

DD

GALLEX

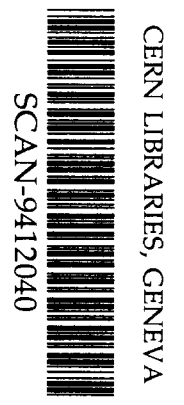
First results from
the ^{51}Cr neutrino source experiment
with the GALLEX detector

GALLEX Collaboration

Submitted to Physics Letters B

November 1994

su 8449



GX 65 - 1994
Chem (BNL)-4165 (1994)
DAPNIA/SPP 94-40
LNGS 94/111
MPI H - V30 - 1994
ROM2F/94/47

First results from
the ^{51}Cr neutrino source experiment
with the GALLEX detector

GALLEX collaboration ^{1,2,3,4,5}

P. Anselmann, R. Fockenbrock, W. Hampel, G. Heusser, J. Kiko, T. Kirsten,
M. Laubenstein, E. Pernicka, S. Pezzoni, U. Rönn, M. Sann, F. Spielker, R. Wink,
M. Wójcik⁶

*Max-Planck-Institut für Kernphysik (MPIK), Postfach 103980, D-69029 Heidelberg,
Germany¹*

R. v. Ammon, K. H. Ebert, T. Fritsch, D. Heidt, E. Henrich, C. Schlosser, L. Stieglitz,
F. Weirich

*Institut für Technische Chemie, Kernforschungszentrum Karlsruhe (KFK), Postfach 3640,
D-76021 Karlsruhe, Germany*

M. Balata, H. Lalla

*INFN – Laboratori Nazionali del Gran Sasso (LNGS), S.S. 17/bis Km 18+910, I-67010
L'Aquila, Italy²*

E. Bellotti, C. Cattadori, O. Cremonesi, N. Ferrari, E. Fiorini, L. Zanotti

*Dipartimento di Fisica, Università di Milano e INFN – Sezione di Milano, Via Celoria
16, I-20133 Milano, Italy²*

M. Altmann, F. v. Feilitzsch, R. Mößbauer, U. Schanda⁷

*Physik Department E15, Technische Universität München (TUM), James-Franck Straße,
D-85748 Garching b. München, Germany*

G. Berthomieu, E. Schatzman⁸

*Observatoire de la Côte d'Azur, Département Cassini, B.P. 229, 06004 Nice Cedex 4,
France*

I. Carmi, I. Dostrovsky

*Department of Environmental and Energy Research, The Weizmann Institute of Science
(WI), P.O. Box 26, 76100 Rehovot, Israel*

C. Bacci⁹, P. Belli, R. Bernabei, S. d'Angelo, L. Paoluzi

*Dipartimento di Fisica, II Università di Roma "Tor Vergata" e INFN – Sezione di Roma 2,
Via della Ricerca Scientifica, I-00133 Roma, Italy²*

A. Bevilacqua¹⁰, S. Charbit, M. Cribier, G. Dupont¹¹, L. Gosset, J. Rich, M. Spiro,
T. Stolarczyk, C. Tao¹², D. Vignaud
*CEA, DAPNIA, CE Saclay, F-91191 Gif-sur-Yvette Cedex, France*³

J. Boger, R. L. Hahn, F. X. Hartmann, J. K. Rowley, R. W. Stoenner, J. Weneser
*Brookhaven National Laboratory (BNL), Upton, NY 11973, USA*⁴

¹ This work has been supported by the German Federal Minister for Research and Technology (BMFT). This work has been generously supported by the ALFRIED KRUPP von BOHLEN und HALBACH-Foundation, Germany.

² This work has been supported by Istituto Nazionale di Fisica Nucleare (INFN), Italy.

³ This work has been supported by the Commissariat à l'énergie atomique (CEA), France.

⁴ This work has been supported by the Office of High Energy and Nuclear Physics of the U.S. Department of Energy, United States.

⁵ This research has been funded in part by CEE Large Installation Plan under contract GE1*CT920048.

⁶ Permanent address : Instytut Fizyki, Uniwersytet Jagiellonski, ul. Reymonta 4, PL-30059 Kraków, Poland.

⁷ Present address : Max-Planck-Institut für Physik, Föhringer Ring 6, Postfach 401212, D-80805 München, Germany.

⁸ Permanent address : DASGAL, Bâtiment Copernic, Observatoire de Paris, 5 place Jules Janssen, F-92195 Meudon Principal, France.

⁹ Permanent address : Dipartimento di Fisica, III Università di Roma, via C. Segre 2, I-00100, Roma, Italy.

¹⁰ Permanent address : SRS/SAPR, CEN Grenoble, F-38041 Grenoble Cedex, France.

¹¹ Present address : DRN/DMT, CE Saclay, F-91191 Gif-sur-Yvette Cedex, France.

¹² Permanent address : LPC du Collège de France, 11, Place Marcelin Berthelot, F-75231 Paris Cedex 05, France.

Abstract

The radiochemical GALLEX experiment, which has been measuring the solar neutrino flux since May 1991, has performed an investigation with an intense man-made ^{51}Cr neutrino source (61.9 ± 1.2 PBq). The source, produced via neutron irradiation of ≈ 36 kg of chromium enriched in ^{50}Cr , primarily emits 746 keV neutrinos. It was placed for a period of 3.5 months in the reentrant tube in the GALLEX tank, to expose the gallium chloride target to a known neutrino flux. This experiment provides the ratio, R , of the production rate of Cr-produced ^{71}Ge measured in these source exposures to the rate expected from the known source activity : $R = 1.04 \pm 0.12$. This result not only constitutes the first observation of low-energy neutrinos from a terrestrial source, but also (a) provides an overall check of GALLEX, indicating that there are no significant experimental artifacts or unknown errors at the 10 % level that are comparable to the 40 % deficit in observed solar neutrino signal, and (b) directly demonstrates for the first time, using a man-made neutrino source, the validity of the basic principles of radiochemical methods used to detect rare events (at the level of 10 atoms or less). Because of the close similarity in neutrino energy spectra from ^{51}Cr and from the solar ^7Be branch, this source experiment also shows that the gallium detector is sensitive to ^7Be neutrinos with full efficiency.

