GALLEX note GX-113
CONF-9709190--
19980401 075
to appear in
Proceedings of the 5th International Workshop on
"Topics in Astroparticle and Underground Physics (TAUP97)

BNL-65069

Results of the whole GALLEX experiment

M. Cribier

CEA-Saclay, DAPNIA/SPP
F-91191 Gif-sur-Yvette Cedex

for the GALLEX collaboration*

After 5.5 years of data taking, GALLEX ended its experimental phase. The solar neutrino production rate, 76.4 ± 8 SNU, represents about 55% of the predicted rate. The As tests prove, at the 1% level, the reliability of the technique and the detection of ^{51}Cr neutrino, with the nominal efficiency (93.0±8%), control the response of the detector to neutrinos in the solar energy range.

INTRODUCTION

The principal aim of the radiochemical GALLEX detector installed by the GALLEX collaboration in the Gran Sasso underground laboratory (LNGS) is the detection of pp neutrinos via the reaction :

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

This reaction has a threshold at 233 keV ; ^{71}Ge ($t_{1/2}$=11.4 d) decays by electron capture.

The target consists of 30.3 tons of gallium (12 tons of ^{71}Ga) contained in 100 tons of $GaCl_3$/HCl solution. This chemical form was chosen to facilitate the extraction of the product, ^{71}Ge as volatile germanium chloride ($GeCl_4$). It is expelled by nitrogen purge of the target liquid [Hen92] ; the average yield on all extrations is 94.3%. Extremely low backgrounds counters (order 1 count per month) are essential to be able to significantly detect the minute neutrino induced activity ; it is done in a small gas proportional counter operating with a GeH_4/Xe mixture as counting gas [Win93]. In a single run, typically only a handful of ^{71}Ge decays are observed via Auger electron and X-ray emission. Energy and pulse shape analysis serve to select the candidate events with an average efficiency of 60%. Then, a maximum likelihood method is used to partition the decaying signal from ^{71}Ge decay and the background constant in time [Cle83, Ans92].

The measurement on solar neutrinos started in May 1991. Since that date, 65 monthly runs were performed till January 1997. The solar neutrinos measurements were interupted by a scheduled change of the target tank and by two periods with exposition to an artificial neutrino-source (^{51}Cr). Finally, after completion of the solar neutrino program, experiments with arsenic were performed. In this paper, we first demonstrate the performance of the detector and thus describe the ^{71}As experiments, then the ^{51}Cr source experiments, before giving the last result of the solar neutrino flux as obtained using all the exposures available in GALLEX.

1. THE ARSENIC EXPERIMENTS

The ^{71}As experiments aim to check and to

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* **MPIK Heidelberg** : W. Hampel, G. Heusser, J. Kiko, T. Kirsten, M. Laubenstein, E. Pernicka, W. Rau, U. Rönn, C. Schlosser, M. Wójcik, **FzK Karlsruhe** : R. v.Ammon, K. H. Ebert, T. Fritsch, D. Heidt, E. Henrich, L. Stieglitz, F. Weirich, **LNGS L'Aquila** : M. Balata, F. X. Hartmann, M. Sann, **INFN Milano** : E. Bellotti, C. Cattadori, O. Cremonesi, N. Ferrari, E. Fiorini, L. Zanotti, **TU München** : M. Altmann, F. v.Feilitzsch, R. Mößbauer, S. Waenninger, **Obs. Côte d'Azur Nice** : G. Berthomieu, E. Schatzman, **WI Rehovot** : I. Carmi, I. Dostrovsky, **INFN Roma 2** : C. Bacci, P. Belli, R. Bernabei, S. d'Angelo, L. Paoluzi, **CEA Saclay** : A. Bevilacqua, M. Cribier, L. Gosset, J. Rich, M. Spiro, C. Tao, D. Vignaud, **BNL** : J. Boger, R. L. Hahn, J. K. Rowley, R. W. Stoenner, J. Weneser

demonstrate the GALLEX detector performance. This approach is complementary to the Cr-neutrino source experiments described below. Here, we add, carrier free, ^{71}As activity to the target solution where it beta-decays into ^{71}Ge with $t_{1/2}$=2.72 d.

