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Solar neutrinos observed by GALLEX at Gran Sasso

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We have measured the rate of production of ⁷¹Ge from ⁷¹Ga by solar neutrinos. The target consists of 30.3 t of gallium in the form of 8.13 M aqueous gallium chloride solution (101 t), shielded by ≈ 3300 m water equivalent of standard rock in the Gran Sasso Underground Laboratory (Italy). In nearly one year of operation, 14 measurements of the production rate of ⁷¹Ge were carried out to give, after corrections for side reactions and other backgrounds, an average value of 83+19 (stat.) ± 8 (syst.) SNU (1 σ) due to solar neutrinos. This conclusion constitutes the first observation of solar pp neutrinos. Our result is consistent with the presence of the full pp neutrino flux expected according to the "standard solar model" together with a reduced flux of ⁸B + ⁷Be neutrinos as observed in the Homestake and Kamiokande experiments. Astrophysical reasons remain as a possible explanation of the solar neutrino problem. On the other hand, if the result is to be interpreted in terms of the MSW effect, it would fix neutrino masses and mixing angles within a very restricted range.

1. Introduction

Fusion reactions in the solar interior give rise to three major neutrino emissions:

(i) pp neutrinos from $p+p\rightarrow d+e^++\nu_e$; $E_{max} = 420 \text{ keV}$,

(ii) ⁷Be neutrinos from ⁷Be+e⁻ \rightarrow ⁷Li+ ν_e ; E = (mainly) 860 keV.

(iii) ⁸B neutrinos from ⁸B \rightarrow ⁸Be+e⁺ + ν_e ; $E_{max} = 14$ MeV.

Star models (e.g. refs. [1-5]) predict their respective fluxes. The relative values are $\phi_{pp}: \phi_{^7Be}: \phi_{^8B} \approx$ 1:0.08:0.0001. Detection of these neutrinos may test solar models [2-5] and/or neutrino properties (see e.g. refs. [6-11]). The radiochemical Chlorine Detector [12] is sensitive both to ⁸B and ⁷Be neutrinos, while the real-time Kamiokande Cherenkov de-

- ¹ Credit is given to valuable contributions of former GALLEX members which have helped to develop the experiment into its present state: B. Pichard [deceased] (Saclay); M. Breitenbach, G. Eymann, M. Hübner, A. Lenzing, G. Monninger, R. Schlotz, K. Schneider, M. Schneller, K. Zuber (all MPIK); J. Römer, J. Unk (KFK); A. Urban (TUM); G. Friedlander (BNL).
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tector [13,14] responds mainly to ⁸B neutrinos. Both have reported fluxes less than half of the theoretical expectations. This discrepancy has become the socalled "solar neutrino problem". Various explanations have been suggested; among them are overestimation of the central temperature in the solar model calculations, or electron-neutrino modifications between Sun and detector, a manifestation of neutrino mass.

The decision between these alternatives would be least ambiguous if a shortage of pp neutrinos were also observed. Given that the present Sun is producing fusion energy in equilibrium with its luminosity, a substantial reduction of pp neutrinos could only be due to some form of electron-neutrino disappearance. Flavor oscillations [7] resonantly enhanced in the dense solar interior, by the MSW effect [6], are a natural consequence of neutrino mass taken together with mixing of mass states in the physical neutrinos. The energy dependence of this effect permits determination of the neutrino-mass and mixing angle parameters.

In any case, the detection of pp neutrinos would be the first *experimental* proof of energy production by fusion of hydrogen inside the Sun. With respect to massive neutrinos we could exclude certain situations free of assumptions, but evaluate the regions of allowed parameter space of neutrino masses and mixing angles only with some ambiguity, since the effect need not be causal for the solar neutrino problem altogether.

A suitable reaction is ⁷¹Ga $(\nu_e, e^-)^{71}$ Ge. It was first proposed by Kuzmin [15] and will remain the only practical choice for a long time to come [16]. Its low threshold of 233 keV [17] allows the detection of pp neutrinos. The product ⁷¹Ge has a convenient halflife (11.43 d) [18] and can be isolated by radiochemical techniques. Two collaborations have set out to perform gallium experiments in underground laboratories, SAGE [19] in Baksan (Caucasus) and GALLEX at Gran Sasso (Central Italy).

In this letter we report the first neutrino data obtained with GALLEX in 14 runs during the period 14 May 1991-31 March 1992 ("GALLEX I") ^{#1}, covering 295 d of exposure.

The history and development of GALLEX as well as many experimental aspects have been given in previous reports, see e.g. refs. [20-29]. Here we describe the experimental aspects (section 2); side reactions and background considerations (section 3); and the runs performed (section 4). In section 5 we sketch the data treatment and present the preliminary results. Implications of these results are dis-

*1 Phase "GALLEX I" extends until 29 April 1992, but run B 50 came too late to be included in the present data analysis (see table 1). cussed in the accompanying Letter [30]. The future experimental program is outlined in section 6 together with our conclusions.

2. The GALLEX experiment

2.1. General description

For the inverse beta-decay reaction ${}^{71}\text{Ga}(\nu_e, e^-){}^{71}\text{Ge}$, standard solar models (SSM) predict production rates ranging from 124 SNU [4] to 132 SNU [3] ${}^{\#2}$. The value from ref.[3], (132_{-17}^{+21}) SNU (3 σ) is composed of 74 SNU from pp (and pep) neutrinos, 34 SNU from ${}^{7}\text{Be}$, 14 SNU from ${}^{8}\text{B}$ and 10 SNU

^{#2} SNU = solar neutrino unit, 10^{-36} captures atom⁻¹ s⁻¹.

