

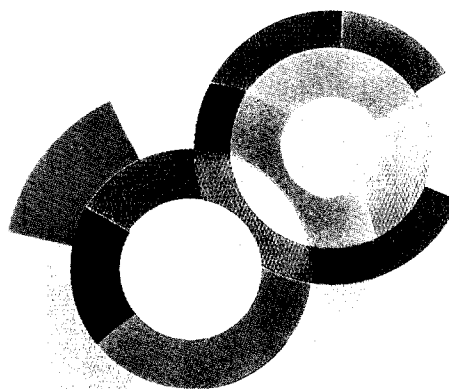
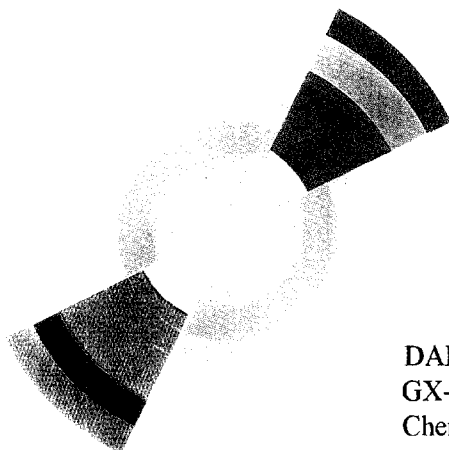
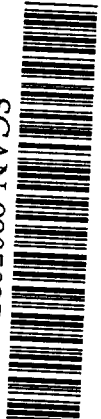
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GALLEX SOLAR NEUTRINO OBSERVATIONS :
RESULTS FOR GALLEX IV

W. Hampel et al.
(GALLEX Collaboration)

Submitted to Physics Letters B

DAPNIA

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CEA/Saclay F-91191 Gif-sur-Yvette Cédex

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Abstract

We report the GALLEX solar neutrino results for the measuring period GALLEX IV, from 14 February 1996 until 23 January 1997. Counting for the GALLEX IV runs was completed on 19 June 1997. The GALLEX IV result from 12 solar runs is $[118.4 \pm 17.8 \text{ (stat.)} \pm 6.6 \text{ (sys.)}] \text{ SNU} (1\sigma)$. The combined result for GALLEX I+II+III+IV, which comprises 65 solar runs, is $77.5 \pm 6.2^{+4.3}_{-4.7} (1\sigma) \text{ SNU}$. The GALLEX experimental program to register solar neutrinos has now been completed. In April 1998, GALLEX was succeeded by a new project, the Gallium Neutrino Observatory (GNO), with newly defined motives and goals.

1 Introduction

The GALLEX detector at the Gran Sasso Underground Laboratories monitors solar neutrinos with energies above 233 keV via the inverse beta decay reaction ${}^{71}\text{Ga}(\nu_e, e){}^{71}\text{Ge}$ in a 100-ton gallium chloride target solution. We apply ultra-low-level counting techniques to detect the ${}^{71}\text{Ge}$ after its extraction from the target solution at the end of each exposure period of typically 3-4 weeks (defined as a run). Descriptions of the project, the experimental procedures, the results, and discussions of their significance have been reported on a regular basis [1-11].

We present here the results from the 12 solar runs which were performed between 14 February 1996 and 23 January 1997 (GALLEX IV). Preliminary results were presented in reference [12]. GALLEX IV was preceded by the GALLEX I, GALLEX II, and GALLEX III solar run series (Table 1), with solar runs being done on a schedule of approximately one per month until January 1997. In total, 65 solar runs were done, comprising 1594 net days of exposure. Table 2 presents a matrix of all GALLEX runs and of their respective publication dates. The GALLEX periods were separated by a scheduled change of the target tanks (after GALLEX I) and by two Cr-source exposure periods (after GALLEX II and GALLEX III, respectively).

The proper operation of the GALLEX detector was demonstrated with the two ${}^{51}\text{Cr}$ neutrino source experiments [13]. Another performance demonstration was done from February to June 1997, by spiking the gallium detector with ${}^{71}\text{As}$ [14].