While this in-situ production mode for the ^{71}Ge is still reasonably soft and therefore relevant for the test (although not quite as direct as in the case of the ^{51}Cr source), the advantage is the possibility to produce as many ^{71}Ge atoms as desired and to perform tests at the percent level. Nevertheless the contamination risk during regular solar neutrino phases forbids the addition of ^{71}Ge at any level. This is why we waited for the end of the GALLEX experiment to perform such a test. The Gallium Neutrino Observatory will not restart operations before beginning of 1998, when all ^{71}Ge would have decayed.

To test possible scenarios (suggested or speculated) of improper admixture of stable germanium carrier, eventual saturation of withholding sites in the presence of carrier germanium, time-dependent hiding and release processes, and variable conditions of Ge-extraction, we have performed several ^{71}As experiments in which we varied the mixing and extraction conditions, the standing time, and the quantity and time of eventual stable germanium carrier additions.

1.1. Preparation of the ^{71}As

^{71}As was produced via the reaction ^{71}Ga(^{3}He,n)^{71}As at the Heidelberg Tandem with a beam energy of 13.4 MeV. Use of isotope separated ^{71}Ga (in oxide form) reduces the production of long-lived side products such as ^{73,74}As.

We produced two ^{71}As samples, the first (A) on January 17, 1997 and the second (B), on March 3, 1997 yielding 2x10^{9} ^{71}As-atoms, sufficient to supply the desired ≈ 10^{6} atoms per batch for about 6 weeks. After dissolving the irradiated Ga oxyde together with inactive As- and Ge-spikes, the arsenic was distilled and transferred into an acidic master solution. Then, a Ge(HP) γ-spectrometric estimate of the activity was made at Heidelberg in order to prepare the approximate dosage for the spikes to be applied. Immediately (1-2 hours) before use at Gran Sasso, all ^{71}Ge is expelled by purging the solution with nitrogen. The expulsion yield was monitored by AAS and turned out to be quantitative in all cases.

1.2. Use of the samples

For each of our 3 spiking experiments (called A1, A2, B3, see table 1), we have prepared 3 samples (few ml scale) in precisely determined weight proportions called t, e, g :

- samples 'g' used to determine the absolute ^{71}As -activity by Ge(HP) spectrometry at Gran Sasso via the 175 keV gamma transition to the ^{71}Ge ground state (branching ratio 0.82±.03). With ≈ 10^{6} atoms sample sizes, the statistical errors ranged from 0.55 to 0.62 %. The ± 4 % absolute error of these determinations is dominated by the γ-branching uncertainty. Relative errors for the 'g'-samples from different experiments (A1g/A2g/B3g) are less than 1 %. This includes the reproducibility of sample positioning.
- samples 't' is the actual spikes added to the GALLEX tank. Sample sizes contains ≈ 10^{5} atoms for A1t, A2t, B3t.
- samples 'e' serve for comparison with each tank sample. This sample, from the same batch, is treated all the way from sample splitting through Ge-synthesis, counter filling, and counting, just like the real spike ('t'-sample), except that it bypasses the target tank, that is, the As-decay does not occurs in the $GaCl_3$-target tank but rather in an external vial, avoiding any effects which have to do with the chemistry in gallium chloride solutions.

1.3. Results

The major variables of the experiments performed and the results can be seen in Table 1. The errors quoted include the reproducibility of the γ-measurements (1%), the errors on the chemical yields (1.7 % for tank samples, 0.5% for e-samples), and the errors on the counter efficiencies (1%). In order to minimize the errors introduced by the uncertainties of the absolute counting efficiencies of the individual

Table 1
Arsenic tank run parameters and overall results

Run	Conditions of the exposure	Duration	^{71}As expect.	% of ^{71}Ge expect.
A1	violent mixing carrier added together with activity	19.92 d	34 780	99.9 ± 1.2
A2	soft mixing carrier free till end	19.92 d	40 820	100.1 ± 1.2
B3_1	short exposure	2.917 d	64 170	100.5 ± 1.2
B3_2	long exposure	22.00 d	21 590	99.6 ± 1.3

counters, we exchanged the same individual counters in subsequent experiments.

