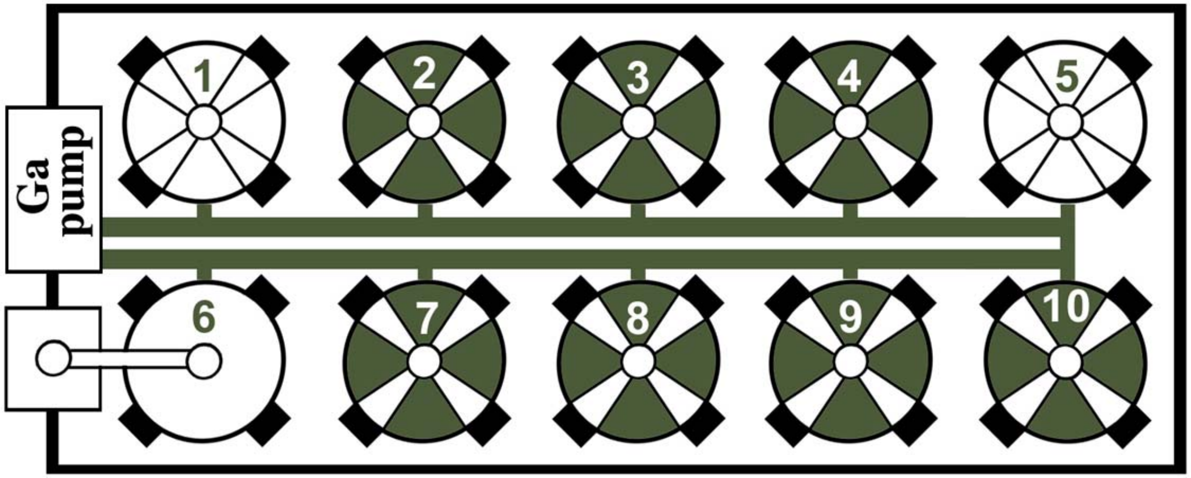
SAGE

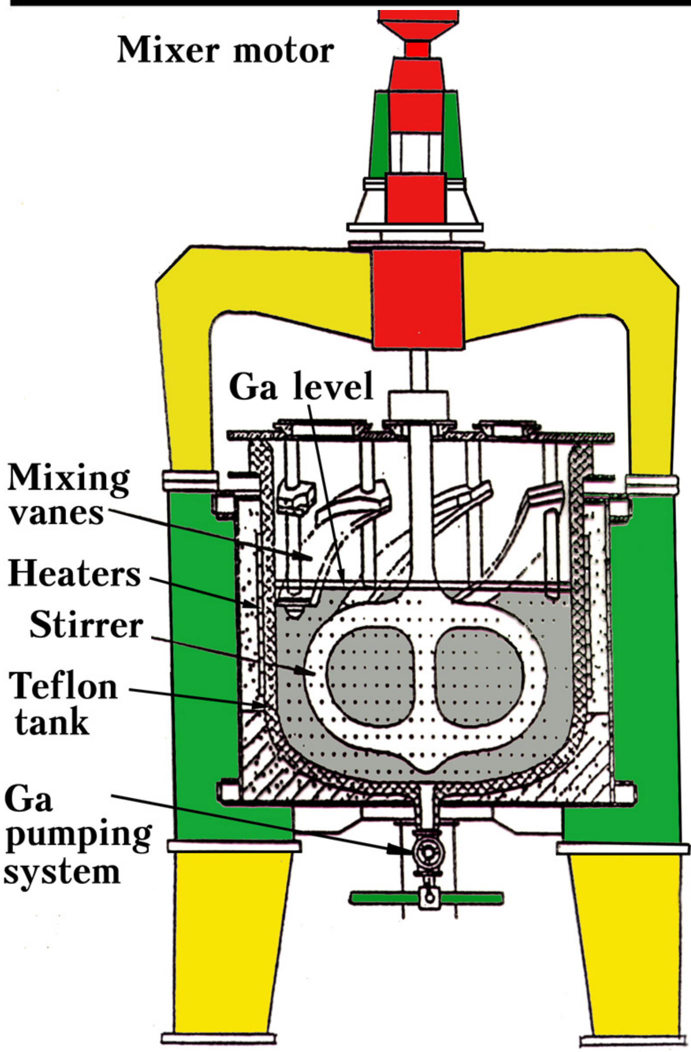

Full data set 01/90-12/05: 145 runs
66.5 ± 3.5 ± 3.4 SNU
Capture rate(SNU)
400
350
300
250
200
150
100
50
0
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
L
K
Mean extraction time