In this paper we first describe some experimental aspects concerning the GALLEX IV runs (sect. 2), and then report the new GALLEX IV solar neutrino data (sect. 3). In the discussion (sect. 4), we address the internal consistency of GALLEX data.

2 Experimental

GALLEX IV, the last GALLEX exposure period, began on 14 February 1996 and lasted till 23 January 1997, including runs from A146 to A168. During this time 12 solar runs (SR54 to SR65) and 5 blank runs (BL32 to BL36) were successfully performed. Blank runs were made after every third solar run. Table 3 lists the characteristics of these runs.

The basic experimental procedures for the germanium extraction and the counting conditions in GALLEX IV were the same as in the previous GALLEX I-III solar runs.

Three runs were unsuccessful and did not provide useful data (A153, A155, A159), one run because of a malfunction in the germanium sample preparation, and the other two because of counting-system failures.

The total GALLEX IV exposure time (without the 3 lost runs and the 5 days for blank exposures) is 268 days.

Special care was required for the pulse shape analysis of the L pulses of 8 runs (A148, A150, A151, A158, A160, A161, A165, A168). In these runs, due to electronic noise problems, it was not possible to perform our standard pulse shape analysis on the portion of the L pulses that

Table 1: *Time schedule of the GALLEX operations.*

Time period	Operations	Data set
May 91 - May 92	solar ν observations	GALLEX I
May 92 - Aug 92	change of the target tank	
Aug 92 - Jun 94	solar ν observations	GALLEX II
Jun 94 - Oct94	1 st source experiment	
Oct 94 - Sep 95	solar ν observations	GALLEX III
Sep 95 - Feb 96	2 nd source experiment	
Feb 96 - Jan 97	solar ν observations	GALLEX IV
Feb 97 - Apr 97	⁷¹ As tests	

Table 2: *Summary of GALLEX runs performed.*

Date of data release	Ref.	Solar runs					Blanks total
		GX I	GX II	GXIII	GXIV	total	
May 1992	[1]	14				14	5
June 1993	[2]	15	6			21	11
Feb. 1994	[3]	15	15			30	19
June 1995	[5]	15	24			39	27
July 1996	[6]	15	24	14		53	31
October 1998	this work	15	24	14	12	65	36

occurred at very low energies (< 0.7 keV). In such cases the lower edge of the L energy window has been slightly raised compared to the standard one, with correction made for the reduction in counting efficiency. This procedure allowed us to use the usual pulse shape analysis method, at the expense of a small reduction of the counting efficiency (a few percent on the average).

3 Results from GALLEX IV

The individual run results for the net solar production rates of ^{71}Ge (based on the counts in the K and L energy and rise time windows [1] [2]) are given in Table 4, after subtraction for side reactions and Rn background effects [7]. Data are evaluated using our standard energy - rise-time and Rn cuts, followed by our maximum likelihood analysis.

The net result of GALLEX IV is $[118.4 \pm 17.8$ (stat.) ± 6.6 (sys.)] SNU (1σ) or 118.4 ± 19 SNU (1σ) with error combined. This is after subtraction of 6.5 ± 2.1 SNU (Table 5), attributed to contributions from side reactions (4.3 ± 1.2) SNU and to the Rn-cut inefficiency (2.2 ± 1.7 SNU). The total number of observed decays of ^{71}Ge due to solar neutrinos in GALLEX IV is 77 (6.4 per run). The systematic errors are specified in Table 6 (see [2] for more details).

The combined result for GALLEX I-IV (65 solar runs) is $[77.5 \pm 6.2$ (stat.) $^{+4.3}_{-4.7}$ (syst.)] SNU (1σ).¹

The result from the 5 GALLEX IV blanks, after subtraction of the expected production rate from solar neutrinos and from side reactions, is 2.7 ± 13.3 SNU (stat) ± 1.8 (sys) (1σ). The result from the total of 36 blanks done in GALLEX I-IV is -4.1 ± 4.3 (stat) ± 1.3 (sys) (1σ) SNU, consistent with a null result.