The results quoted in the last column of Table 1 compare between the tank spike (t)-samples and the respective external (e)-samples which have not even seen the target solution.

These results are very satisfactory. There is no indications for any withholding mechanisms at the 1% level in this relative comparison, even under the most "critical" conditions (no carrier, long exposure, soft mixing). Considering also the systematics (chemical yields, counting efficiencies, γ-calibrations and geometry), the intrinsic uncertainty of our experiments is conservatively estimated to be < 3 %.

We have also very good absolute agreement of our counting results with the gamma-counted g-samples ; however as mentioned, this is only within ± 4% because of the uncertainty of the branching ratio. Note that the fit would be ideal for a branching ratio of 82.8 %, instead of the nominal 82 ± 3.

2. THE ^{51}Cr SOURCE EXPERIMENTS

The most straightforward check to guarantee the trustworthiness of the experimental technique is to expose the experiment to neutrino sources with known activity levels and appropriate energies, under conditions identical to those used in solar exposures. The GALLEX collaboration performed such a comprehensive test a first time in the summer 1994 and a second time during the fall of 1995.

2.1. Production of the sources

^{51}Cr was chosen as the most convenient neutrino source. It is produced by neutron capture on ^{50}Cr and decays by electron capture with an half-life of 27.706 ± 0.007 days. 90 % of the decays involve the emission of a ≈ 750 keV neutrino, while in 10 % of the decays, a ≈ 430 keV neutrino and a 320 keV gamma are emitted.

Many details on the production of the first source are given in reference [Cri96]. 36 kg of chromium enriched by the Kurchatov Institute to about 40 % in ^{50}Cr were used in the form of small irregular chips (≈ 1 mm^3). The irradiation, in the Siloé reactor, in Grenoble, lasted 23.8 days for the first source and 26.5 days for the second source. After the irradiation ended, chromium where unloaded in a hot cell, mixed and samples were taken. Then it was placed in a sealed stainless-steel container and inserted into the tungsten shield. Results of the 1st source is published [Ans95a], whereas results of the 2nd source, and the final results of both sources are being published [Ham97]. We emphasize here the second source experiment.

2.2. Measurement of the source activity

The total amount of irradiated chromium comprising the second neutrino source within the tungsten shield was 35575 ± 10 g.

Different independent methods have been used to measure the activity of the sources ; details of these methods are given in reference [Cri96]. As is indicated below, the measurements of the 320-keV gamma ray of ^{51}Cr consistently gave results with the smallest experimental uncertainties.

In the following, the quoted activities refer to the values at EOB (end of the irradiation in the reactor).

2.3. Sampling and activity measurements based on the 320-keV line

The sampling procedure allowed to collect 30 samples, each with an average weight of 0.56 g, for activity measurements at Saclay. In addition, we performed 3 sampling operations to collect one large representative sample of 41.4 g.

In Saclay, the activity of the 320-keV gamma ray from each small sample was measured in a ionization chamber, which had been calibrated with a standard ^{51}Cr source. The precision of the method has been estimated as 2 %. The average specific activity of the samples is 1.895 TBq/g.

At FzK, Karlsruhe, the large sample was split into 3 parts, dissolved in H_2SO_4, and diluted by a factor 10000. The large dilution factor allowed us to measure the 320-keV line directly by high-resolution γ-ray spectroscopy of aliquots of this solution.

Total activity (in PBq) is deduced from independant measurements at FzK (70.2), at Heidelberg (68.3) and at BNL (70.1), with different spectrometer and calibrations done with standard sources from the respective National Bureau of Standards. ; the errors on all of these values are dominated by the systematic errors of the calibration standards ; the statistical errors due to counting were <1 %.