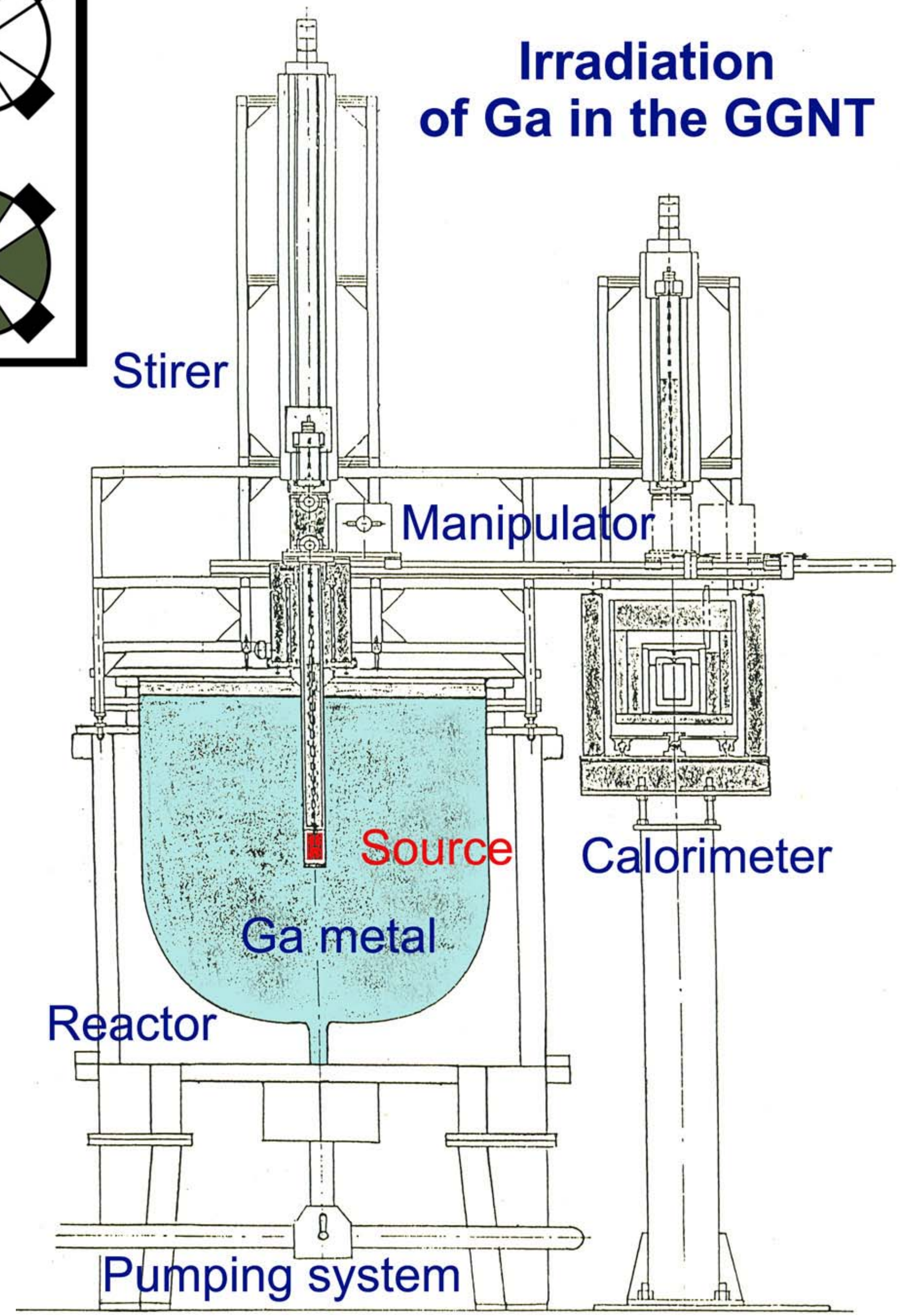
Measurement of the response of a Ga solar neutrino experiment to neutrino from an ^{37}Ar source

Physical Review C73, 045805 (2006)

Irradiation of Ga in the GGNT







Extraction schedule and related parameters

The times of exposure are given in days of year 2004

Extraction name	Extraction date (2004)	Source exposure Begin	Source exposure End	Solar neutrino exposure Begin	Solar neutrino exposure End	Mass Ga (tones)	Carrier mass (mg)	Extraction efficiency from Ga into GeH4 (1)	Extraction efficiency from Ga into GeH4 (2)
Ar 1	6 May	121.17	127.71	118.48	127.78	13.085	0.0	0.93	0.59
Ar 2	14 May	128.42	135.71	125.38	135.78	13.084	2.15	0.96	0.93
Ar 3	29 May	136.42	150.71	133.51	150.81	13.063	2.11	0.93	0.90
Ar 3-2	30 May	136.42	150.71	150.91	151.81	13.049	2.74	0.93	0.87
Ar 4	13 Jun	151.42	165.71	147.47	165.77	13.055	2.08	0.97	0.92
Ar 5	28 Jun	166.40	180.71	162.47	180.77	13.018	2.10	0.98	0.97
Ar 6	13 Jul	181.42	195.71	173.57	195.77	13.025	2.19	0.98	0.97
Ar 7	28 Jul	196.42	210.71	193.49	210.79	12.974	2.15	0.98	0.97
Ar 8	12 Aug	211.42	225.71	208.48	225.78	12.997	2.09	0.98	0.96
Ar 9	27 Aug	226.42	240.71	223.47	240.77	12.945	2.14	0.98	0.96
Ar10	11 Sep	241.42	255.71	238.38	255.78	12.969	2.11	0.98	0.96

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.

Extraction name	Number of candidate events	Number fit to ^{71}Ge	Number of events assigned to ^{37}Ar source production	Number of events assigned to Solar ν production	^{71}Ge production rate by ^{37}Ar source (atoms/day)	Nw^2	Probability (percent)
Ar 1	28	20.1	19.4	0.7	$10.3^{+3.2}_{-2.8}$	0.065	60
Ar 2	48	29.9	28.7	1.2	$10.5^{+2.5}_{-2.2}$	0.048	73
Ar 3	69	52.9	51.3	1.6	$14.5^{+2.3}_{-2.1}$	0.110	35
Ar 3-2	13	2.4	2.3	0.1	$0.8^{+1.0}_{-0.8}$	0.273	7
Ar 4	45	25.4	23.8	1.6	$9.5^{+2.4}_{-2.2}$	0.142	13
Ar 5	38	25.6	23.8	1.8	$11.5^{+2.9}_{-2.6}$	0.108	29
Ar 6	34	11.6	9.7	1.9	$6.5^{+3.2}_{-2.7}$	0.042	81
Ar 7	18	8.4	6.7	1.7	$6.1^{+3.3}_{-2.7}$	0.079	43
Ar 8	29	12.8	11.2	1.6	$14.5^{+6.3}_{-5.5}$	0.055	68
Ar 9	20	9.0	7.3	1.7	$12.1^{+6.6}_{-6.1}$	0.068	58
Ar10	34	6.7	5.1	1.6	$12.0^{+9.1}_{-7.3}$	0.293	3
Combined	363	203.4	188.0	15.4	$11.0^{+1.0}_{-0.9}$	0.063	55

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.