Table 1			
Gallex I	runs B	29-B	50

Type/ctd. # ^{a)}	Run #	Time period	Duration (d)	Carrier ^{b)}	(%)Ge yield ^{c)}	Position ^{d)}	End of counting
SR I	B 29	14.05.91-04.06.91	20.96	74	83.7	а	07.01.92
e)	B 30	04.06.91-05.06.91	1.27	72	88.0	а	-
SR 2	B 31	05.06.91-26.06.91	20.77	76	84.4	а	07.01.92
SR 3	B 32	26.06.91-17.07.91	21.00	74	85.0	а	ongoing
SR 4	B 33	17.07.91-07.08.91	21.00	72	87.0	а	18.02.92
SR 5	B 34	07.08.91-28.08.91	21.00	76	85.2	а	10.03.92
SR 6	B 35	28.08.91-19.09.91	22.25	74	92.6 ^f)	а	30.03.92
SR 7	B 36	19.09.91-09.10.91	19.70	72	93.5	р	ongoing
BL 1	B 37	09.10.91-10.10.91	1.17	76	92.8	р	30.03.92
SR 8	B 38	10.10.91-30.10.91	19.87	74	88.8	p	ongoing
SR 9	B 39	30.10.91-20.11.91	20.96	72	92.4	р	ongoing
BL 2	B 40	20.11.91-21.11.91	1.17	76	92.8	р	ongoing
SR 10	B 41	21.11.91-11.12.91	19.88	74	90.9	р	ongoing
SR 11	B 42	11.12.91-08.01.92	27.96	72	90.6	р	ongoing
BL 3	B 43	08.01.92-09.01.92	1.17	76	94.2	р	28.04.92
g)	B 44	09.01.92-29.01.92	19.88	74	-	р	-
SR 12	B 45	29.01.92-19.02.92	20.96	72	92.8	р	ongoing
BL 4	B 46	19.02.92-20.02.92	1.21	76	93.8	р	ongoing
SR 13	B 47	20.02.92-11.03.92	19.81	74	86.1	р	ongoing
BL 5	B 48	11.03.92-12.03.92	1.19	72	92.8	р	ongoing
SR 14	B 49	12.03.92-31.03.92	18.83	76	93.2	р	ongoing
SR 15 ^h	B 50	31.03.92-29.04.92	29.00	74	89.1	р	ongoing

^{a)} SR = solar neutrino run, BL = short exposure blank run (full scale, involving target).

^{b)} 72, 74, 76 indicate the use of carrier solutions enriched in ⁷²Ge, ⁷⁴Ge, ⁷⁶Ge, respectively.

^{c)} Integral tank to counter yield, errors are $\pm 1.7\%$.

^d) a = active (NaI) counting position; p = passive counting position (see text).

e) Not used because of malfunction of HV-supply while counting.

⁽⁾ Since B 35, yields are higher due to mist acidification applied in the desorption steps.

^{g)} Run lost in preparation.

^{h)} Too late to be included in the present data analysis.

from $({}^{13}N + {}^{15}O)$. Our target is 30.3 t of gallium containing 12 t of ${}^{71}Ga$ in the form of an 8.13 M aqueous solution acidified to 2 M in HCl. For our target, the 132 SNU value of ref.[3] would yield an expected production rate of 1.18 atoms d^{-1} of ${}^{71}Ge$ or approximately 14 atoms of ${}^{71}Ge$ present in the target solution after \approx three weeks of exposure.

To minimize interfering ⁷¹Ge production through (p, n) reactions, the target must be free of radioactive impurities and effectively shielded from cosmic rays. Also, the local fast neutron flux must be low to avoid the creation of secondary protons.

The high concentration of chloride and the acidity of the solution ensure that the Ge will be in the form of the tetrachloride. The volatility of $GeCl_4$ allows it to be separated from the non-volatile $GaCl_3$ by bubbling an inert gas through the solution. Extensive experiments at several of our laboratories and on various scales showed that this separation can be carried out quantitatively, even without the addition of carriers [31–34]. In practice, a small known amount of non-radioactive germanium (about 1 mg) is added to the solution in each run to determine the actual yield of the process and to monitor its efficiency.

The GeCl₄ swept out of the solution by the stream of nitrogen is reabsorbed in water and after several stages of volume reduction is chemically converted to the gas, germane (GeH₄). After purification, the germane is introduced into a special miniaturized very-low-background proportional counter where the EC decay of ⁷¹Ge is detected. The radiations actually observed are Auger electrons and stopped X-rays (keV range). To achieve the very low and constant backgrounds required for a reliable detection of the few ⁷¹Ge decays expected during the first two months of counting, ultimate low-level techniques must be applied in a very stable experimental environment. Four years of running time are scheduled to achieve the desired statistical significance

Special tests using samples of actual B-tank solution (see below) were carried out to seek any "hot atom" effects that might influence the Ge recovery:

In one such test, ⁶⁹Ge was produced in situ via ⁶⁹Ga(p, n)⁶⁹Ge with ≈ 10 MeV protons and subsequently purged. The extraction efficiency of > 99% was directly determined from the ratio of the 1106 keV y-lines of ⁶⁹Ge measured with a Ge detector before and after desorption in the unchanged irradiation vessel.