2.4. Other methods

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. The source power is obtained by comparing the measured rate with that in similar measurements where known amounts of thermal power were supplied by a resistance heater.

Combining these data with the calibrations done with electric heating, we deduce a total activity of (65.2 ± 6.0) PBq.

The chemical analysis of the vanadium content after nearly complete decay of the source can be used to determine the strength of the ^{51}Cr source at EOB.

At BNL, the equivalent ^{51}Cr source strengths at EOB derived from these vanadium values determined by neutron activation are (65.2 ± 1.2) PBq for the first source, and (67.1 ± 2.5) PBq for the second source, where the errors include the 1 % systematic error in the concentration of the vanadium standard. The vanadium content of the ^{51}Cr samples was analyzed chemically at FzK, by ICP-AES and by AAS. The equivalent values of the ^{51}Cr activity at EOB are (66.0 ± 2.1) PBq for the first source, and (72.3 ± 3.2) PBq for the second, where the errors include the 3 % systematic errors in the ICP-AES and AAS analytical methods, combined in quadrature with the statistical errors.

The knowledge of the flux of neutrons and the relevant cross sections to produce ^{51}Cr provides an independent method to evaluate the final activity of the source. A total activity of (75.1 ± 6.0) PBq is derived.

2.5. Mean value of the source activity

Combining all these independent activity measurements by weighting them by their variances, we deduce the values of the source activity at EOB in Siloé of (63.4 ± 0.5) PBq for the first source, and (69.1 ± 0.6) PBq for the second source. To our knowledge, these are the strongest low-energy neutrino sources ever produced.

The large dispersion of the different methods can be used as an estimate of unknown

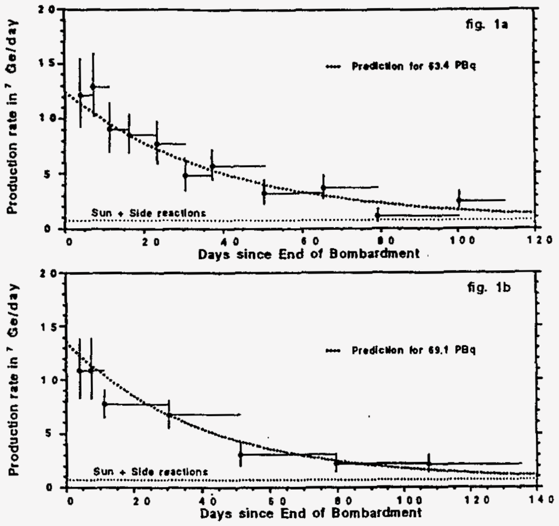

Figure 1. Number of ^{71}Ge atoms produced per day a) during the first source experiment, b) during the second source experiment. The points for each run are plotted at the beginning of each exposure (the horizontal lines show the duration of the exposures). The predicted curve (dotted line) decreases with the known half-life of ^{51}Cr and corresponds to the expected rate for a source activity of 63.4 PBq (first source) and 69.1 PBq (second source). Vertical bars are statistical errors. The horizontal line (small dots) corresponds to the production rate due to solar neutrinos and side reactions.

systematic errors ; we use as one sigma the 68.3 % of the data closest of the central mean value ; this gives +1.0 -1.6 PBq for the first source and +3.3 -2.1 PBq for the second source. Adding quadratically the two errors, the values for the activity are then $63.4^{+1.1}_{-1.6}$ PBq for the first source and $69.1^{+3.3}_{-2.1}$ PBq for the second source, that we call our best estimates.

2.6. The source experiments

The sources remained for 3-4 months in the reentrant tube in the center of the GALLEX detector (see figure 16 in [Cri96]).