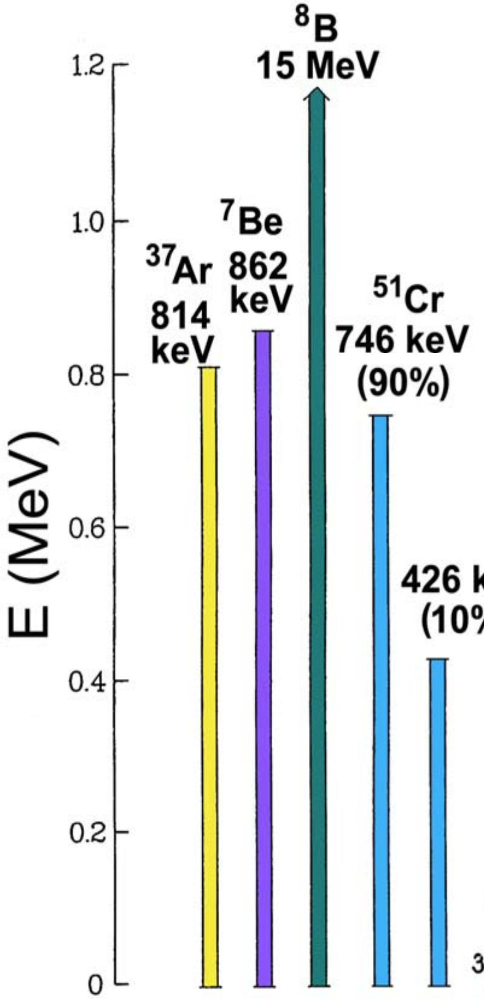
Origin of uncertainty	Uncertainty (%)
Chemical extraction efficiency	
Mass of added Ge carrier	2.1
Amount of Ge extracted	3.5
Carrier carryover	0.5
Mass of gallium	0.5
Chemical extraction subtotal	4.1
Counting efficiency	
Calculated efficiency	
Volume efficiency	0.5
Peak efficiency	2.5
Simulations to adjust for counter filling	1.7
Calibration statistics	
Centroid	0.1
Resolution	0.3
Rise time cut	0.6
Gain variations	+0.5
Counting efficiency subtotal	+3.2, −3.1
Residual radon after time cuts	−1.7
Solar neutrino background	0.4
^{71}Ge carryover	0.0
Total systematic uncertainty	+5.2, −5.4

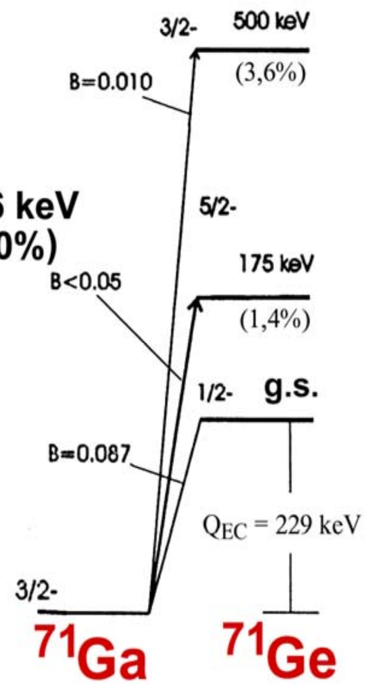
Summary of the contributions to the systematic uncertainty in the measured neutrino capture rate.

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

$$p_{measured} = $$
$$= 11.0 \; +1.0/-0.9 \text{ (stat)} \pm 0.6 \text{ (syst)}$$

PHYSICAL REVIEW C VOLUME 38, NUMBER 5 NOVEMBER 1988





^{37}Ar as a calibration source for solar neutrino detectors

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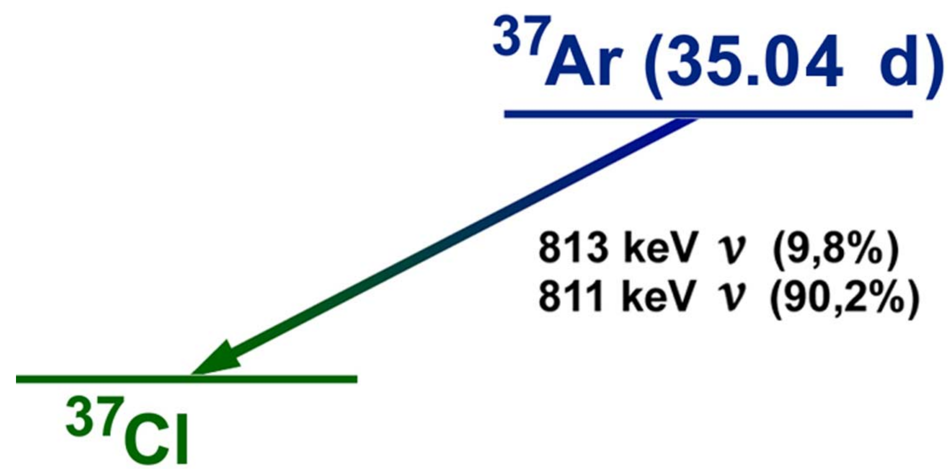
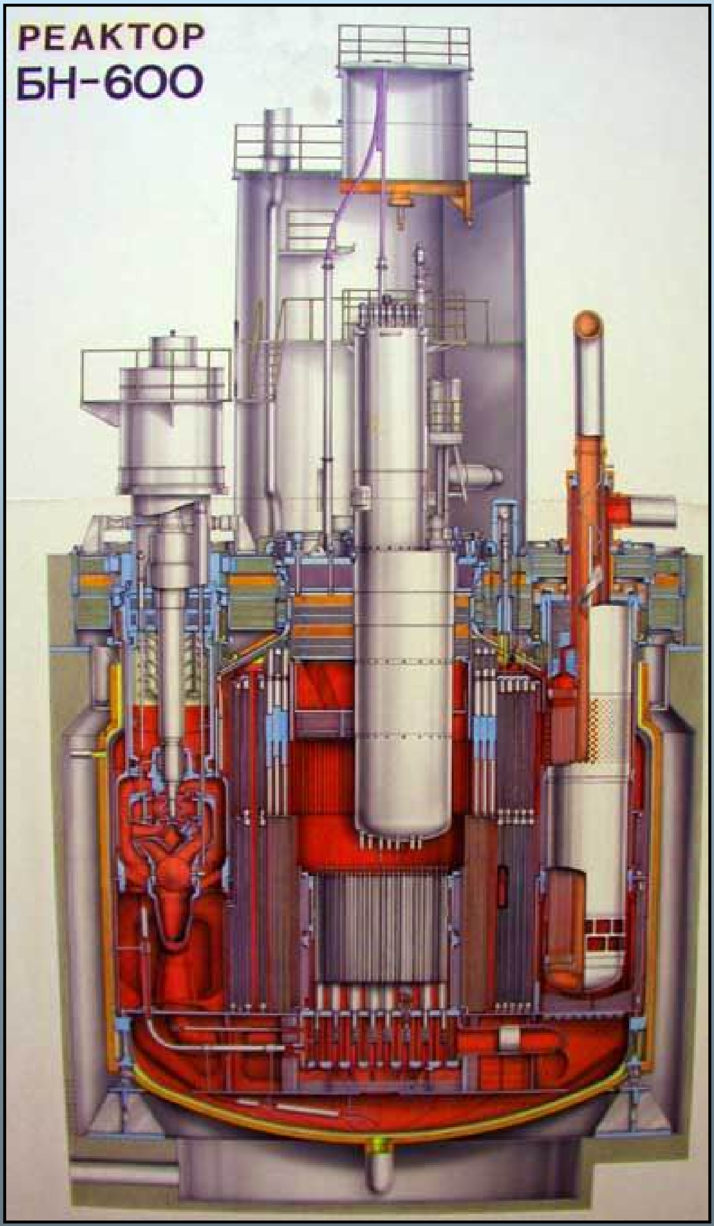
(Received 18 July 1988; revised manuscript received 12 September 1988)