In another series of tests, ⁷¹Ge was produced in situ by EC decay of ⁷¹As. This decay approximately reproduces the kinematics of neutrino capture in ⁷¹Ga. The results from counting of ⁷¹Ge showed that these daughter atoms behaved identically chemically to the 1 mg of germanium carrier that had been added to the gallium chloride solution. Recovery of the ⁷¹Ge was quantitative, (99.8 \pm 3.7)%.

In summary, there were no Ge "hot atom-chemistry" effects which would effectively influence our results. Yet we are aware that these conditions are not *fully* identical to the capture of solar neutrinos in the gallium chloride target. Thus, a full-scale test of the GALLEX experiment is planned for 1993, when we will produce $a > 5 \times 10^{16}$ Bq ⁵¹Cr neutrino source that will be inserted into the target tank.

2.2. Experimental setup

This description is condensed. We refer to an illustrated version in ref. [23] and reports as quoted.

The GALLEX underground facilities are located in hall A of the Laboratori Nazionali del Gran Sasso (LNGS) [35,36], easily accessible by a 6.3 km highway from the tunnel entrance. One building accommodates two 7 m high 70 m³ target tanks, the Ge extraction facilities (absorber columns and automatic control system), duplicate GeH₄ synthesis and counter-filling stations, and a calcium-nitrate neutron monitor. Nearby, another building houses the main counting station enclosed in a Faraday cage, and the computer and electronics laboratory. Above ground, near the tunnel entrance, is the Technical Outside Facility ("TOF"), where the target solution was received and preconditioned.

We have installed two similar tanks, "A" and "B", for redundancy and safety [31]; only one is used at a time. All experiments reported here were done in tank B, runs B 29–B 50. The tanks are made from vinylester resin reinforced by special glass fibers selected for low U/Th content (Corning "S2"). Inside, they are lined with PVDF. This teflon-like material is also used for the sparger pipes within the tanks. These pipes are perforated to distribute the purging gas throughout the solution. The gas used is nitrogen, generated by the evaporation of liquid nitrogen stored in a vessel nearby.

The target tank A is equipped with a central elongated thimble designed to contain the ⁵¹Cr neutrino source, as well as to accommodate a 470 L vessel containing the calcium-nitrate solution to monitor the fast-neutron background (see section 3).

In many years of proportional counter development, we have continuously refined and optimized the counter design and operating conditions for performance, stability, efficiency, and background [37-40]. The final model, "HD2-Fe/Si" is made from hyperpure Suprasil quartz. It is miniaturized and features a solid Fe or Si cathode (made from single silicon crystals with impurities ≤ 2 ppt ²³⁸U; ≤ 0.2 ppt 232 Th; ≤ 0.1 ppb 40 K) and a 13 μ m tungsten anode wire directly sealed into quartz. Active volumes are typically 87%. At present, 22 low-background counters of this type are in use. Special quartz-blowing technology is used to standardize dimensions (6.4 mm diameter, 32 mm length, $\approx 1 \text{ cm}^3$ total volume) so that all counters are similar to each other. The counters are inserted into form-fitted Cu/low activity-Pb housings with void space minimized for radon suppression. The counters operate within a large shield tank inside a Faraday cage. This tank is fitted with 8.6 t of low radioactivity lead. Two sliding-end doors, also filled with lead, are attached to the tank. Entry is via flexible glove-boxes designed to allow handling of counters without venting the low-radon atmosphere inside. At present we can simultaneously operate eight "active" counter lines positioned in the well of a NaI-pair spectrometer at the front end of the shield tank [41] and sixteen "passive" lines positioned in a low radioactivity copper block at the opposite end. The choice of which positions to use is a trade-off between the lower counter backgrounds on the passive side and the diagnostic power of the NaIspectrometer (see table 1).

The pulses from the proportional counters are amplified with fast charge-sensitive preamplifiers, wideband low noise amplifiers for pulse shape analysis, and shaping amplifiers for pulse-height analysis. Pulse heights are measured in 12 bit ADCs. The rise time can be determined by measuring the amplitude of the differentiated pulse (ADP, time constant 10 ns). Moreover, in order to discriminate later between the desired events and background, the whole pulse shape is recorded with transient digitizers on different time scales (smallest bin width 0.4 ns). We prefer this superior technique and use it exclusively. We define the rise time as the time elapsing between 10% and 70% of the pulse height, registered with the fast transient digitizer. Multiple lines are served by a self-switching multiplexer system connecting to a single Tektronix 7912 AD fast transient digitizer. The overall bandwidth is 100 MHz. The amplitudes of the pulses in the NaI-pair crystal are measured with a 13-bit buffer ADC and a slow transient digitizer. All modules are read out over a CAMAC bus linked with optical fiber cable to a MicroVAX II outside the Faraday cage [42].

2.3. Experimental procedures

A new run starts with the addition of $\approx 1 \text{ mg of a}$ stable germanium carrier to the target solution after the end of the previous extraction. The carrier solution is added during 10 min through a pipe at ≈ 1 m below the liquid surface. During and after the addition, the solution is stirred by a gentle stream of nitrogen for ≈ 9 h in a closed loop. To monitor carryover from one run to the next by means of a subsequent mass-spectrometric analysis of the counting gas, we successively use carrier solutions of stable enriched isotopes: 72Ge, 74Ge and 76Ge. The Ge concentrations of the stock solutions are determined by atomic absorption spectroscopy and cross checked by other methods. During two years of operation, no measurable concentration changes have been found. At the end of the exposure time, usually three weeks, the Ge in the solution is recovered by purging with 1900 m³ of nitrogen during 20 h at 20°C. Typically 99% of the carrier is extracted. Proper corrections are made for carryover from previous runs.