4 Discussion

4.1 Consistency of the GALLEX results

The individual run results for GALLEX IV (from Table 4) are plotted in Figure 1 together with the respective data for GALLEX I, II and III. The scatter of single run results is compatible with a Monte-Carlo generated distribution of single run results for a constant production rate of 77.5 SNU under the conditions of normal single runs, using the actual conditions of the different runs in appropriate proportions (Figure 2).

We compare now the GALLEX overall result with the partial results for the runs grouped in the four exposure periods GALLEX I, II III, and IV (Table 7). The results for the four measuring periods show appreciable scatter. We note that GALLEX III is 2.2σ below, and GALLEX IV 2.2σ above the mean value. The χ^2 -test, for the result of the four data-taking periods to be compatible with the mean, yields only a 1.5% probability ($\chi^2=10.4$ with 3 D.O.F.), which is quite low, but nevertheless compatible with a normal distribution. However there is nothing special in grouping the runs in this way. For example, if we divide all 65 solar runs into four equal quarters (subsequent run numbers 1-17, 18-33, 34-49, 50-65), the respective probability is 26.7% ($\chi^2=3.9$ with 3 D.O.F.). Other groupings tend also to give probabilities $> 10\%$; in this sense it is just the GALLEX grouping of measuring periods (I-IV) which exhibits this extreme behavior.

¹If we apply instead the alternative pulse shape fit analysis described in [15] the result of GALLEX IV is 99.4 ± 15.5 (stat.) SNU, and the combined result for GALLEX I-IV is 74.9 ± 5.9 (stat.) SNU. The explanation of the fact that this is consistent with our standard pulse shape analysis requires elaborations which will be included in our forthcoming final GALLEX summary paper (see section 4.3).

Table 3: Characteristics of the GALLEX IV runs A146-A168.

Type ^a	Run#	Time period	Duration (days)	Carrier ^b	Yield		Pos. ^c	Counter			End of counting	Counting on-time (days)
					yield ^c	MS corr. ^d		label ^f	eff L (%)	eff K (%)		
SR54	A146	14.02.96 06.03.96	20.9	70	98.8	97.8	a	(Fe)118	28.0	33.2	17.09.96	194.5
SR55	A148	07.03.96 29.03.96	22.0	72	106.4	96.7	p	(Fe)112	27.2 ^h	34.4	17.09.96	171.6
SR56	A149	29.03.96 17.04.96	19.0	74	98.2	95.0	p	(Si)114	29.2	31.3	08.11.96	204.9
BL32	A150	17.04.97 18.04.97	1.0	70	103.9	99.5	p	(Si)108	22.5 ^h	32.3	08.11.96	203.8
SR57	A151	18.04.96 08.05.96	20.0	76	94.6	94.0	p	(Fe)103	24.2 ^h	34.4	10.12.96	215.8
	A153 ^g	09.05.96 05.06.96	27.0	74				Ge lost				
	A155 ^g	06.06.96 26.06.96	20.0	76	95.2	94.8		(SC)138	HV unstable		08.01.97	195.7
BL33	A156	26.06.96 27.06.96	1.0	72	100.8	96.1	p	(SC)136	33.0	38.3	08.01.97	194.6
SR58	A157	27.06.96 17.07.96	20.0	74	97.5	95.8	a	(SC)130	33.0	38.3	10.02.97	207.5
SR59	A158	17.07.96 07.08.96	21.0	70	97.7	96.1	p	(Si)119	24.9 ^h	31.1	10.02.97	186.5
	A159 ^g	07.08.96 28.08.96	21.0	76	94.2	93.5		(SC)135	HV unstable		03-03-97	186.4
BL34	A160	28.08.96 29.08.96	1.0	72	100.0	95.5	p	(Si)106	29.1 ^h	32.0	03-03-97	185.4
SR60	A161	29.08.96 18.09.96	20.0	74	96.2	95.0	a	(Si)113	27.9 ^h	32.4	31-03-97	193.6
SR61	A162	18.09.96 10.10.96	22.0	70	98.9	98.4	p	(Fe)039	28.9	34.3	31-03-97	171.5
SR62	A163	10.10.96 20.11.96	41.0	76	94.0	93.4	p	(FC)093	33.0	38.1	14-05-97	174.5
BL35	A164	20.11.96 21.11.96	1.0	72	100.4	95.5	p	(Fe)118	28.0	33.2	27.04.97	156.7
SR63	A165	21.11.96 11.12.96	20.0	74	96.5	94.7	p	(Fe)112	24.9 ^h	34.4	19.06.97	189.5
SR64	A166	11.12.96 09.01.97	29.0	70	98.1	96.9	p	(Si)114	29.2	31.3	19.06.97	160.5
SR65	A167	09.01.97 22.01.97	13.0	76	94.2	94.0	p	(Si)108	30.2	32.3	19.06.97	147.6
BL36	A168	22.01.97 23.01.97	1.0	72	102.5	96.7	p	(SC)138	31.6 ^h	38.2	19.06.97	146.6