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…

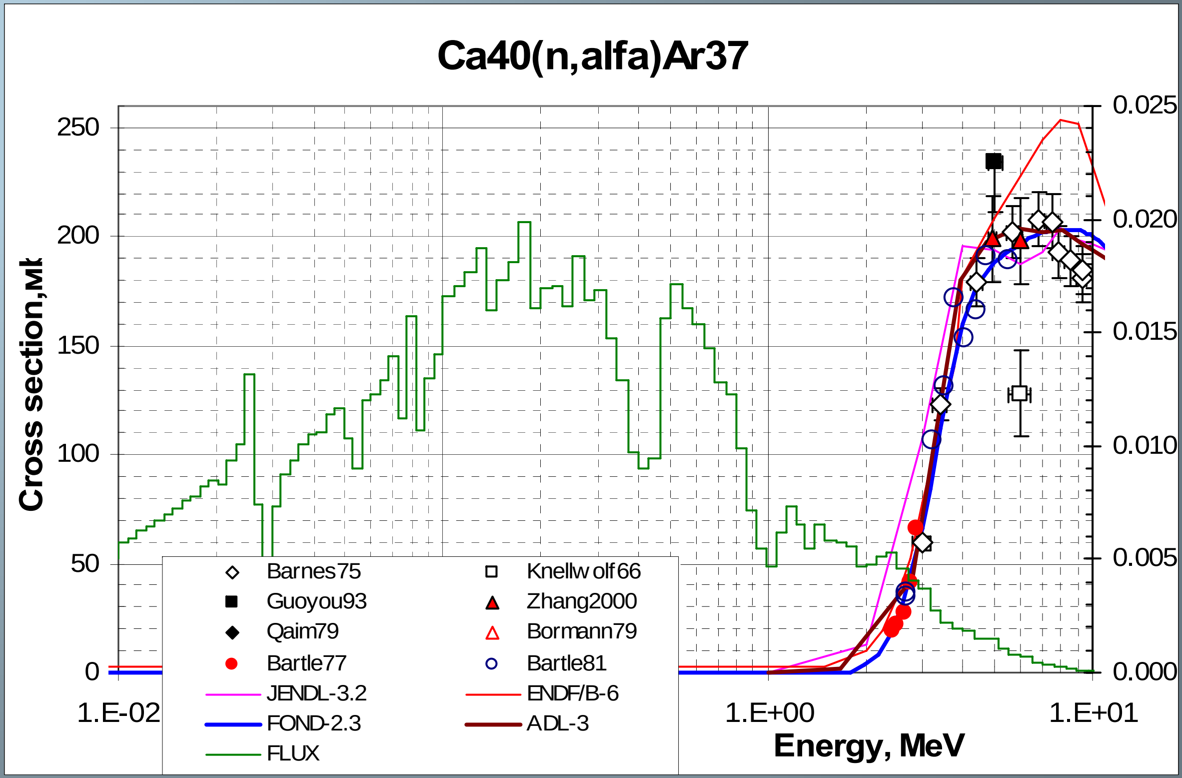


The advantages of a ^{37}Ar source compared to a ^{51}Cr source

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%).



^{37}Ar production cross-section



The total fast flux at this reactor is 2.3 · 10^{15} neutrons/(cm^2 · s), of which 1,7 · 10^{14} neutrons/(cm^2 · s) have energy above the 2 MeV threshold of the production reaction ^{40}Ca (n, alpha) ^{37}Ar.