The volatile germanium tetrachloride is recovered by scrubbing the gas with 50 L of counter-flowing water at $12 \,^{\circ}$ C in three large absorber columns (3 m height, 0.3 m diameter), packed with glass helices. The resulting aqueous solution of Ge is further concentrated by acidifying it with HCl gas to 30% hydrochloric acid, purging the solution again with a stream of nitrogen and reabsorbing the volatilized GeCl₄ in about 1 L of water. Further volume reduction is effected by acidifying this solution and extracting the Ge in 500 mL of carbon tetrachloride. The GeCl₄ is then back extracted into 50 mL of tritium-free water, and this final solution is used to generate germanium hydride (GeH₄). At pH of 11.4, the Ge solution is mixed with a solution of 0.3 g of low-tritium sodium borohydride in tritium-free water and gently heated. The germane produced is entrained in a stream of helium and passed through a gas-chromatographic column for purification. The volume of the purified germane is measured with high precision using a McLeod gauge. To optimize the counting performance [39], the gas mixture introduced into the low-background counters at a slight overpressure is germane (30%), old xenon (70%).

The integral yield of the germanium recovery is defined as that fraction of the carrier added to the GaCl₃ solution in the tank that ends up in the counter. The integral yields for the individual runs are given in table 1.

After the counter is filled, it is imbedded in its lead mold, fitted into the preamplifier box and transported into the Faraday cage. The counter box is inserted by way of the air lock. After connection to the counting system, it is calibrated with the Gd(Ce) source (see below) inside the tank shield and then inserted into its final counting position. The operating voltage is ≈ 1600 V. The period from the end of extraction to the start of counting is typically 14 h.

To insert the newly filled counter into its operating position, all counting has to be stopped. In routine operation, such interventions occur approximately every three weeks, and we have adopted the procedure of calibrating half of the counters at each interruption. Thus, every counter is calibrated every six weeks. To obtain accurate backgrounds, each sample is counted for > six months, a period that is very long compared to the 11.43 d half-life of ⁷¹Ge.

The Ge-decay (gallium) peaks occur at 1.17 keV (L-peak) and 10.37 keV (K-peak). For energy calibration, we use fluorescent X-rays from the xenon in the counting gas. These are produced by ≈ 35 keV Ce X-rays from the excitation of cerium by europium X-rays from the EC decay of a ¹⁵³Gd source (half-life 242 d). This method has the great advantage that the entire active counter volume is rather homogeneously illuminated, and that three lines are available at energies of 1.03, 5.09 and 9.75 keV [43]. From such calibrations, one also derives the energy resolution of the counters.

Energy resolutions (FWHM) of our counters are typically 26% for the K-peak and 43% for the L-peak. The K-peak resolution is not as good as one would expect from the value for the L-peak because we choose to operate at a rather high gas-amplification for a better signal-to-noise ratio for superior pulse shape analysis. This is particularly beneficial for Lpulses (see below). For this, we accept a slightly nonlinear energy scale above 5 keV.

The energy resolution and the absolute counting efficiencies for both peaks are obtained from a comparison with Ce source calibrations of counters filled with high ⁷¹Ge activities. This was done in Heidelberg using a counting system similar to that at Gran Sasso. The Ce source obviates the need to bring highactivity ⁷¹Ge sources to the Gran Sasso Laboratory with the attendant risk of contamination. Average counting efficiencies (2FWHM) are $\varepsilon_L = 30.6\%$ and $\varepsilon_{\rm K}$ = 35.2%; hence the overall efficiency is 65.8%. Individual values depend mainly on the ratio of the active volume to the total volume of a counter. The total relative error of the efficiencies is $\pm 4\%$. The error sources are: (i) determination of L- and K-peak positions and of energy resolutions by means of Ce calibrations, (ii) absolute ⁷¹Ge counting efficiency calibrations at MPIK, away from Gran Sasso, and (iii) application of these values to the counters used in the actual solar neutrino runs.

The stability of the counting system is very good; the energy scale and the energy resolution have not changed significantly during the counting times relevant in our experiment.

Pulse shape analysis distinguishes between genuine *fast* rising pulses due to point-like ⁷¹Ge decays and *slow* pulses of extended ionization tracks from Compton-like background events where the primary ionization occurs at various radial distances from the anode wire. Since this analysis is the basis for the recognition of ⁷¹Ge counts, and defines the pulse shape acceptance cuts, the pulse shape stability over extended time periods is crucial. It is checked at each calibration. In addition, there is routine monitoring of the shapes of the test pulses that are regularly fired at each line, currently once every two hours of counting.

During regular counting, the environment inside the Faraday cage remains very stable, the room is never entered and the temperature and the radon concentration inside and outside the shield tank are continuously monitored.

The final acts in an individual run are the quantitative recovery of the counting gas after the end of counting, and the mass-spectrometric isotope analysis to check carryover, as described above.

3. Side reactions and background considerations

⁷¹Ge production from non-neutrino sources ("side reactions") is largely dominated by the reaction ⁷¹Ga(p, n)⁷¹Ge, with the threshold energy of 1.02 MeV. The protons may be secondaries induced by cosmic-ray muons, fast neutrons, or residual radioactivities in the target, e.g. (α, p) , (n, p) or knock-on protons. The measured contributions from different side reactions are subtracted from the measured ⁷¹Ge rate to give the net rate induced by solar neutrinos.