1 Introduction.

The results of the radiochemical GALLEX experiment [1] show a deficit of solar neutrinos : 79 ± 10 (stat.) ± 6 (syst.) SNU, compared to the standard solar model (SSM) predictions of 123 SNU [2] to 132 SNU [3]. GALLEX is the first experiment to have detected the primary pp neutrinos [4] from the most abundant and best predicted of the solar neutrino branches. The radiochemical chlorine detector [5], which has been operating for the last 25 years, is not sensitive to these pp neutrinos but can detect the more energetic yet less abundant ^7Be and ^8B solar neutrinos; its result is about one third of the SSM predictions. The real time Kamiokande experiment, which uses a Cerenkov technique and is sensitive only to the most energetic ^8B neutrinos, observes a deficit of a factor of 2 [6]. The other radiochemical gallium detector, SAGE, now yields a rate, 73 ± 18 (stat.) ± 6 (syst.) SNU [7], very similar to that of GALLEX. All of these solar neutrino results, even if the experimental and theoretical errors are considered, are not easily reconciled with the SSM and could imply neutrino oscillations [8].

Since the consequences of these results are crucial for particle and astrophysics,

it is very important to place the trustworthiness of the experimental techniques beyond any reasonable doubt ; the scientific community concurs in requiring such a demonstration. The most straightforward check is to expose these experiments to neutrino sources with known activity levels and appropriate energy, under conditions nearly identical to those used in solar exposures : the fewer the changes made in the methods, the more convincing the proof will be. Until now, no test of this type has been performed for any solar neutrino experiment.

This GALLEX letter reports on the first experiment of this kind and its preliminary results. In spite of many controls of each individual experimental step in GALLEX, including tests that showed that hot atom effects were insignificant, and continual measurement of the germanium desorption efficiency through monitoring the carrier yields [9], unforeseen effects could not be a priori excluded. This source test represents a check of the overall performance of the GALLEX detector, addressing systematic errors of both known and unknown origin.

Since neutrinos from accelerators are not appropriate for these radiochemical experiments, our approach is based on the fabrication and use of an intense and portable neutrino source. The specifications for this source are more or less fixed by the Sun : a) the source activity level must be such that the measurement reaches the precision of the measurement of the solar neutrino flux expected after 4 years of data collection, i. e., about 9% ; b) the energy of the emitted neutrinos must be close to the mean energy of solar neutrinos detected by GALLEX ; c) the source lifetime must be long enough to allow transport of the source to the underground detector and still leave enough time to perform a reliable experiment. Added to the scientific constraints, economic and safety considerations restrict the list of possible nuclides. Other potential sources, such as ^{65}Zn , ^{152}Eu , and ^{37}Ar , were considered before choosing ^{51}Cr as the most suitable nuclide. The activity required for this ^{51}Cr source must be $\geq 50 \text{ PBq}$ in order to produce a signal about one order of magnitude greater than that of the Sun.

In this letter, we first describe how the ^{51}Cr source was produced in the Siloé reactor in Grenoble, and how its activity was measured. We then analyze the data taken with the source placed inside the GALLEX target and discuss the results.

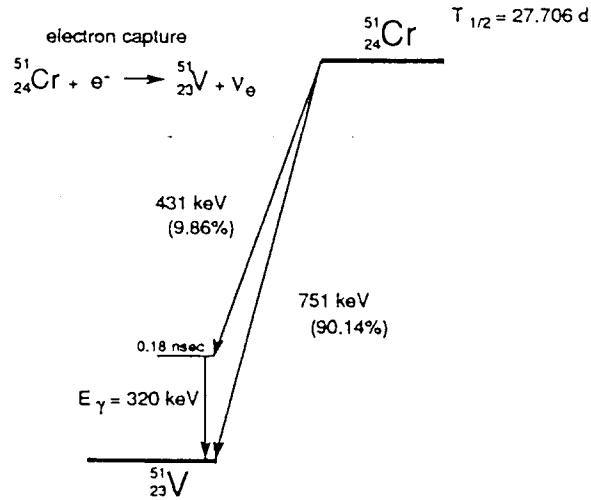


Figure 1: Characteristics of the decay of ${}^{51}\text{Cr}$. The “751 keV” line combines the 746 and 751 keV lines and the “431 keV” line combines the 426 and 431 keV lines.

2 Fabrication of the ${}^{51}\text{Cr}$ source.

a) Characteristics of chromium isotopes and choice of the material. ${}^{51}\text{Cr}$ is produced by neutron capture on ${}^{50}\text{Cr}$; its half-life is 27.706 ± 0.007 days [10]. ${}^{51}\text{Cr}$ decays by electron capture with a Q-value of 751 keV (see figure 1) to the ground state of ${}^{51}\text{V}$ (90.14 % branching ratio [10]) and to the first excited state (9.86 ± 0.05 %), which deexcites to the ground state with emission of a 320 keV γ ray. Aside from the low intensity internal bremsstrahlung, the neutrino spectrum consists of four monoenergetic lines (746 keV (81 %), 751 keV (9 %), 426 keV (9 %) and 431 keV (1 %)).

Natural chromium consists of 4 stable isotopes, as listed together with their respective thermal neutron capture cross-sections in table 1. The low natural abundance of ${}^{50}\text{Cr}$ along with the high cross-section of ${}^{53}\text{Cr}$ makes it technically impossible to reach the required activity level, ≈ 50 PBq, by using natural chromium (as was made evident in preliminary tests [11]). Instead, chromium enriched in ${}^{50}\text{Cr}$ (and depleted in ${}^{53}\text{Cr}$) is needed. The composition of our enriched chromium, purchased from the Kurchatov Institute in Moscow, is also given in table 1. With these characteristics, it became clear that 35-40 kg of such material could provide a

neutrino source having the required activity.

	Isotopic composition of natural Cr	Isotopic composition of the enriched Cr used in GALLEX	Thermal neutron capture cross-sections (barns) [12]
^{50}Cr	4.35 %	38.6 %	15.9
^{52}Cr	83.8 %	60.7 %	0.76
^{53}Cr	9.5 %	0.7 %	18.2
^{54}Cr	2.35 %	<0.3 %	0.36

Table 1: *Isotopic composition of chromium and thermal neutron capture cross-section (measured at 2200 m/s).*

b) **Chromium isotopic enrichment.** The Kurchatov Institute used the gaseous compound, chromyl fluoride, CrO_2F_2 , to enrich chromium in ^{50}Cr [13] by gas centrifugation. Because this compound is very hazardous and corrosive, it was transformed by hydrolysis into solid chromium trioxide, CrO_3 , immediately after the enrichment. The enriched CrO_3 was received between August 1992 and February 1994.