^a SR=solar neutrino run, BL=short exposure, blank run.

^b 70,72,74,76 indicate the use of carrier solutions enriched in ⁷⁰Ge, ⁷²Ge, ⁷⁴Ge, ⁷⁶Ge respectively.

^c Integral tank-to-counter yield of Ge carriers, errors are $\pm 1.7\%$.

^d See [5] and [6] for detailed explanation.

^e a = active (NaI) counting position; p = passive counting position [2]

^f Counters have either iron (Fe) or silicon (Si) cathode. SC = counter with silicon shaped cathode.

FC = counter with iron shaped cathode.

^g Unsuccessful runs in which counting data were not obtained

^h Special data treatment for L pulses (see text).

We also note that there is no significant dependence of the GALLEX result on whether we evaluate K-pulses or L-pulses. This is shown in Table 7 where we compare the results obtained selecting only L events, only K events, and both L and K events.

4.2 The overall GALLEX result

The results of the two Cr source experiments [13] and of the Arsenic experiments [14] validate the GALLEX solar neutrino experiment, and limit any systematic biases to less than a few percent. After 65 solar runs, the total number of measured ^{71}Ge events in GALLEX is 300, and the neutrino interaction rate is $[77.5 \pm 7.7]$ SNU (1σ). It is substantially below the predictions of the various standard solar models (about 130 SNU [18]). The latest update for the result of the SAGE experiment $[67 \pm 7]$ SNU (1σ) [19] agrees well with our result.

Given that the solar luminosity is provided by the pp-fusion reaction in the core of the Sun, and the ^8B solar neutrino flux is as measured by Superkamiokande, one can conclude from our result alone that the ^7Be solar neutrino flux is much below what is expected from the standard solar model. This has been already extensively discussed by us [5] [10], and by others [20]. Our final result, with its reduced errors, reinforces this conclusion and makes it almost inescapable to invoke neutrino mass.

4.3 Outlook

The end of the GALLEX observations in early 1997 was followed by a break until the spring of 1998. During this period, a major overhaul and modernisation of the experimental set-up (which had been continuously in operation since 1990) has taken place. This lengthy period also allowed all the ^{71}Ge activity imported into Gran Sasso for the arsenic experiments to decay completely away. Then in April 1998 solar neutrino observations resumed within the framework of the Gallium Neutrino Observatory (GNO), the successor project to GALLEX, with newly defined motives and goals, and a revised list of collaboration members [21]. The GALLEX collaboration plans to prepare an extensive account of all of its experimental and theoretical activities throughout the project, in a concluding publication forthcoming in early 1999.

Acknowledgements

We wish to acknowledge the competent and skillful technical staffs in the participating institutes.

Table 4: Results for individual solar neutrino runs in GALLEX IV. The results are obtained by applying the GALLEX standard rise-time cut, as discussed in sect. 2. All SNU-values shown are net solar production rates of ^{71}Ge after subtractions for side reactions, and Rn-cut inefficiency (6.5 ± 2.1 SNU, see Table 5). Errors are statistical only.