Concerning penetrating muons, we have redetermined the relevant ⁷¹Ge production rate in GaCl₃ solution at the CERN muon beam [44]. Together with the measured muon flux at the underground site $((27\pm3)m^{-2}d^{-1})$ [45], this led to an estimate of the cosmic-ray induced ⁷¹Ge production rate in the target geometry equivalent to 3.7 ± 1.1 SNU [44]. ⁷¹Ge production from atmospheric high energy neutrinos is negligible (see e.g. ref. [46]).

The target solution was conditioned to a Cl/Ga ratio of 3.24, suitable for Ge extractions according to our extraction pilot experiments. The levels of impurities specified for the gallium chloride solution, which were met by the manufacturers, guaranteed that their contributions were negligible *3 (see table 2). The purity specifications are based on the rate of production of ⁷¹Ge by α -particles and fast neutrons as measured in experiments with concentrated GaCl₃ solutions irradiated with α -particles at various energies and with fast neutrons from a Pu-Be source [32]. The levels of critical impurities were checked by neutron activation analysis (for U, Th, Fe, As, Se) and by radon determinations using proportional counting (table 2) [47]. Note the remarkably low value for the critical ²²⁶Ra concentration. We check the pu-

Table 2

Key properties of the target solution.	Colour is water clear with a
slight yellowish shade.	

	Measured	Specification
Ga (g/L)	567 $\pm 2^{a}$	565 ± 10
Cl(g/L)	937 ±4°)	
Cl/Ga (mol/mol)	3.24 ± 0.01	> 3.15
density (g/mL)	1.887	
²²⁶ Ra (pCi/kg)	≤0.04	< 0.50 ^b)
U(ppb)	< 0.04	<25 ^b)
Th (ppb)	< 0.04	< 2 ^b)
Zn (ppb)	≈20	
Se (ppb)	0.2	
As (ppb)	0.6	
Ge (ppb)	< 0.5	

a) Statistical error of multiple analyses.

^{b)} These specifications would lead to a 1% contribution to the SSM ⁷¹Ge production rate for each individual background source.

rity of the target solution at approximately yearly intervals and so far it has not changed. Quantitatively, the contributions from internal U, Th and Ra are limited to less than the equivalent of 0.2 SNU.

The impurity levels are specified for the natural radioisotopes. Contamination with transuranic nuclides is not impossible in today's environment, and therefore we have checked for the presence of transuranium elements by means of hypersensitive α spectrometry. The levels found for these nuclides are negligible in terms of their ⁷¹Ge production.

The environmental fast neutron flux at the GALLEX site is measured to be $\phi_n (\ge 2.5 \text{MeV}) = 0.23 \times 10^{-6} \text{ cm}^{-2} \text{ s}^{-1}$ [48,49]. This flux, together with neutrons from the tank walls, was effectively monitored with our 470 L Ca(NO₃)₂ solution [44]. By measuring the ³⁷Ar produced in the ⁴⁰Ca(n, α)³⁷Ar reaction, the ⁷¹Ge production rate can be scaled. The ⁷¹Ge production rate due to fast neutrons at the experimental site is estimated to be equivalent to 0.15 ± 0.10 SNU [44].

In the early testing phase of GALLEX, we have encountered an unexpected, and temporary, background effect caused not by a side reaction but by residual cosmogenic long-lived ⁶⁸Ge (half-life 288 d) [26,27,29,33]. This isotope is produced in GaCl₃ solutions exposed to cosmic rays at the surface; we estimate that $\approx (1.7 \pm 0.2) \times 10^{7}$ ⁶⁸Ge atoms were produced in the target before it was brought underground

^{*3} We acknowledge the personal concern of Dr. H. Pfeiffer (Gebr. Sulzer) and of Dr. Y. Calvez (Rhône-Poulenc) to meet our quality requirements for the target solution.

[26]. To eliminate this isotope, we purged the solutions received from the manufacturers in the TOF immediately before transfer of the material into the underground laboratory. Purging was continued after the target solution was in tank B (see refs. [26,29]); however, residues of this initially high activity proved hard to remove. It seems that a small fraction of the ⁶⁸Ge activity was picked up by some trace impurity in the material – most likely polysilicic acids – which released it only slowly. Heat treatment and repeated purging in 28 extraction runs reduced this extraneous activity due to 68Ge to the level of our very low general counter backgrounds (see section 5). The long life of this isotope and its characteristic decay (positrons from the 68 min ⁶⁸Ga daughter) make it distinguishable from ⁷¹Ge. It should be emphasized that this effect is of such a small magnitude as to make it undetectable in terms of recovery yields. If it were not for the very high initial level of ⁶⁸Ge in the solution, the effect would not have been detected.

⁶⁹Ge is not formed in appreciable yield by solar neutrinos, but can be produced from ⁶⁹Ga by (p, n) secondary reactions. Hence, it can serve as a useful monitor of various side reactions caused by impurities, such as the various α -induced reactions discussed above. In none of the runs employing the NaI spectrometer have we seen a single decay with the specific EC/ γ signature of this short-lived isotope (half-life of 39 h), but we have not yet fine tuned this check to its full potential sensitivity by tailoring exposure time in devoted runs.

Another possible source of background is the tritium content of the hydrogen atoms of the germane in the counting gas. We have reduced this factor by using low tritium material in all the relevant steps in the synthesis of germane. We estimate that the tritium contribution to the background is negligible (<0.01 cpd in the acceptance windows).