Although the 320 keV γ rays of ^{51}Cr are easily stopped by a few cm of tungsten shielding, high-energy γ 's (above 1 MeV) from impurities can pose radiological problems. Thus, severe specifications were demanded for possible impurities in the enriched chromium, of the order of ppm for Na, La, Sc, Sb, Co, Ag, Th, As, Tb and of ppb for Ga, Fe, Zn, Cd, Br, Te and U.

Since CrO_3 is thermally unstable, it is unacceptable as a target for irradiation in a nuclear reactor. We have chosen to transform it into metallic chromium by electrolysis, taking special care not to introduce impurities during this step. The Cr metal was then broken into irregular chips of $\approx 1 \text{ mm}^3$ volume, and outgassed under vacuum to remove the large quantities of hydrogen that had been absorbed during electrolysis, so that $\approx 36 \text{ kg}$ of product could be placed in the nuclear reactor.

c) **Chromium irradiation.** Among the different reactors which one could consider to irradiate large quantities of chromium, only Siloé is flexible enough to accommodate a customized irradiation and to allow rapid removal of the target.

Siloé, located at the "Centre d'études nucléaires de Grenoble" (France) and operated by CEA (Commissariat à l'énergie atomique), is a swimming pool reactor,

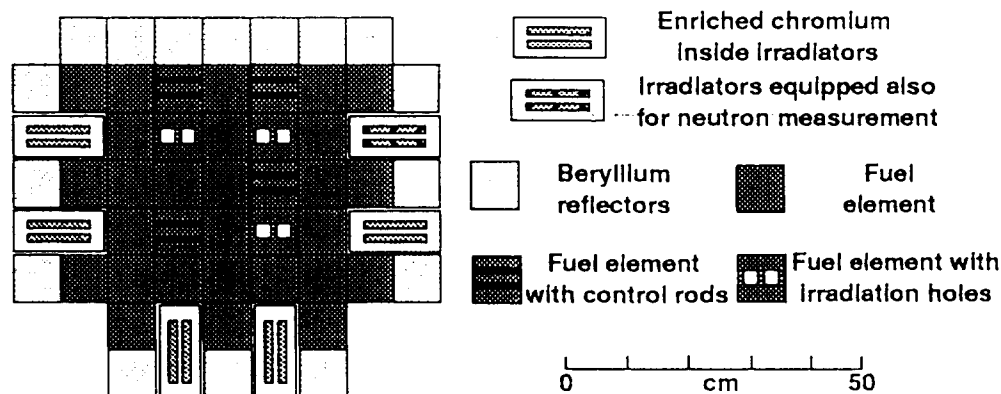


Figure 2: *Special Siloé core configuration for chromium irradiation*

with 35 MW thermal power. The dedicated core for the chromium irradiation was specially built to contain 34 fuel elements, enriched to 93 % in ^{235}U , and arranged in a checker-board configuration, as shown in figure 2. The core is immersed in water, which serves as moderator, coolant, and shielding. The effective cross-section of ^{50}Cr for the spectrum of thermal and epithermal neutrons in Siloé is 17.2 barns.

The full amount of chromium is too large to fit into the usual irradiation holes inside the core. Instead, the chromium had to be placed around the fuel elements. Thus the reactor core was reconfigured to form 6 crenels to contain the chromium targets, with beryllium reflectors arranged to enhance the neutron flux in the chromium.

The chromium chips were placed in 12 special irradiator containers that were constructed of zircalloy so as to be as transparent to neutrons as possible; two irradiator containers were placed in each crenel. The chromium was exposed to an average perturbed neutron flux of $5.2 \times 10^{13} \text{ n}/(\text{cm}^2.\text{s})$, with large variations around this mean value that depended on the positions of the irradiator containers in the reactor; these variations reflect the vertical and radial flux gradients which in turn are influenced by the self-shielding of the chromium [14]. The core was loaded with fuel elements to allow an irradiation time of 23.8 days, instead of the usual fuel cycle of 21 days. The irradiation started at 10 am on May 27, 1994, and lasted without any interruption to end-of-bombardment (EOB = t_0), June 20 at 6 am.

The irradiated material was unloaded in a hot cell at Siloé. The chromium chips

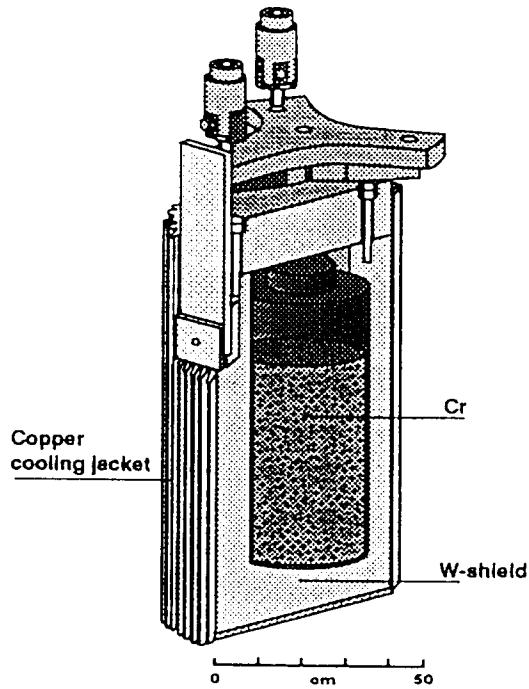


Figure 3: *Schematic drawing of the Cr-source inside the W-shield.*

were then placed in a sealed stainless-steel container and inserted into a tungsten shield (8.5 cm wall thickness) for biological protection. The source configuration inside the shield is represented in figure 3. Very sensitive measurements showed that the external dose at any position on the surface of the tungsten shield was less than $7 \mu\text{Sv/h}$ [15], well below the maximum $200 \mu\text{Sv/h}$ -level allowed by the safety authorities. Gamma-ray spectroscopy outside the shield showed activation of impurities in the chromium of Na, Sc, Cu, As, Ag, and Sb at levels that are orders of magnitude lower than specified [15].

More details on the production of this chromium source are given elsewhere [14].