The second source experiment started on October 5, 1995, at 22h47, when the ^{51}Cr neutrino source was inserted in its final position, in the A-tank (at a position 32 cm lower than the position of the first source). The experimental conditions for the runs performed with the ^{51}Cr source were kept as close as possible to those for the solar runs. The main difference between the two source experiments consists in the different lengths of time chosen for the exposures of the gallium target to the source. In the first one, the 11 exposure times were chosen to optimize the use of the source by producing about the same number of ^{71}Ge atoms per exposure. So, we used rather short exposures, ranging from 3 days to 2 weeks, and only one 3-week exposure at the end of the experiment. For the second source, the exposure times were chosen to resemble more closely the durations of the solar exposures : after two short exposures, we switched to two 3-week exposures (as in GALLEX 1), followed by three 4-week exposures (as in GALLEX 2). In total, 7 exposures were performed in the second source experiment whose characteristics are given in table 2

An unusually large radon signal was observed for exposure S142, reducing the effective counting live-time for ^{71}Ge to 72% (instead of 92 % for typical runs) ; this effect has been taken into account in the analysis. The standard analysis is performed with two components : one that decays with the ^{51}Cr lifetime and represents production of ^{71}Ge by ^{51}Cr neutrinos, and the second, a constant term that corresponds to the production of ^{71}Ge by the Sun and by side reactions. The latter term has been taken equal to (0.67 ± 0.11) ^{71}Ge atoms/day. The analysis program fits the value of the initial activity of the source at EOB at Siloé, taking into account the appropriate elapsed time.

Table 2
Second source parameters and results

Run	Days after EOB	Duration	Activity (PBq)	^{71}Ge /day
S138	3.95 d	3.3 d	$59.6^{+17.8}_{-15.5}$	$10.1^{+3.0}_{-2.6}$
S139	7.3 d	4.0 d	$65.0^{+19.8}_{-17.2}$	$10.2^{+3.1}_{-2.7}$
S140	11.3 d	19.0 d	$50.9^{+9.7}_{-8.8}$	$7.1^{+1.4}_{-1.2}$
S141	30.3 d	21.0 d	$10.1^{+3.0}_{-2.6}$	$6.1^{+1.4}_{-1.3}$
S142	51.3 d	28.0 d	$45.1^{+24.0}_{-20.4}$	$2.4^{+1.3}_{-1.1}$
S143	79.3 d	28.0 d	$59.4^{+35.5}_{-29.6}$	$1.5^{+0.9}_{-0.8}$
S144	107.3 d	28.0 d	$115.5^{+69.2}_{-58.2}$	$1.5^{+0.9}_{-0.7}$

2.7. Results

The individual results for the sources are shown in figure 1. We note the large deviation of the third data point, run S140 (which is expected to contain about 30 % of the data), from the expected curve.

A global fit to all of the ^{71}Ge data for the second source gives a value of the activity at EOB of $57.9^{+6.5}_{-6.2}$(stat.)$^{+3.9}_{-3.7}$(syst.) PBq, where the systematic error comes from the uncertainty on the cross section [Bah97].

The ratio, R, between this activity deduced from ^{71}Ge counting and the directly measured activity, is equal to $0.84^{+0.12}_{-0.11}$.

A reevaluation of the ^{71}Ge activity for the first source has been made, mainly due to updated determinations of the germanium recovery yields. The activity from ^{71}Ge data for the first source is $64.0^{+6.1}_{-5.8}$(stat.)$^{+3.9}_{-3.7}$(syst.) PBq. The corresponding value of R is $1.01^{+0.12}_{-0.11}$.

A combined analysis of the two source experiments has been performed, asking the program to fit directly a single number for the ratio R, using the value of the directly measured activity of each source as a normalization. This analysis gives $R = 0.93 \pm 0.08$.

The agreement between the predicted and the measured signal, the ratio R, is very satisfactory for the first source, but less for the second source experiment, being 1.6 σ from unity. The results of the two ^{51}Cr source experiments are each within 1 σ of the mean. We have considered possible systematic effects, but so far have found no indications of any experimental effects that might lower the results. We can conclude that the ^{51}Cr source experiments, supplemented by the ^{71}As data, validate the methods used in the GALLEX radiochemical neutrino detector.