²²²Rn (half-life 3.82 d) and its daughters are ubiquitous constituents of laboratory air, especially underground, and at our level of operation are great nuisances. Great pains have been taken to avoid even traces of radon inside and outside our counters [50]. Nevertheless, we have not yet succeeded in eliminating this interference entirely. On the average, the level of this impurity per run introduced with the counting gas is about three ²²²Rn atoms, which produce about one count in the ⁷¹Ge acceptance windows. Fortu-

nately it is possible to recognize the signature of the decay of Rn and its daughters and thus minimize their interference. The radon decay chain includes three α - and two β -decays within less than 3 h. The signatures are overflow counts produced by the energetic α -particles and a very characteristic delayed coincidence of ²¹⁴Bi β - and ²¹⁴Po α -decays ("BiPo" events). The delay due to the 164 μ s ²¹⁴Po half-life is registered with a slow transient digitizer. We have adopted respective cuts to eliminate radon-related counts from the data (see section 5). Their efficiency is 92%; the dead time imposed during the first month of counting is 4% in typical runs. From the tagged Rn events and from their known influence on the final result if they were falsely attributed to ⁷¹Ge decays, we remain with a 2 ± 1 SNU equivalent subtraction for unidentified Rn events.

4. GALLEX 1: run schedule from B 29-B 50

Since 14 May 1991 we have monitored the solar neutrino signal continuously, at the very low background level for which the experiment was designed. In table 1 we list the dates and the chemical yields of the individual runs from B 29–B 50. These runs define the data taking period "GALLEX 1", terminated on 29 April 1992. During these 50 weeks we have performed 16 solar neutrino runs, 14×3 weeks and 2×4 weeks . One of them (B 44) was lost in preparation; the other fifteen are consecutively labeled ^{#4} SR 1–SR 15; see table 1 for their B number equivalent. In addition, five blank runs (BL 1–BL 5) have been carried out with minimal exposure times.

The duty factor of 94% for the preparative part of the experiment is well matched by the 97% running time of the counting system. This time splits into 94.5% for sample counting, 2.2% for calibration runs and 0.2% for test runs.

In order to determine the counter background rates properly, it is necessary to count much longer than a few ⁷¹Ge life-times. This Letter is based on data taken until 18 May 1992. As of that date, 13 out of the 20 SR and BL runs of GALLEX I were still counting; only seven experiments have really been completed (see table 1). For this reason and for the limited

^{#4} SR stands for solar neutrino run.

number of runs done, the data reported in this paper should be considered preliminary. They will be reevaluated in due time with the complete experimental information then available and probably treated with more sophisticated pulse shape criteria than at present. We do not expect, however, any *substantial* changes in the preliminary data presented here.

5. Data treatment and results

5.1. Data treatment

The first phase of data treatment is to eliminate obvious background events.

(i) *Nal-veto* cancels counter pulses which are time coincident with a signal above a defined noise level in either half of the NaI anticoincidence pair-spectrometer. This cut applies only for runs in the active positions, SR 1–SR 6 (see table 1). Nuclides other than ⁷¹Ge can be observed in the coincidence mode (e.g., 69 Ge, 214 Bi).

(ii) Radon daughters outside the counter can stick on the outside surfaces of the counter during handling. Because they are short lived, we cancel the first three hours after start of counting. Since SR 5, this disturbance has been eliminated by a minor modification of the counter filling procedure.

(iii) Radon inside the counter is eliminated by the following cuts: We ignore all events occurring up to 3 h after and 15 min before an unvetoed overflow event ($\geq 16 \text{ keV}$). This covers all cases where at least one of the initial two α -particles of the radon decay chain is seen. In addition, we ignore all counts occurring up to 3 h before a BiPo event.

Having removed these background events, we plot the rise time versus energy for the remaining events. Fig.1 shows such data combined, for all but two ^{#5} solar neutrino runs collected during the first 16.49 days (mean life of ⁷¹Ge) respectively.

Groupings of fast pulses are seen in the relevant energy regions around 1 and 10 keV. The energy spectrum of the "fast" events (for all 14 SR runs) is shown in fig. 2a for the first mean life $(0\tau-1\tau)$ of ⁷¹Ge. The L- and K-peaks of ⁷¹Ge are clearly seen. Similar plots for the time periods $(1\tau-2\tau)$ and $(2\tau-4\tau)$, re-



Fig. 1. A plot of all events occurring in 12 solar runs during the first 16.49 days (one mean life of ⁷¹Ge) after the respective ends of extraction. The L- and K-energy windows are expanded to cover *all* individual runs included in this illustration. Runs SR 10 and SR 11 are not included since complete rise-time information is not available for them.

spectively, are shown in figs. 2b and 2c. The decay of the peaks over the characteristic ⁷¹Ge lifetime is evident. For comparison, fig.2d shows the energy spectrum of a ⁷¹Ge calibration sample.

To quantify the magnitude of the signal, we select the events that are candidates for 71 Ge decays by applying the following cuts (fig.1):

(i) *Energy* acceptance windows for L- and K-peaks are determined for each counter individually using all available calibrations for that run as described in section 2 (2FWHM acceptance).

(ii) Pulse shape acceptance windows are based on short rise times. These rise-time cuts encompass 97.7% of L-pulses ("L-fast") and 95% of K-pulses ("K-fast"). For runs SR 10, SR 11, and BL 3 the risetime windows were completely opened since there was a fluctuation (the energy remained stable). ADP values are also available for eventual cross-checks.