3 Measurement of the source activity.

The amount of irradiated chromium composing the neutrino source within the tungsten shield was $35530 \pm 10 \text{ g}$. The activity of this source was determined by three fully independent methods, as described below. Preliminary results of these mea-

surements are reported here. Further improvements will be made in these determinations. In addition, a new method is being developed to determine the ^{51}Cr source activity by measuring the concentration of its decay daughter, stable ^{51}V .

a) **The ionization chamber technique.** The granular form of the chromium metal was chosen to enable thorough mixing of the irradiated material in the hot cell, in order to average out the large neutron flux variations to which the chromium had been exposed. To verify that representative samples of this mixture were taken for assay, 31 samples with individual weights ranging between 0.5 and 1.0 gram were extracted from various positions in the mix. The activity of each very active sample (about 2 TBq/g) was measured via the 320 keV γ ray, using an ionization chamber which was calibrated with a standard ^{51}Cr source [16]. As cross checks, some of these samples were totally dissolved, diluted, and aliquots taken, which were then assayed by gamma-ray spectroscopy, using Ge crystals calibrated with other absolute ^{51}Cr standard sources. It is reassuring that the results of these different absolute γ -ray measurements are consistent.

The variance of the 31 individual results is consistent with the assumption that the total of all these samples is representative of the full 35.53 kg of chromium. The average specific activity of the 31 metal samples is 1.71 ± 0.04 TBq/g [16] and, consequently, the total activity of the source is 60.8 ± 1.4 PBq at EOB.

b) **Calorimetry.** The calorimetric method has the advantage that, since it measures the activity of the total source, it does not depend on our ability to take representative samples. Immediately after insertion of the source into the tungsten shield, the total thermal power of the source was determined by placing the source-plus-shield configuration in a thermally shielded vacuum vessel and measuring the rate of the ensuing temperature increase. By comparing the measured rate with that in similar measurements where known amounts of thermal power were supplied by a resistance heater to 35.5 kg of chromium metal, we deduce a source power of 385 ± 13 W at EOB. The mean energy release of ^{51}Cr is known to be 36.51 ± 0.16 keV per decay [10], emitted in the form of 320 keV γ -rays (9.86 % abundance), X-rays, and Auger electrons. Due to the very low rate of impurities in the chromium, the amount of energy deposited in the calorimeter by these contaminants is negligible. Thus we deduce that the source neutrino activity is 65.9 ± 3.0 PBq at EOB [17].

c) **Neutronics and gamma-scanning.** The knowledge of the neutron flux and of the relevant capture cross-section for producing ^{51}Cr provides another method for evaluating the final activity of the source. The relative energy spectrum of the

neutrons, as a function of the position in the median plane of the reactor, is found by numerically solving the neutron transport equation for the Siloé configuration described in figure 2 [18]. An on-line neutron measurement in one crenel gives the overall normalization. The axial neutron-flux distribution is deduced from the activity measured in the irradiator containers, as a function of the height above the median plane. The value of the source activity deduced from these neutron measurements is 64.4 ± 5.2 PBq at EOB [18].

Gamma-ray scanning of the 320 keV γ ray, measured in half of the irradiators in the reactor pool, yields the total source activity in a more or less independent way : the result is 64.0 ± 5.2 PBq at EOB [18].

d) Mean value of the ^{51}Cr source activity. The agreement between the results of the independent methods discussed above allows us to take a weighted average of their values. The resulting mean activity of the ^{51}Cr source at EOB in Siloé is $A_0(t_0) = 61.9 \pm 1.2$ PBq (1.67 ± 0.03 MCi), stated with a one- σ error. To our knowledge, this is the strongest neutrino source ever produced.

For the transport between Grenoble and Gran Sasso, the source inside its sealed tungsten shield was placed in a special certified container used for transport of radioactive material. All technical and legal aspects of this transport had been previously approved by safety authorities in France and in Italy.

The total time from EOB to the introduction of the source into the reentrant tube in the GALLEX target tank at Gran Sasso was 3.69 days, equivalent to an 8.8% decrease of activity.

4 Source experiment.

To avoid any heat transfer from the source to the gallium solution, which could change the kinetics of the germanium desorption [9], a copper thermal shield, cooled with tap water (60l/h), was placed between the source and the wall of the reentrant tube. The ^{51}Cr neutrino source was inserted in its final position, in the A-tank, on June 23, 1994 at 10:36 pm (see figure 4). It was removed on October 10 at 2pm and returned to Grenoble. Since fast neutrons could produce ^{71}Ge nuclei in gallium, we searched for a flux of neutrons from the source after its removal from the gallium target. No excess of the fast neutron flux above the background was seen, as expected [15]. As a consequence a contribution by neutrons to production of ^{71}Ge atoms is excluded at the level of 1% of the expected neutrino signal (at 90%

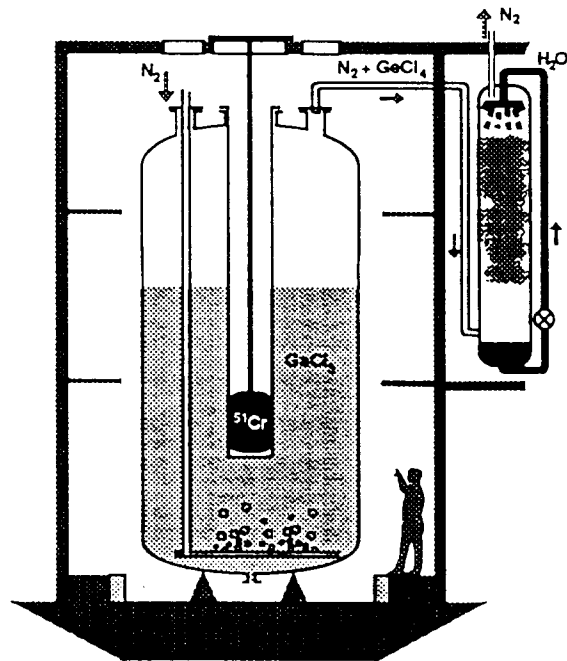


Figure 4: Scheme of the GALLEX A-tank containing the 53.65 m^3 gallium chloride solution with the chromium source inside the central reentrant tube. The germanium desorption system is also sketched.

c.l.).