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, V. A. Matveev, I.N. Mirmov, A. A. Shikhin, E.P. Veretenkin, V. M. Vermul, V. E. Yants, and G. T. Zatsepin
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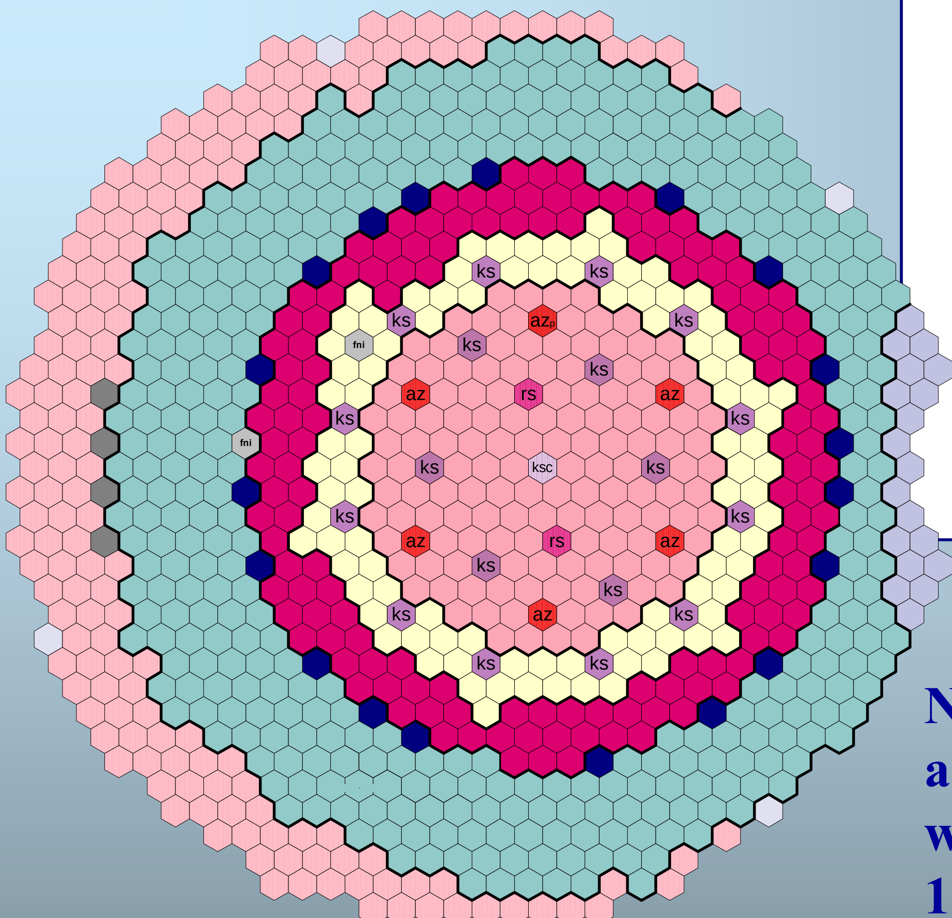
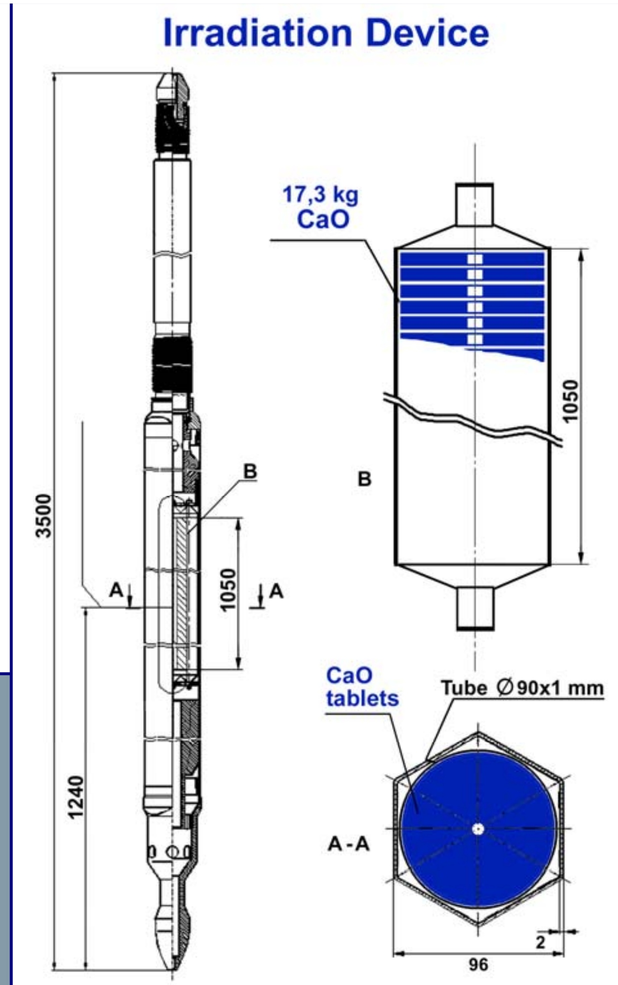
Institute of Nuclear Materials, Zarechny 624250, Sverdlovsk region, Russia

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"

Map of BN-600 Reactor

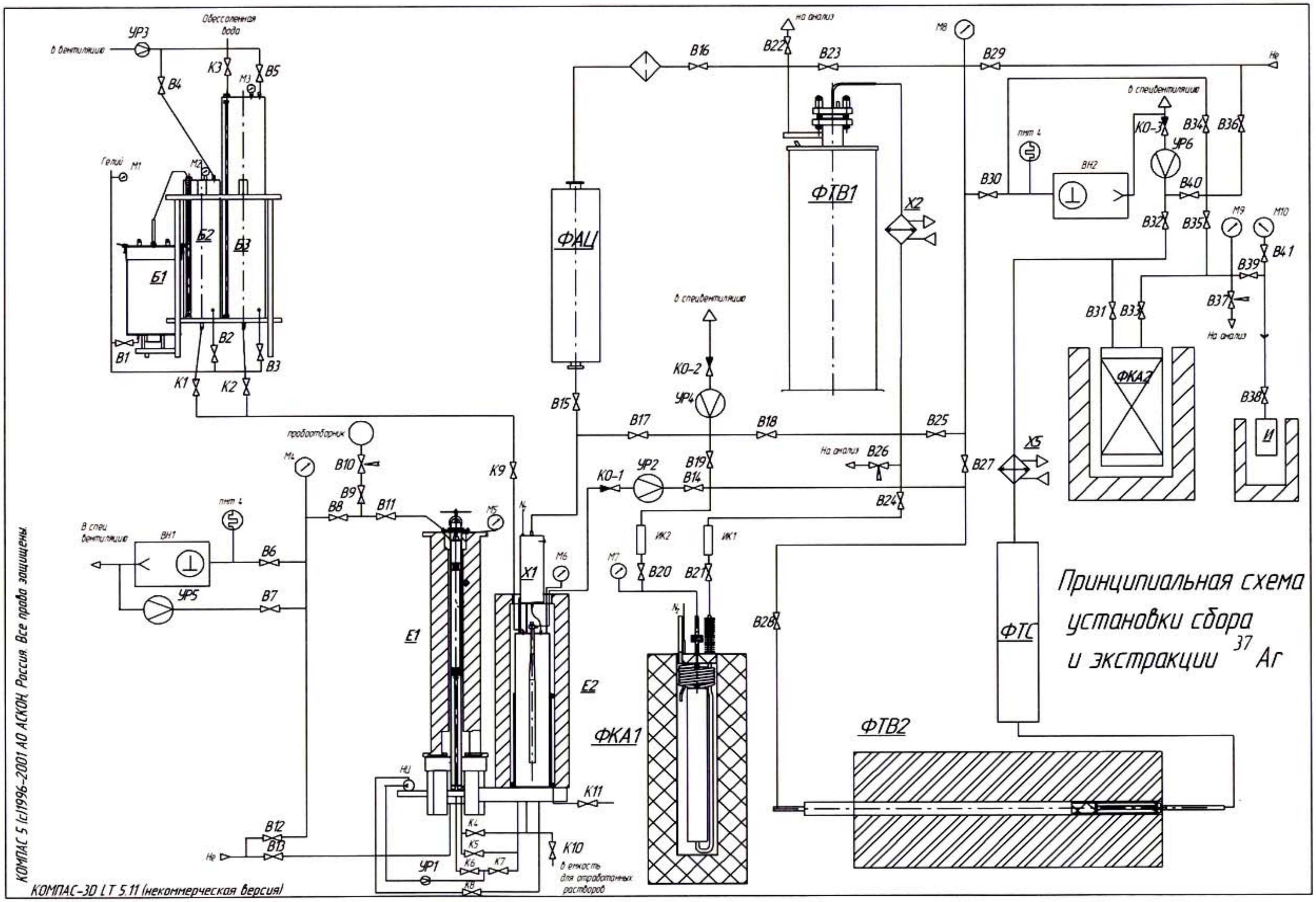




Nineteen irradiation assemblies, each of which contained 17.3 kg of CaO (12.36 kg Ca), were placed in the blanket zone of the reactor.