The event list obtained is used for a maximum likelihood analysis, as conveniently summarized for this type of application by Cleveland [51]. The initial number of ⁷¹Ge atoms is obtained by fitting the data to the assumption of a component decaying with 16.49 d mean life plus a constant background, determined for each individual measurement.

⁶⁸Ge can not be identified on an individual basis but only on its long time effects on the counter backgrounds. With the described coincidence method we

^{*5} For runs SR 10, SR 11, the rise-time information is incomplete.



Fig. 2. Energy spectra for the fast events of 14 solar neutrino runs during different counting periods after the end of extraction: (a) $(0\tau-1\tau)$ ($\tau=^{\tau_1}$ Ge mean life); (b) $(1\tau-2\tau)$; (c) $(2\tau-4\tau)$; (d) measured spectrum from a ⁷¹Ge calibration sample. The decay of ⁷¹Ge during subsequent mean lives is evident. Identical curves are inserted in (a) – (c) to facilitate cross comparisons.

have identified in six runs during their total counting time altogether eight ⁶⁸Ge decays. Using this information, we assume in the maximum likelihood analysis also a known background component decaying with 288 d half-life.

The result of the likelihood analysis is plotted in fig. 3 (solid line) as a function of counting time along with the count rates of fast L- and K-events averaged over all 14 solar neutrino runs. Although individual



Fig. 3. Count rate of fast L- and K-events averaged over all 14 solar neutrino runs as a function of counting time. The solid line represents the best fit to the data obtained with the maximum likelihood method allowing: (i) 71 Ge, (ii) counter backgrounds, and (iii) a small fixed contribution from 68 Ge (see text).

data points deviate from the fitted curve due to statistical fluctuations, the signal attributed to the decay of solar neutrino produced ⁷¹Ge can clearly be seen in the data.

We do analyses (i) for the individual runs, (ii) for all SR runs combined, and (iii) for all BL (blank) runs combined. Furthermore, we analyse the K- and L-windows separately, as well as the K- and L-windows combined.

The resulting decay rates in atoms per day are converted into production rates by taking into account the extraction yields, the individual counter volume efficiencies, and the exposure and delay times respectively of the individual runs. Common to all runs and contributing to the systematic errors are the uncertainties of quantities such as the target size, the general extraction efficiency, the normalized counting efficiency when using the standard cuts, and the side-reaction corrections. The correction for ⁶⁸Ge before-hand taken care of in the likelihood treatment (see above) has a magnitude equivalent to 9 SNU and introduces an error equivalent to ± 5.5 SNU.

5.2. Results

The ⁷¹Ge production rates measured for the individual solar neutrino runs are plotted versus the date of the respective exposures in fig. 4, left-hand scale. Monte Carlo simulations have shown that their distribution is fully consistent with statistical fluctua-



Fig. 4. Results of the first year of solar neutrino recording for runs SR 1–SR14. The left-hand scale is in units of the measured production rate, the right-hand scale, in units of the net solar production rate. Error bars shown are 1σ . The individual data are consistent with statistical fluctuations only.

tions. For the combined SR runs, the analysis gives a mean production rate of $(90 \pm 19) \times 10^{-36}$ ⁷¹Ge atoms (target atom)⁻¹ s⁻¹ (1 σ) before corrections for side reactions. The answers obtained if L- or K-peaks are analyzed separately do not differ significantly from the combined result.

Next, we subtract the known contributions which are not due to solar neutrinos (see section 3): muon induced production: (3.7 ± 1.1) SNU,

actinides in the target: <0.2 SNU,

fast neutrons: 0.15 ± 0.10 SNU.

radon cut scaled to 100% efficiency: 2 ± 1 SNU,

 69 Ge from muons and 8 B neutrinos falsely attributed to 71 Ge: 1 ± 1 SNU.

This yields a net rate associated with solar neutrinos of 83 ± 19 (stat.) ± 8 (syst.) SNU (1 σ) (fig. 4, right-hand scale).

Apart from the side reactions and the ⁶⁸Ge correction mentioned above, additional contributions to the final systematic error (expressed in SNU equivalents) come from uncertainties in the chemical yield (± 1.5) , the counting efficiency (± 3.6) , and the risetime cut (± 1.8) .

The systematic errors were estimated from the figures quoted under the additional assumption that: (i) no unidentified background reactions exist and (ii) that the extraction yield is not much different from the monitored efficiency due to hot atom effects. These conjectures seem justified to us in view of the results from the relevant investigations (see sections 2 and 3).

The statistical errors are consistent with the results of respective Monte Carlo simulations.

The final results for the individual SR runs are given explicitly in table 3, last column. For comparison, we also list the results obtained if K- and L-windows are analyzed separately by maximum likelihood.

The counter backgrounds (without sample) are typically 0.10 cpd (L-fast) and 0.05 cpd (K-fast) in the "active" counting positions and 0.07 cpd (K+L fast) in the "passive" lines [41]. Our combined analysis for B runs since B 29 reveals that the additional ⁶⁸Ge contribution per run contributes about 0.03 cpd (L-fast) and 0.04 cpd (K-fast). This component stems from the target tank where it is decaying with 288 d half-life. It corresponds to 2.5 ± 1.5 ⁶⁸Ge atoms released per day of standing time and is taken into account as described.