The experimental conditions were kept exactly as in the solar runs, except that the collection of the ^{71}Ge produced by the decaying ^{51}Cr was optimized by doing shorter exposures. That is, the duration of each source exposure was selected so that about the same number of ^{71}Ge atoms was desorbed in each run; in particular, the first desorption was done 3.35 days after the insertion of the source, while the last 5 exposures each lasted about 2 weeks. No blank runs were done between these exposures. The parameters of the 11 source runs are given in table 2. Note that the correction to account for production of ^{71}Ge during desorption and carry-over from one source exposure to the next can be as large as 3%, compared to 0.5% in the solar runs [19]. Counting procedures in these runs were identical to those used in our solar runs [1, 4].

The average path of neutrinos emitted from the ^{51}Cr source inside the gallium solution, computed by a Monte-Carlo simulation, is $\langle L \rangle = 1.90 \pm 0.01\text{ m}$. Combin-

ing this with the values of the concentration of 1.946×10^{21} $^{71}\text{Ga}/\text{cm}^3$ [4, 9], and with the neutrino capture cross-section of 59×10^{-46} cm^2 for ^{51}Cr neutrinos [20, 21], yields a calculated production rate of 11.7 ± 0.2 ^{71}Ge atoms/day at EOB for the measured source strength, $A_0 = 61.9 \pm 1.2$ PBq. This may be compared to 0.90 ^{71}Ge atoms/day for a production rate of 100 SNU.

A simulation of the various parameters of the source experiment shows that the above production rate is not very sensitive to the precise position of the source inside the tank, nor to the precise schedule of the desorptions [22].

Source run number	Exposure number	Exposure time		Duration (days)	Counting live time until 08.11.94 (days)	Ge yield (%)	Counting efficiency (%)		^{71}Ge atoms produced per day	\tilde{A}_0 (PBq)
		Start	Stop				L	K		
Cr1	S107	23.06.94	27.06.94	3.35	127.2	95.6	32.2	37.4	11.2 ± 3.2	65.4 ± 18.7
Cr2	S108	27.06.94	01.07.94	4.00	124.5	98.7	29.9	32.0	11.7 ± 2.9	74.3 ± 18.2
Cr3	S109	01.07.94	06.07.94	5.00	119.7	95.0	33.0	38.3	8.1 ± 2.5	57.0 ± 17.4
Cr4	S110	06.07.94	13.07.94	7.00	112.0	99.3	28.9	34.3	8.2 ± 1.8	64.9 ± 14.3
Cr5	S111	13.07.94	20.07.94	7.00	106.4	99.4	29.2	31.3	7.4 ± 2.0	70.1 ± 19.0
Cr6	S112	20.07.94	27.07.94	7.00	99.6	99.6	30.3	32.4	5.0 ± 1.6	55.8 ± 18.5
Cr7	S113	27.07.94	09.08.94	13.00	86.4	96.0	28.0	33.2	4.5 ± 1.3	60.4 ± 17.5
Cr8	S114	09.08.94	24.08.94	15.00	72.1	99.3	29.1	34.4		
Cr9	S115	24.08.94	07.09.94	14.00	57.9	96.6	28.7	34.0		
Cr10	S116	07.09.94	28.09.94	21.00	38.9	99.1	30.2	32.3		
Cr11	S117	28.09.94	10.10.94	12.00	27.5	94.9	29.1	34.4		

Table 2: *Parameters and results of the source runs. Only the first 7 runs are considered in the present analysis. The number of ^{71}Ge atoms produced per day by the source is the number fitted at the start of each exposure; it is equal to p_{Cr} multiplied by $e^{-\lambda_{51}(t_k - t_0)}$ (see formula (1)). \tilde{A}_0 is the apparent source strength at EOB deduced from this production rate.*

5 Data taking and analysis.

The data taking and the ^{71}Ge data analysis were performed exactly as for the solar runs. We used only proportional counters that had been used previously for solar runs. The ^{71}Ge candidates were obtained by selecting valid decay events in the L and K energy and rise-time windows [1, 4]. However, the maximum likelihood fit to the time sequence of counter events of a given exposure has been modified to depend on three terms : a_{Cr} , a_\odot and b . a_{Cr} characterizes the production of ^{71}Ge by the source (which decays with the ^{51}Cr half-life) and is proportional to the activity \tilde{A}_0 at EOB, now treated as an unknown that is determined from the fit. a_\odot characterizes the production of ^{71}Ge by the Sun and by side reactions [4], and is treated as a constant input term; this production rate (0.78 ± 0.11 ^{71}Ge atoms

per day) is taken from solar exposures [1]. b is the constant background during the counting. Only a_{Cr} and b are fitted. In the notation of Cleveland [23], the relevant expression for the likelihood function is :

$$\mathcal{L}(a_{Cr}, b; a_{\odot}) \propto \prod_i [b + [a_{\odot} + a_{Cr} e^{-\lambda_{51}(t_k - t_0)}] e^{-\lambda_{71} t_i}]$$

$$a_{Cr} = \epsilon_c \epsilon_e \frac{p_{Cr}}{1 - (\lambda_{51}/\lambda_{71})} (e^{-\lambda_{51} \theta_k} - e^{-\lambda_{71} \theta_k}) \quad (1)$$

$$p_{Cr} = 0.189 \text{ } ^{71}\text{Ge}/d \times \tilde{A}_0 \text{ (PBq)}$$

where $t_k - t_0$ is the time elapsed from EOB to the start of exposure k , θ_k the length of exposure k , t_i the time of the i^{th} counting event; ϵ_e and ϵ_c are the respective extraction and counting efficiencies; λ_{51} and λ_{71} are the decay constants of ^{51}Cr and ^{71}Ge , respectively. Note that the standard counting period in GALLEX of 6 months per run has not ended as yet, so that the results reported in table 2 from the present analysis are preliminary. We set a requirement of a 3-month minimum counting period per run for this letter, so that only the first 7 runs were included.

Figure 5 presents the cumulative counting data from these first 7 source runs; a clear signal from ^{71}Ge is evident in (a) the L and K-peak energy spectra of the events within the rise-time windows and (b) the decay data. The curve in (b) is the maximum likelihood fit to the data, for the known 11.43-day half-life of ^{71}Ge and a constant background. (If the half-life is treated as a free parameter, the result is $T_{1/2} = 12.4 \pm 1.5$ days.) The number of observed events attributed to the ^{71}Ge in these runs is 154, with 138 events attributed to neutrinos from the ^{51}Cr source and 16 to neutrinos from the Sun.