Run number		K+L result (SNU)
SR54	A146	140^{+75}_{-63}
SR55	A148	57^{+54}_{-40}
SR56	A149	118^{+71}_{-56}
SR57	A151	155^{+73}_{-59}
SR58	A157	108^{+74}_{-61}
SR59	A158	151^{+73}_{-59}
SR60	A161	-78^{+62}_{-52}
SR61	A162	106^{+57}_{-46}
SR62	A163	186^{+63}_{-54}
SR63	A165	70^{+54}_{-41}
SR64	A166	184^{+71}_{-60}
SR65	A167	101^{+72}_{-54}
GALLEX IV		118.4 ± 17.8

Table 5: Side reaction subtractions (in SNU) to be applied to solar neutrino runs (for details see [2]).

	GALLEX IV	GALLEX(I-IV)
Muon induced background [16]	2.8 ± 0.6	2.8 ± 0.6
Fast neutrons [17]	0.15 ± 0.1	0.15 ± 0.1
^{69}Ge produced by muons and ^8B -neutrinos falsely attributed to ^{71}Ge [2]	1.0 ± 1.0	1.0 ± 1.0
Rn outside the counters [2]	0.3 ± 0.3	0.3 ± 0.3
Subtotal	4.3 ± 1.2	4.3 ± 1.2
Rn-cut inefficiency	2.2 ± 1.7	2.2 ± 1.2
Total to subtract	6.5 ± 2.1	6.5 ± 1.7

Table 6: *Main factors contributing to the systematic error in GALLEX*

	GALLEX IV	GALLEX(I-IV)
Counting efficiency including energy and risetime cuts	$\pm 4.7 \%$	$\pm 4.5 \%$
Target size and chemical yield	$\pm 2.2 \%$	$\pm 2.2 \%$
^{68}Ge correction error	$^{+0.0}_{-0.1} \%$	$^{+0.9}_{-2.6} \%$
Side reaction subtraction error	$\pm 1.8 \%$	$\pm 2.2 \%$
Total systematic error	$\pm 5.5 \%$	$^{+5.6}_{-6.1} \%$

Table 7: *Results from solar exposure periods*

	GALLEX I	GALLEX II	GALLEX III	GALLEX IV	GALLEX I-IV
Time period	14.05.91 - 29.04.92	19.08.92 - 22.06.94	12.10.94 - 04.10.95	14.02.96 - 23.01.97	14-05.91 - 23.01.97
net exp. days	324	649	353	268	1594
runs	15	24	14	12	65
L only (SNU) ^a	111 ± 28	68 ± 14	41 ± 17	116 ± 28	74.4 ± 10.0
K only (SNU) ^a	64 ± 21	82 ± 13	61 ± 14	120 ± 23	79.5 ± 8.2
L+K (SNU) ^b	83.4 ± 17.2 $^{+6.8}_{-9.0}$	75.9 ± 9.7 $^{+4.2}_{-4.6}$	53.9 ± 10.6 ± 3.1	118.4 ± 17.8 ± 6.6	77.5 ± 6.2 $^{+4.3}_{-4.7}$
L+K (SNU) ^c	83.4 ± 18.5 -19.5	75.9 ± 10.5 -10.7	53.9 ± 11.0	118.4 ± 19	77.5 ± 7.6 -7.8

^a Statistical error only (1σ)

^b Statistical and systematic error (1σ)