3. SOLAR NEUTRINOS

The GALLEX experiment measured the solar neutrino flux during the last six years. A total of 65 runs (1593 net days of exposure between May 1991 and January 1997) have been performed : 324 days in GALLEX 1 (15 runs), 648 days in GALLEX 2 (24 runs), 353 days in GALLEX 3 (14 runs) and 268 days in GALLEX 4 (12 runs).

Whereas the exposure to solar neutrino lasted 3-4 weeks, counting of a run lasted typically for about 6 months in order to fully characterize the very low background after the decay of ^{71}Ge. The individual run results are shown in Figure 2.

A single run result has little meaning because the error is large (typically only about five ^{71}Ge counts are recorded per solar run). However, the statistics assembled during more than 5 years of data taking allowed us to reduce the statistical error to ± 6.3 SNU. This is 9% of the measured signal under the assumption of a production rate constant in time.

Table 3
GALLEX 4 results (statistical errors only)

Run	Time period	SNU
A146	14-Feb-1996 - 6-Mar-1996	170^{+86}_{-72}
A148	7-Mar-1996 - 29-Mar-1996	130^{+72}_{-60}
A149	29-Mar-1996 - 17-Apr-1996	102^{+74}_{-56}
A151	18-Apr-1996 - 8-May-1996	90^{+74}_{-58}
A157	27-Jun-1996 - 17-Jul-1996	62^{+79}_{-63}
A158	17-Jul-1996 - 7-Aug-1996	107^{+69}_{-56}
A161	29-Aug-1996 - 18-Sep-1996	-57^{+80}_{-62}
A162	18-Sep-1996 - 10-Oct-1996	85^{+50}_{-50}
A163	10-Oct-1996 - 19-Nov-1996	173^{+66}_{-56}
A165	21-Nov-1996 - 11-Dec-1996	131^{+71}_{-58}
A166	11-Dec-1996 - 9-Jan-1997	164^{+71}_{-60}
A167	9-Jan-1997 - 22-Jan-1997	105^{+79}_{-59}

Altogether about 320 ^{71}Ge atoms produced by solar neutrinos have actually been seen to decay.

During the GALLEX 4 period several problems of electronics (noise, instabilities) affected mostly, the low energy pulses. The results given here do not use the rise time criterium for L-events, contrary to the previous periods, thus increasing the error. There is hope that further studies underway will lead to a recovery of the rejection power against background. The result is 117.0 ±1 8.8 (stat.) ± 8.1 (syst.) SNU

The last column of table 4 displays how the cumulative published GALLEX result has evolved in time. The data are self-compatible since the beginning and the errors shrunk in a consistent fashion. The combined result for the 4 periods is 76.4 ± 6.3(stat.)$^{+4.5}_{-4.9}$(syst.) SNU. A description of the systematic errors and of the side reaction contribution can be found in [Ham96]. This result account for 55-60% of the SSM expectation [Bah95, Tur93]

Table 4
Evolution of GALLEX results

Date	Ref.	# runs	SNU
May 92	[Ans92]	14	83±21
June 93	[Ans93]	21	87±16
Feb. 94	[Ans94]	30	79±12
June 95	[Ans95b]	39	77±10
June 96	[Ham96]	53	70±8
Dec. 97	this paper	65	76±8