Table 2 lists the results of the maximum likelihood analysis of the counting data from each run, in terms of the number of ^{71}Ge atoms produced per day at the start of each run, i.e. p_{Cr} multiplied by $e^{-\lambda_{51}(t_k - t_0)}$. Figure 6 presents the time dependence of these results during the course of the source experiment. The results for each run are plotted at the time that the exposure to the source neutrinos began. The horizontal lines show the duration of each exposure. The fitted half-life of the ^{51}Cr obtained with the maximum likelihood method from these ^{71}Ge data is 24.4 ± 7.1 days. The curve in figure 6 is the number of ^{71}Ge atoms produced per day predicted from the measured A_0 value of the source, 61.9 PBq, assuming the known half-life of ^{51}Cr plus the known 0.78 ^{71}Ge atoms per day produced by solar neutrinos

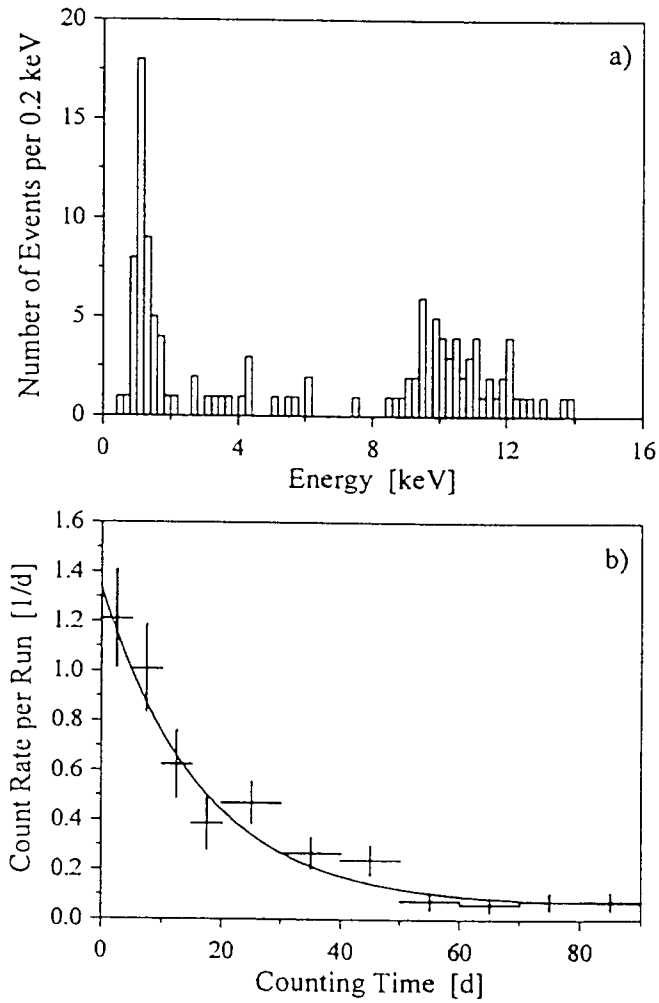


Figure 5: Cumulative counting results of the source experiment from runs Cr1-Cr7 : (a) the energy spectrum of the events within the rise-time windows obtained during the first mean lifetime of ^{71}Ge , showing the L (1.17keV) and K (10.37keV) peaks, and (b) the decay data, where the curve is the maximum likelihood fit for the known half-life of ^{71}Ge and a constant background.

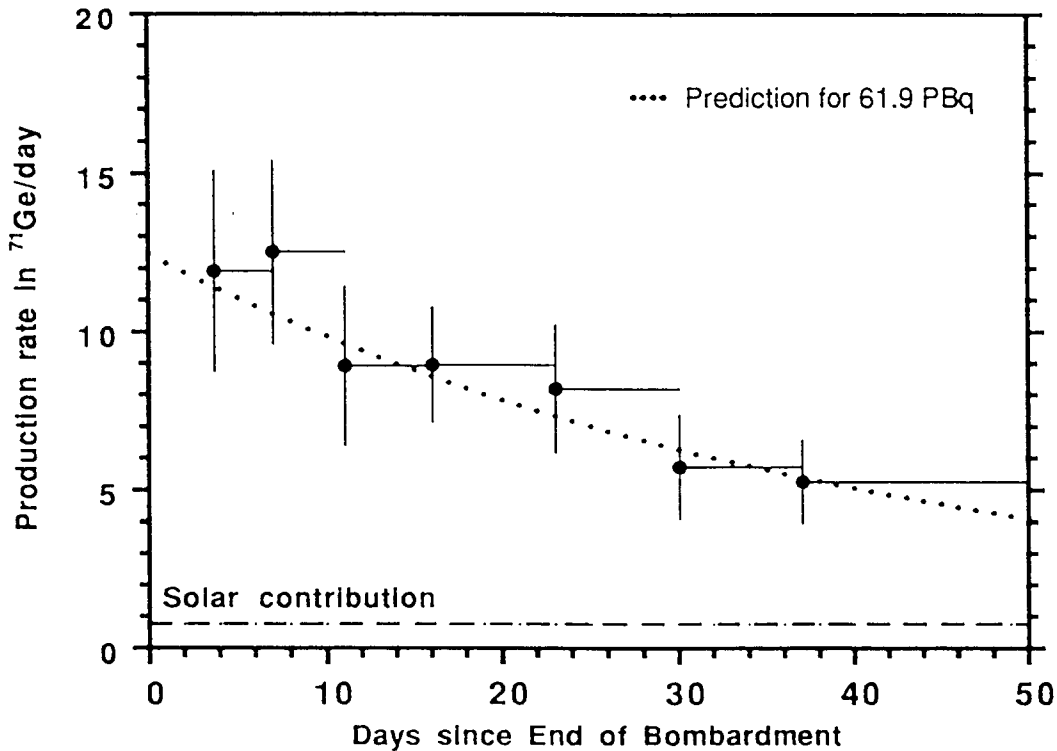


Figure 6: Number of ^{71}Ge atoms produced per day during the course of the source experiment (first 7 runs only). The points for each run are plotted at the beginning of each exposure, with the horizontal lines showing the duration of the exposures. The predicted curve (dotted line), which decreases with the known half-life of ^{51}Cr , is based on the relationship between the directly measured source strength and the 0.189 ^{71}Ge production rate per day. The curve also includes the constant $0.78/\text{day}$ production rate due to solar neutrinos and side reactions (dashed line).

and side reactions. Conversely, the last column of table 2 lists the \tilde{A}_0 values derived from the ^{71}Ge data obtained in each run. We see that the agreement of the \tilde{A}_0 values is good among these different runs.