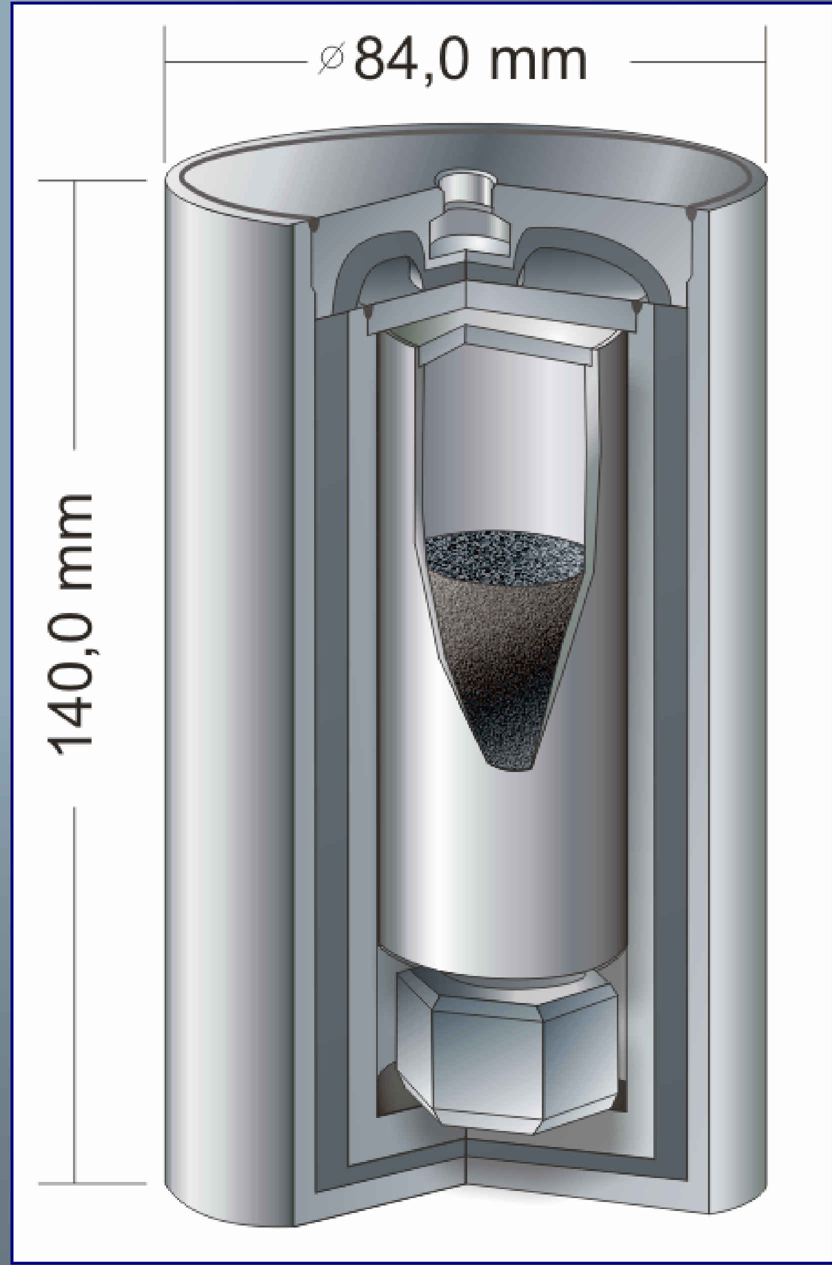
Irradiation began on 31 October 2003 and continued until 12 April 2004, the normal reactor operating cycle. After a cooling period of a week, the assemblies were removed from the reactor and moved to a hot cell of BNPP where ampoules with irradiated target were taken out from assemblies and moved to 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.

^{37}Ar was extracted from acid solution by a He purge and then stored on charcoal at LN_2 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 ^{37}Ar, 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}Ar was cryopumped. When essentially all the ^{37}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}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.

Measurement method	Activity (kCi ^{37}Ar at 04:00 on 30 April 2004)
Volume of gas	409 ± 6
Mass of gas	412 ± 4
Calorimetry at Zarechny	401 ± 4
Calorimetry at Baksan	422 ± 9
Proportional counter	405 ± 4
Isotopic dilution	410 ± 5

The six completed activity measurements are given in the Table. These measurements are adopted in the weighted average, 409 ± 2 kCi.