In order to check the reliability of the result of the experiment, we have performed a number of tests which corroborate the findings:

(i) The overall result is notably stable to changes in the energy and rise-time cuts, even to complete opening of the rise-time windows.

Table 3 Results for individual solar neutrino runs^{a)}.

Run #	L-only (SNU)	K-only (SNU)	L+K combined (SNU)
SR 1	97	49	72+64
SR 2	69	33	48^{+79}_{-48}
SR 3	339	255	291^{+121}_{-106}
SR 4	10	94	54^{+72}_{-54}
SR 5	0	0	0^{+47}_{-0}
SR 6	67	177	131^{+87}_{-74}
SR 7	41	179	109^{+62}_{-50}
SR 8	176	102	134^{+85}_{-71}
SR 9	200	48	108^{+80}_{-63}
SR 10	0	83	41^{+89}_{-41}
SR 11	156	62	96^{+70}_{-58}
SR 12	24	0	0+55
SR 13	317	78	187^{+81}_{-74}
SR 14	0	0	0^{+167}_{-0}

a) Negative production rates or errors occur for individual runs due to statistics and are truncated at the end since they are unphysical. This effect does not apply to the combined analysis which yeidls the mean production rate. (ii) A comparison of the SR runs with the BL (blank) runs should reveal effects which do not depend on exposure time. With only five blanks at hand, their combined result, equivalent to 8^{+16}_{-18} SNU, is not yet statistically very revealing but consistent with the absence of a signal in the blanks.

(iii) In a maximum likelihood analysis in which the mean life of the decaying component is entered as a free parameter, the fit yields a mean life of $\tau = (13.5^{+5.2}_{-3.5})$ d (1 σ), compatible within statistics with 16.49 d for ⁷¹Ge.

The main result of 83 ± 19 (stat.) ± 8 (syst.) SNU (1 σ) is to be compared with the outcome of the SAGE experiment: $20^{+15}_{-20}(\text{stat.}) \pm 32$ (syst.) SNU (1 σ) [19] and with the standard solar model prediction range 132^{+21}_{-17}) SNU (" 3σ ") [3]. For 1 σ -comparability we have, in SNU, 83 ± 21 (GALLEX), $20^{+35}_{-20}(\text{SAGE})$ and 132 ± 7 (SSM [3]). We have no explanation of the discrepancy between our results and those of the SAGE Collaboration [19].

Our result implies the first detection ever of the pp neutrinos associated with the bulk of the energy production inside the Sun by nuclear fusion. Further astrophysical and particle physics consequences of this result are discussed in the following Letter [30].

6. Outlook and conclusions

6.1. Next steps

GALLEX is one of the few low-rate experiments to claim a positive signal rather than a limit. To improve the quantitative implications of the result already obtained, more measuring time is needed to reduce the *statistical* error. Conceptually, GALLEX is designed for four years of solar neutrino recording to lower the statistical error to approximately 10 SNU. Our first year of taking data permits only a preliminary result. Based on our experience to date, we fully agree with the original concept of running for several years in order to achieve the needed accuracy. This in turn will allow firmer conclusions to be drawn in comparisons with theory.

In radiochemical solar neutrino experiments it is necessary to ascertain, beyond any reasonable doubt: (i) the complete extraction of the product (^{71}Ge) from the target and (ii) the absence of sources that might mimic a solar neutrino signal. Having observed a *positive* signal, we concentrated on the exclusion of side reactions as being of more immediate importance than the proof of complete germanium extraction. We have therefore devoted considerable effort to reduce the possibilities of side reactions, as discussed above. In this respect our situation is quite opposite to that in which virtually *no* signal is seen [19].

As a further test of the whole experimental procedure, we are planning a calibration experiment in which the target will be irradiated with a man-made neutrino source. The latter will be in the form of $> 5 \times 10^{16}$ Bq ⁵¹Cr (half-life 28 d) made by neutron irradiation of isotopically enriched ⁵⁰Cr (see refs. [52,53] for details). The source is expected to produce a signal at least seven-fold that of the Sun (SSM prediction). The execution of the Cr source experiment is well advanced [52]; the first irradiation at the Grenoble Siloe reactor is scheduled for fall 1993.

To prepare for this, the gallium target solution was transferred from tank B to tank A just after B 50 on 30 April 1992, thus terminating the B series of runs ("GALLEX I"). According to our planning, in the fall of 1992 we shall start another year of solar neutrino measurements, ending with the arrival of the chromium source at LNGS. After the source exposures, solar neutrino runs will continue for about two more years. Afterwards, it seems likely that new physical insights from the results of upcoming solar neutrino experiments as well as from GALLEX itself will require the continuation of this experiment for many years to come.

6.2. Conclusions

The GALLEX experiment can truly claim to have observed, for the first time, the primary pp neutrinos.

Our central value, 83 SNU, is to be compared with the 74 SNU attributed to the pp and pep cycles in the SSM. Further, a model in which all of the solar luminosity is attributed only to this cycle gives the somewhat larger value of 79 SNU. Within the 2σ range of the present statistics, the GALLEX result is even compatible with the full SSM prediction. In this sense, neutrinos that have come through unaltered are allowed. However, to explain the GALLEX results plus those of ³⁷CI and Kamiokande in this way requires stretching the solar models and the data to their error limits; yet the possibility remains open. On the other hand, the results are interpretable in terms of a MSW mechanism, with the neutrino mass and mixing angle parameters fixed within narrow ranges. These conclusions are more fully discussed in our accompanying Letter [30].

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