From the global analysis of the first 7 source exposures, we deduce a mean initial source strength $\tilde{A}_0 = 64.1 \pm 6.6$ (statistical) ± 3.3 (systematic), i.e. 64.1 ± 7.4 after adding quadratically the statistical and systematic error. This value is to be compared with the directly measured ^{51}Cr source strength, $A_0 = 61.9 \pm 1.2$ PBq. The ratio of these values is $R = 1.04 \pm 0.12$, where the quoted error includes the experimental errors in ^{71}Ge counting and in the source activity determinations, but does not include errors in the neutrino-absorption cross-sections.

6 Discussion.

The close agreement between the numbers of ^{71}Ge atoms determined in the gallium desorptions and that predicted from the measured ^{51}Cr source strength provides a quantitative demonstration of the overall reliability of the GALLEX experiment. The ratio of 1.04, with its present 11 % error, clearly shows that the 40 % deficit of the solar neutrino flux observed by GALLEX, as compared to the SSM prediction, cannot be attributed to experimental artifacts. In fact, this source experiment directly demonstrates the validity of the basic principles of the radiochemical methods used in our solar neutrino detector : that on the order of ten radioactive atoms produced by neutrino capture can be removed from tons of target material, purified and counted quantitatively.

With particular regard to GALLEX, this comparison clearly demonstrates the absence of any significant mechanisms (such as “hot atom chemistry”) which could prevent the quantitative desorption of ^{71}Ge from the gallium chloride target solution, and validates the cuts for energy and rise-time that we use in our data analysis procedures. The result also shows that there are no serious discrepancies in the values of the neutrino cross-sections in ^{71}Ga leading to the ground state and the first two excited states of ^{71}Ge .

Figure 7 shows the energy levels of ^{71}Ge along with the corresponding energies of the monoenergetic neutrinos from the ^{51}Cr source and the solar ^7Be branch, as well as the end-point energy of the pp solar neutrinos. The cross-section for absorption of ^{51}Cr neutrinos by ^{71}Ga is $59 \times 10^{-46} \text{ cm}^2$, with a 10 % uncertainty [20, 21], dominated by the uncertainties on the correction due to the excited states (which represent 5 % of the ground state contribution) and the correction due to the forbidden terms in the capture rate [20]. We point out that the energies of these neutrinos are very close to the energies of ^7Be solar neutrinos (861 keV and 383 keV). In particular, the ^{51}Cr neutrinos, as well as the ^7Be neutrinos, can populate the first two excited states ($5/2^-$, $3/2^-$), as well as the $1/2^-$ ground state, of ^{71}Ge by allowed Gamow-Teller transitions.

To this point, our analysis has been based on the accepted values of the neutrino cross-sections. Now, we invert the argument by taking the value of the ratio, R , 1.04 ± 0.12 as fixed and free of systematic errors, and investigate how it affects the values of the cross-sections for the ground and reachable excited states of ^{71}Ge . In order to maximize the possible consequences for the ^7Be cross-section, and thereby

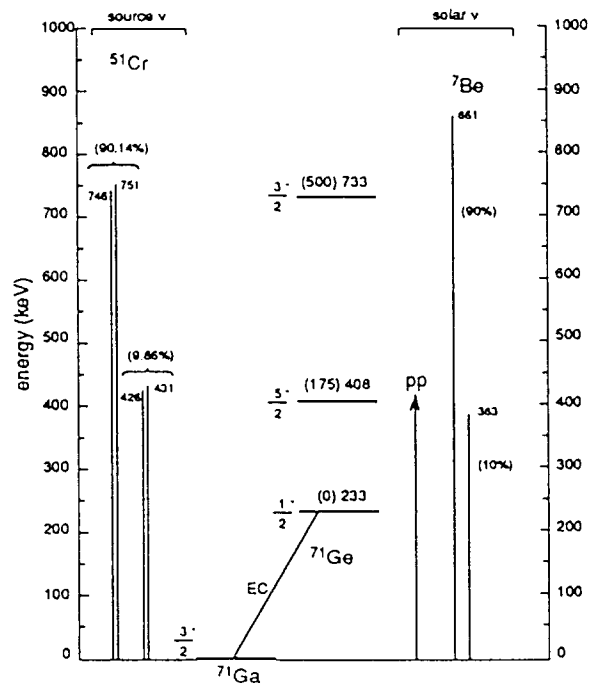


Figure 7: Energies of neutrinos from ^{51}Cr and the Sun (^7Be and pp branches), compared to the excitation energies of levels in ^{71}Ge . The vertical lines represent monoenergetic neutrinos and the arrow line the continuous energy spectrum of pp neutrinos.

understand the limits of possible changes, we attribute the full 5% of the excited state contribution to the highest reachable state of ^{71}Ge , at 500 keV. Then corresponding to the ± 0.12 range in R , the maximum spread in the strength of the transition to the 500 keV state is from 0 to ≈ 4 times the transition strength derived from the (p,n) reaction studies [24]. This result then indicates at most a small range from 6% below to 18% above the standard ^{71}Ga cross-section value for the ^7Be neutrino spectrum, corresponding to less than 5% uncertainty on the solar neutrino signal predicted by the SSM for gallium.

In summary, this test of GALLEX with an intense ^{51}Cr source that has a known, measured activity level has demonstrated that no unknown systematic effects take place at a level $\geq 10\%$. Because of the similarity of the neutrino energy spectra from ^{51}Cr and from the solar ^7Be branch, this experimental result also means that GALLEX is able to detect ^7Be neutrinos with close to full efficiency. This conclusion has important ramifications because the results of all the current solar neutrino experiments (but also of the gallium experiments alone) have recently been interpreted in terms of a severe depression of ^7Be neutrinos [25, 26]: for example, the low GALLEX solar production rate can be interpreted in a straightforward way to be caused by the full flux of pp and pep neutrinos as given by the solar luminosity value, but with a ^7Be neutrino flux that is very much below the predicted SSM value [26].

We note that, since the individual errors on the various experimental factors in the GALLEX experiment are evaluated independently as described in [4] and are smaller than the $\approx 10\%$ error on the measured value of 1.04, it is not justified to scale our published solar neutrino value by this factor.