Predicted production rate

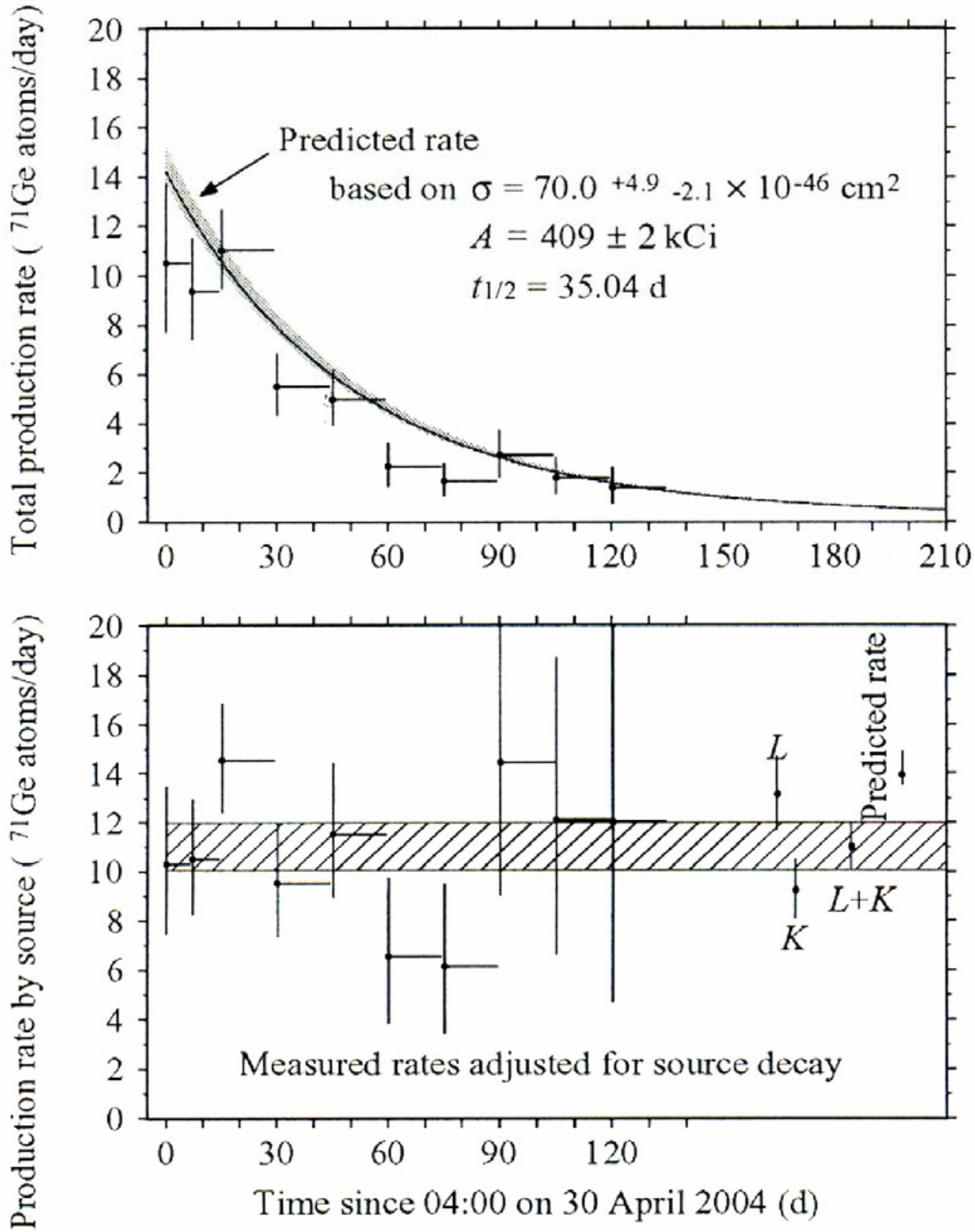
$$p = AD\langle L\rangle\sigma, \qquad \langle L\rangle = \frac{1}{4\pi V_S}\int_{\text{absorber}} dV_A \int_{\text{source}} \frac{dV_S}{r_{SA}^2}$$

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

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

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 atoms of ^{71}Ge produced per day.**



Upper panel: comparison of measured total production rate for each extraction with predicted rate.

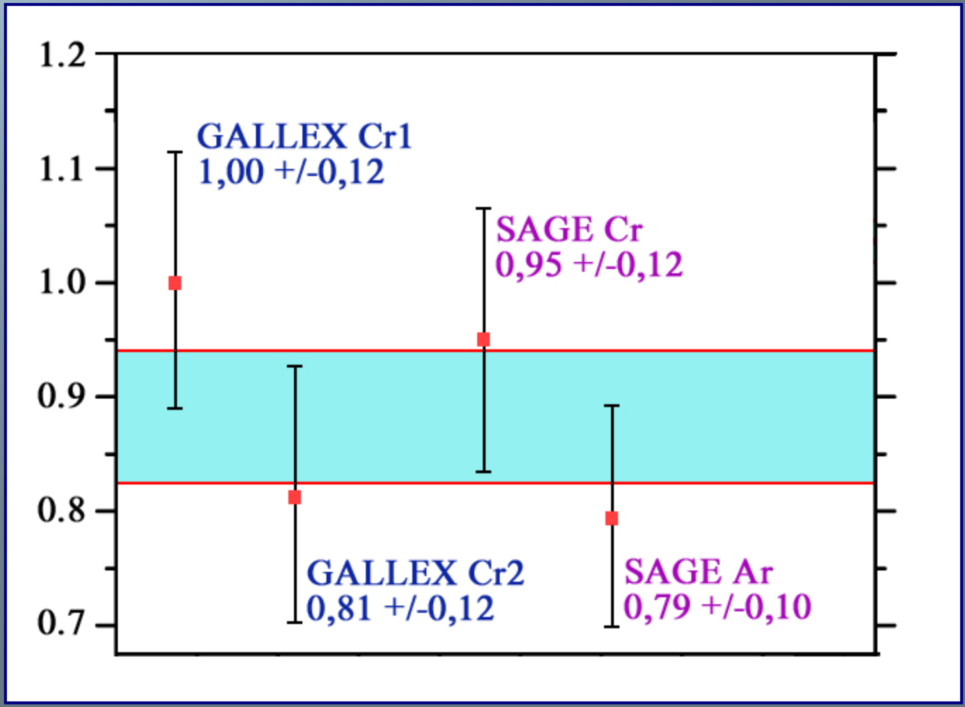
Lower panel: measured rates from the ^{37}Ar source extrapolated back to the start of the first extraction. The combined results for events in the the *L*- and *K*- peaks and for all events are shown separately at the right and compared to the predicted rate.