3.1 Discussion

As evident from Figure 2, the results for the four periods GALLEX 1, 2, 3 and 4 show appreciable scatter. They are respectively 83 ± 19, 76 ± 11, 54 ± 11 and 117 ± 21 SNU (errors combined). We note that GALLEX 3 is half GALLEX 4, which is 1.5 above the mean value. Obviously there is no compelling evidence for any time variability of the solar neutrino flux ; but, for a better apprehension of the situation, we have analysed the statistics of these low rate data by Monte-Carlo simulations. First we investigated whether the scatter of the 65 single run results is compatible with a Monte-Carlo generated distribution of 20000 single run results for an (uncorrected) constant production rate of 76.4 SNU under the conditions of normal single run, using the actual conditions of GALLEX 1, 2, 3 and 4 in appropriate proportions. The result is positive, the fit of the two distributions is almost ideal. Hence, if anything, it is the time sequence of high and low results, not the results themselves, which display larger statistical departures from the mean. The χ^2 test for the results of the four data taking periods to be compatible with the mean has only a 2 % probability. However, another grouping of the successive runs like dividing into 4 equal quarters gives a respective probability of 31.6 %. With this respect it is just the GALLEX grouping of measuring periods (1-4) which behaves extreme.

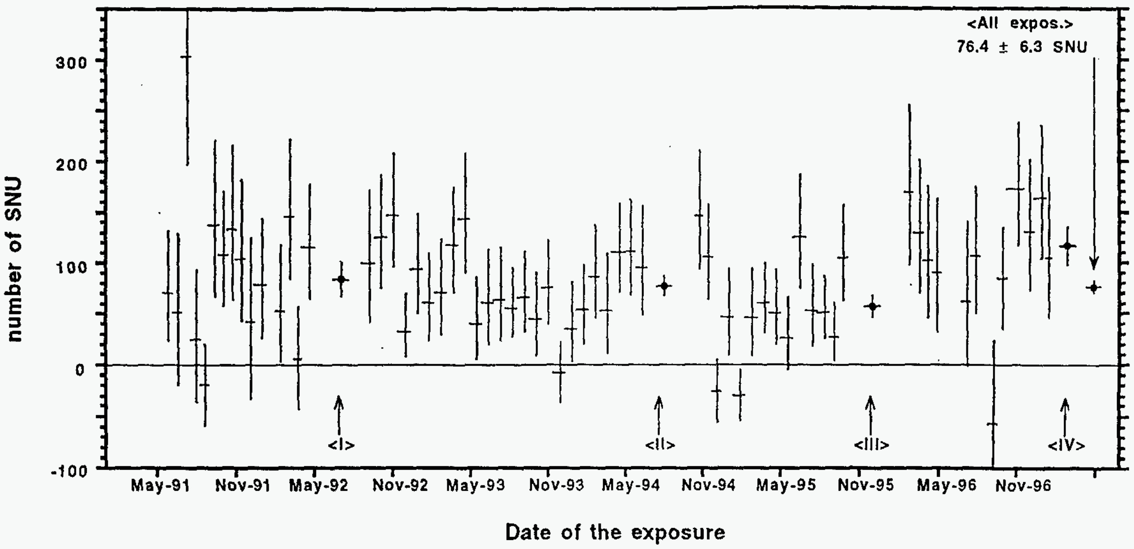

Figure 2. GALLEX single run result overview. The right hand scale is the net solar neutrino production rate (SNU) after subtraction of side reaction contributions. Vertical error bars are statistical only ; horizontal bars represent run duration, their asymmetry reflects the "mean age" of the ^{71}Ge produced. After each period, the dot represent the average value of this period ; the last point is the combined value of all solar exposures. See Table 4 for references (source of data).

CONCLUSION

After 6 years of data taking, the GALLEX experiment comes to an end. The final result, 76±8 SNU, confirmed by the successful experimental tests (As and Cr), establish on a firm experimental basis the deficit of solar neutrinos to a level of about 40% compared to solar model predictions. A new collaboration, GNO [Bel96] will pursue the measurement of the solar neutrinos with a renewed apparatus in a first time, and with more gallium in the future ; this new experiment will be the only one to monitor the low energy solar neutrinos during a solar cycle.

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ACKNOWLEDGEMENT. This research was carried out at Brookjaven National Laboratory with the Department of Energy and supported by Nuclear Physics.

M98003080

Report Number (14) BNL--65069

CONF-9709190--

Publ. Date (11) 199801

Sponsor Code (18) DOE/ER, XF

UC Category (19) UC-401, DOE/ER

DOE