After the ^{51}Cr source was removed from the GALLEX target, solar neutrino exposures recommenced on October 12, 1994. Another source experiment is planned in the autumn of 1995. It will be done by reirradiating the same enriched material in Siloé; indeed less than 0.5% of the ^{50}Cr was converted to ^{51}Cr in the first irradiation. The aim will be to reach with all the source runs an accuracy similar to that expected for the solar production rate after four years of data taking.

Acknowledgements

Many people contributed to the success of this experiment. We thank all the technical staff in Gran Sasso, Grenoble, Heidelberg, Karlsruhe, Kurchatov and Saclay, especially the team of the Siloé reactor for its efficient work before, during and after the

irradiation. We particularly thank F. Caperan, D. Franciotti, J. Gorry, P. Lamare, J. C. Languillat, P. Pagnozzi, P. Perrin, M. Renard and J. P. Soirat. J. Horowitz, D. Cribier and R. Aymar of the CEA and N. Cabibbo of the INFN strongly supported our scientific program and helped us to realize it. The GALLEX collaboration compliments the Kurchatov Institute, especially V. N. Prusakov and A. Tikhomirov, for the excellent quality of the enriched chromium provided to us in a timely manner. We would like also to express our appreciation to L. Lembo for his high skill and professionalism which insured work in strict compliance with all safety requirements. Finally, we thank J. N. Bahcall, for discussions concerning the neutrino capture cross-sections.

References

- [1] GALLEX Collaboration, P. Anselmann et al., Phys. Lett. B327 (1994) 377
- [2] S. Turck-Chièze and I. Lopes, Ap. J. 408 (1993) 347
- [3] J. N. Bahcall and M. H. Pinsonneault, Rev. Mod. Phys. 64 (1992) 885
- [4] GALLEX Collaboration, P. Anselmann et al., Phys. Lett. B285 (1992) 376, Phys. Lett. B314 (1993) 445
- [5] R. Davis, Prog. Part. Nucl. Phys. 32 (1994) 13
- [6] K. S. Hirata et al., Phys. Rev. D44 (1991) 2241, Y. Suzuki, Nucl. Phys. B (Proc. Suppl.) 35 (1994) 407
- [7] J. N. Abdurashitov et al., Phys. Lett. B328 (1994) 234
- [8] See for example N. Hata, S. Bludman and P. G. Langacker, Phys. Rev. D49 (1994) 3622; V. Berezhinsky, Comments on Nucl. and Part. Phys. (1994); J. N. Bahcall and H. A. Bethe, Phys. Rev. D47 (1993) 1298; S. Turck-Chièze, H. Dzitko and I. Lopes, in "Neutral Currents, 20 years after", Paris, July 1993, ed. by U. Nguyen-Khac and A. M. Lutz, p. 423; V. Castellani et al., "Neutrinos from the Sun : experimental results confronted with solar models", Preprint INFNFE-3-94, May 1994, submitted to Phys. Rev. D; X. Shi, D. N. Schramm and D. S. P. Dearborn, Phys. Rev. D50 (1994) 2414
- [9] E. Henrich and K. H. Ebert, Angew. Chem., Int. Ed. (engl.) 31 (1992) 1283

- [10] U.Schötzig and H.Schrader, Halbwertszeiten und Photonen-Emissionswahrscheinlichkeiten von häufig verwendeten Radionukliden, PTB-Bericht PTB-Ra-16/4, Braunschweig, 1993
- [11] M. Cribier et al., Nucl. Instr. and Methods A265 (1988) 574
- [12] S. F. Mughabghab, National Nuclear Data Center, Brookhaven National Laboratory, Neutron resonance parameters and thermal cross-sections (1984)
- [13] A. Tikhomirov, Nucl. Instr. and Methods B70 (1992) 1
- [14] M. Cribier et al., "Production of a 62 PBq ^{51}Cr artificial neutrino source for GALLEX", to be submitted to Nucl. Instr. and Methods
- [15] E. Bellotti et al., "Measurements of the gamma and neutron activity outside the GALLEX neutrino source", GALLEX internal note GX-63, to be submitted to Nucl. Instr. and Methods ¹
- [16] M. Cribier and J. Gorry, "Measurements of the ^{51}Cr source activity with the ionization chamber technique", GALLEX internal note GX-64, November 1994 ¹
- [17] Saclay group, "Calorimetric measurements of the ^{51}Cr source activity", GALLEX internal note GX-58, October 1994 ¹
- [18] A. Bevilacqua, "Production de la source de chrome de GALLEX et détermination de l'activité", GALLEX internal note GX-59, September 1994 ¹
- [19] M. Cribier, "Correction factor for finite extraction time and carry-over for source exposures", GALLEX internal note GX-55, August 1994 ¹
- [20] J. N. Bahcall, private communication
- [21] J. N. Bahcall and R. K. Ulrich, Rev. Mod. Phys. 60 (1988) 297
- [22] M. Cribier, "Optimization of the length of the exposures for the chromium neutrino source", GALLEX internal note GX-46, April 1994 ¹
- [23] B. Cleveland, Nucl. Instr. and Methods 214 (1983) 451.
- [24] D. Krofcheck et al., Phys. Rev. Lett. 55 (1985) 1051; D. Krofcheck, Ph. D. Thesis, 1987.

¹GALLEX internal notes are available on request by email at galexcoord@vaxgs.lngs.infn.it.

- [25] See for example W. Kwong and S. P. Rosen, Phys. Rev. Lett. 73 (1994) 369 ; J. N. Bahcall, Phys. Lett. B338 (1994) 276 ; S. Degl'Innocenti, G. Fiorentini and M. Lissia, "Where are the beryllium neutrinos", Preprint INFNFE-10-94, August 1994, submitted to Phys. Lett. B
- [26] GALLEX Collaboration, P. Anselmann et al., "Update of GALLEX solar neutrino results and implications", paper presented by T. Kirsten at the XVIth Int. Conf. on Neutrino Physics and Astrophysics, Eilat, Israel, May 29 - June 3, 1994, to be published in the Conference Proceedings (GALLEX internal note GX-60¹); W. Hampel, paper presented at the 3rd Int. Symp. on Nuclear Astrophysics, Nuclei in the Cosmos, Gran Sasso, Italy, July 1994, to be published in the Symposium Proceedings, American Institute of Physics (GALLEX internal note GX-62¹)