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

Comparison of source experiments with Ga

Item	GALLEX Cr1[2, 3]	GALLEX Cr2 [2,3]	SAGE ^{51}Cr [1]	SAGE ^{37}Ar
Source production				
Mass of reactor target (kg)	35.5	35.6	0.512	330
Target isotopic purity	38.6% ^{50}Cr	38.6% ^{50}Cr	92.4% ^{50}Cr	96.94% ^{40}Ca
Source activity (kCi)	1714 +30/-43	1868 +89/-57	516.6 ± 6.0	409 ± 2
Specific activity (kCi/g)	0.048	0.052	1.01	92.7
Gallium exposure				
Gallium mass (tones)	30.4 ($GaCl_3$:HCl)	30.4 ($GaCl_3$:HCl)	13.1 (Ga metal)	13.1 (Ga metal)
Gallium density (10^{21} $^{71}Ga/cm^3$)	1.946	1.946	21.001	21.001
Measured production rate ρ (^{71}Ge/d)	11.9 ±1.1 ±0.7	10.7 ±1.2 ±0.7	14.0 ±1.5 ±0.8	11.0 +1.0/-0.9 ±0.6
R=P(measured)/P(predicted)	1.00 +0.11/-0.10	0.81 ±0.10	0.95 ±0.12	0.79 +0.09/-0.10

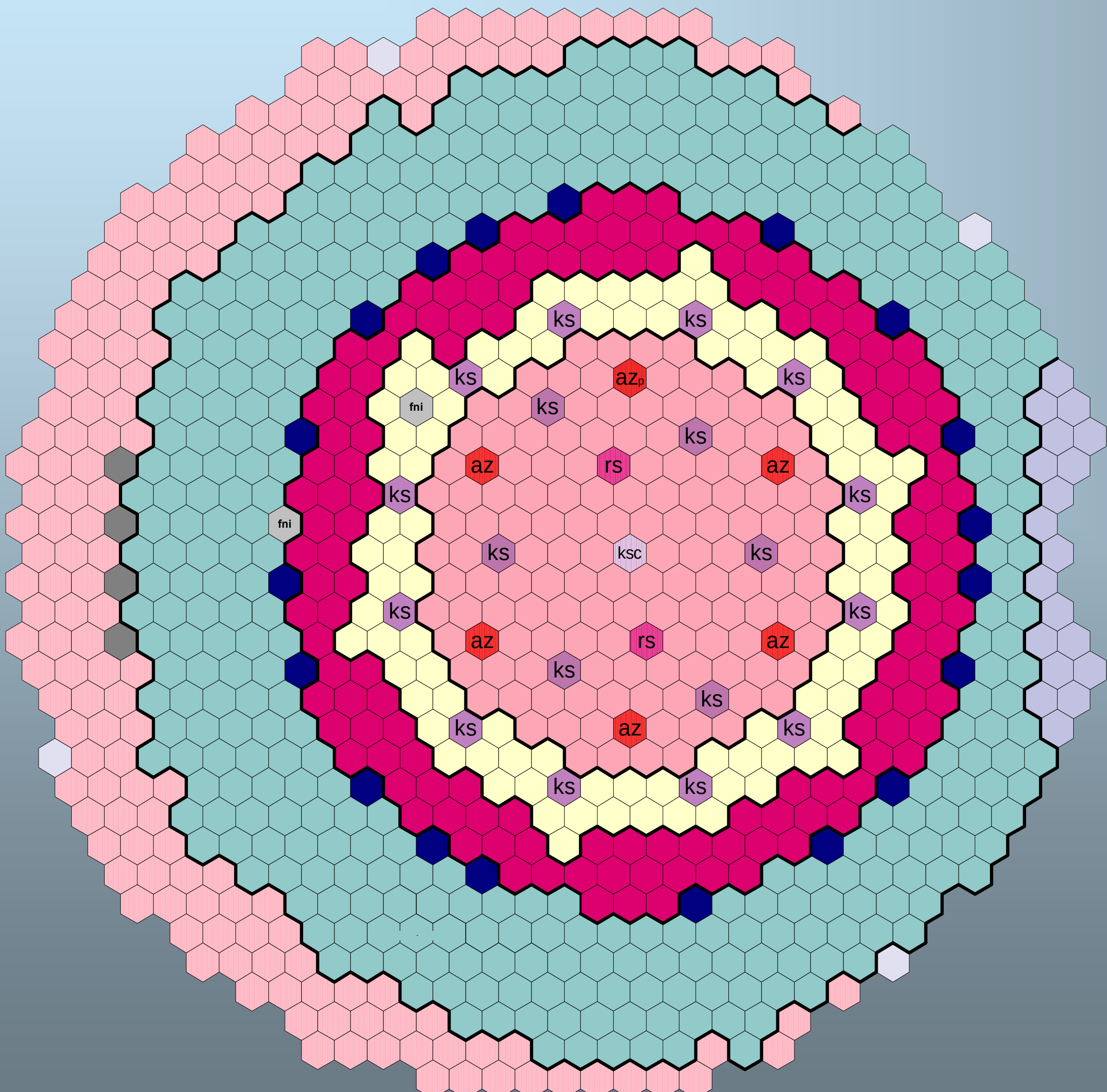
The weighted average value of *R*, the ratio of measured to predicted ^{71}Ge production rates, is 0.88 ± 0.05, more than two standard deviations less than unity.



Conclusions

- Prototype ^{37}Ar neutrino source with strength of 409 ± 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}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 = P(measured) / P(predicted) = 0.79 +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.

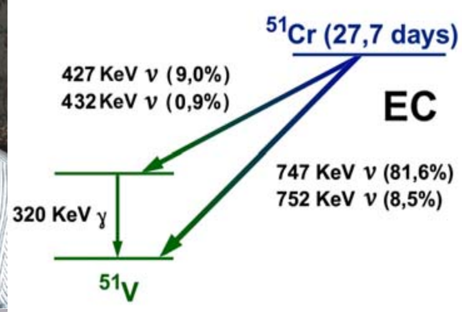
М.А. Марков и Б.М. Понтекорво на Международной конференции по физике нейтрино и нейтринной астрофизике. Баксанское ущелье, Чегет, 1977 г.

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.


12м
10м
60м

$^{71}Ga + \nu \rightarrow {}^{71}Ge + e^-$

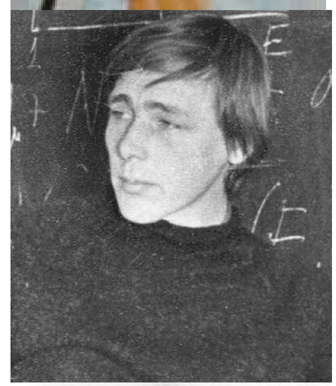
Vadim Kouzmine, 1965



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

M
S
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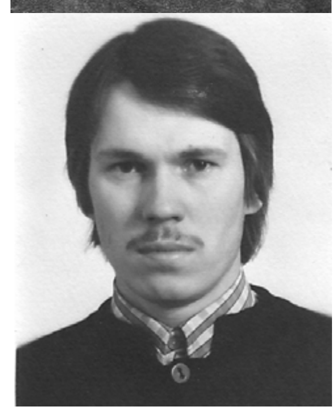
effect



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