^c Statistical and systematic error combined in quadrature

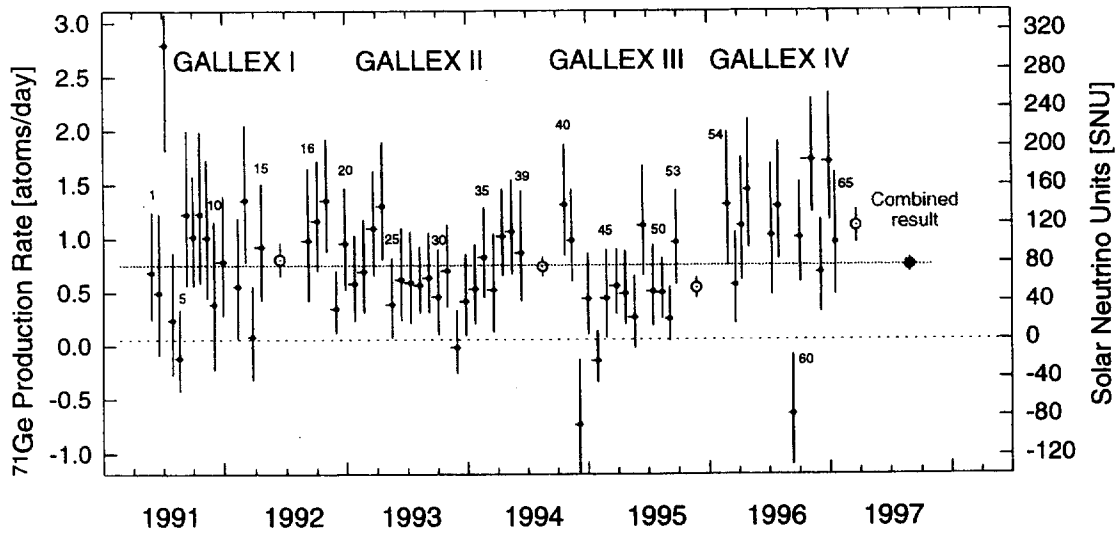


Figure 1: Summary of the results of GALLEX individual solar runs (closed points). The left hand scale is the measured ^{71}Ge production rate; the right hand scale, the net solar neutrino production rate (SNU) after subtraction of side reaction contributions. Error bars are $\pm 1\sigma$ statistical only. Open circles are the combined results for each of the measuring periods, GALLEX I, II, III and IV (see Table 1). The label 'combined' applies to the mean global value for the total of all 65 runs. Horizontal bars represent run duration; their asymmetry reflects the 'mean age' of the ^{71}Ge produced

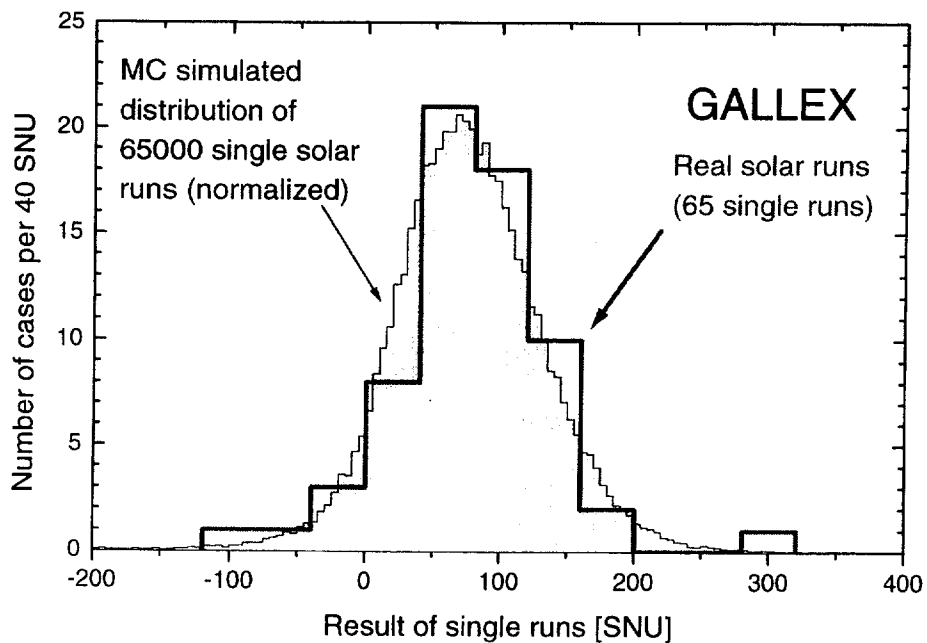


Figure 2: Monte-Carlo distribution deduced from 65000 single run simulations using the actual conditions of the 65 runs in appropriate proportions (thin line). Superimposed is the histogram for the real 65 GALLEX single run results (thick line).

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