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# SERVICE DE PHYSIQUE DES PARTICULES

DAPNIA/SPP 96-10 Juillet 1996

## GALLEX SOLAR NEUTRINO OBSERVATIONS: RESULTS FOR GALLEX III

**GALLEX Collaboration**

*Submitted to Physics Letters B*

DAPNIA

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July 1996

GX-91/1996
Chem(BNL) C-4376 (1996)
DAPNIA/SPP 96-10
MPI H - V20 -1996

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1 This work has been supported by the German Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie (BMBF). 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 German Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie (BMBF).

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**Abstract**

We report the GALLEX solar neutrino results for the measuring period GALLEX III, the period from 12 October 1994 - 4 October 1995. Counting for these runs was completed on 29 March 1996. The GALLEX III result (14 runs) is [53.9 ± 10.6 (stat.) ± 3.1 (syst.)] SNU (1$\sigma$). The new combined result for GALLEX (I+II+III) (53 runs) is [69.7 ± 6.7(stat.) $\pm^{3.9}_{4.5}$(syst.)] SNU (1$\sigma$) or (69.7$\pm^{7.8}_{8.1}$) SNU with errors quadratically added. The GALLEX III result, with its stated errors, differs from the mean value of GALLEX(I+II+III) by about 1.5 $\sigma$, and is therefore within credible statistics. We also give the preliminary result from our second $^{51}$Cr-source experiment: the measured detector response is 83±10 % of expectation. The combined result from both GALLEX $^{51}$Cr-source experiments is 92±8 % of expectation.


## 1. Introduction

The GALLEX detector at the Gran Sasso Underground Laboratories (L.N.G.S.) monitors solar neutrinos with energies above 233 keV via the inverse beta decay reaction $^{71}$Ga($\nu_e$,e$^-$)$^{71}$Ge in a 100-ton gallium chloride target solution. We apply low-level counting of the $^{71}$Ge after its extraction from the target solution at the end of each exposure period of typically 3-4 weeks (defined as a 'run').

We have been recording solar neutrinos since May 1991. Descriptions of the project, the experimental procedures, the results, and discussions of their significance have been reported regularly [1-10].

GALLEX has observed a flux of solar neutrinos in sufficient quantity to account for the solar luminosity as reflected in the flux of low-energy pp-neutrinos from the primary hydrogen fusion reaction in the solar core. However, in assigning the measured signal to pp-neutrinos, little or no signal is left to account for the other neutrino fluxes also expected from the Standard Solar Model (SSM), in particular the $^7$Be neutrinos ('the $^7$Be-neutrino problem' [5,10]).

Since all solar neutrino experiments have data collection rates that are low by any usual standard, a long measurement time is required to achieve satisfactory statistical and systematic significance. Consequently, data-taking has continued, both for the solar neutrino flux and for the calibrated neutrino source exposures [4,11,12]. The latter were performed to reliably judge the systematic confidence levels for the experiment.

In this 5th release of GALLEX solar data, we present the complete data set for GALLEX III. This covers 14 runs which were performed between 12 October 1994 and 4 October 1995. GALLEX III was preceded by the GALLEX I and GALLEX II series of runs performed between 14 May 1991 and 22 June 1994 [1,2,3,5]. (Between 22 June and 12 October 1994 we have exposed the GALLEX target to the above mentioned reactor produced $^{51}$Cr neutrino source and thereby verified the proper operation of the GALLEX detector [4]).

Table 1 is a compilation of the GALLEX data base for Solar runs (SR) and for short (1 day) exposure runs (blank runs, BL).

| Date of data release | Ref. | SOLAR RUNS GX I | GX II | GX III | total | BLANKS (total) |
|---|---|---|---|---|---|---|
| **May 1992** | [1] | 14 | | | 14 | 5 |
| **June 1993** | [2] | 15 | 6 | | 21 | 11 |
| **Febr.1994** | [3] | 15 | 15 | | 30 | 19 |
| **June 1995** | [5] | 15 | 24 | | 39 | 27 |
| **July 1996** | this work | 15 | 24 | 14 | 53 | 31 |

Table 1. Summary of GALLEX runs performed.

In this paper, we first describe some experimental aspects that were not explicitly covered in earlier publications [1-8,13] (sect.2), and then report the new GALLEX III solar neutrino data (sect.3). In the discussion (sect.4) we first address the combined data analysis for GALLEX(I+II+III) and the internal consistency of the results. The data base from as many as 53 solar runs is sufficiently large for this exercise to be meaningful (sect.4.1). In section 4.2, we investigate the possibility of time variations of the neutrino signal that are related to solar activity. The Cr-neutrino source experiments and other tests of the GALLEX detector performance are covered in section 4.3. Then we comment on the overall result (sect.4.4) and on future plans (sect.5).

## 2. Experimental

All basic procedures in GALLEX III were the same as described in earlier publications, except that blank runs were done only after every third solar run instead of after every one as in GALLEX II. The results of all earlier blank runs, for which we now have sufficient statistics, showed such regular behaviour that further blank runs were needed only to assure us that conditions remained stable.

Efforts are presently underway to refine the determination of the absolute detection efficiencies for the individual counters in order to check our previously described method of 'prototype calibration' and Monte-Carlo simulation [13]. The latter is based on determinations of the $^{71}$Ge activity in some representative counters filled with samples from $^{71}GeH_4$ standards that had been calibrated with large Ballentine counters with exactly defined active volumes. We remind the reader that in our solar neutrino runs, the few atoms of neutrino-produced $^{71}$Ge and the carrier-Ge are introduced into small gas proportional counters as germane ($GeH_4$). Because of the contamination risk that would compromise the experiment's single-atom detection level, the counters actually used for the GALLEX solar runs cannot be exposed to activity standards (typically $10^5$ atoms of $^{71}$Ge). We must therefore rely on near identity of different counters of a given type (except for volume efficiencies [13], which are individually determined) and on checks with Monte-Carlo simulations of the $^{71}$Ge decays in the counters. We have generally good agreement between these two methods, but have achieved further improvements by the following method. It is based on the registration with an external detector of a 1106 keV $\gamma$-quantum in coincidence with an electron capture decay of $^{69}$Ge (half-life 1.6 days) inside the counter filled with $^{69}$Ge-containing $GeH_4$. The signature of $^{69}$Ge-electron capture inside the counter is identical to that of a $^{71}$Ge decay.

Table 2: Characteristics of GALLEX III runs A119 - A136

| Type[a] | Run # | Time period | Duration [days] | Carrier[b] | Ge yield [%] yield[c] | MS-corr.[d] | Pos.[e] | Counter label[f] | efficiency[g] [%] L | K | End of counting | Counting on-time [days] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SR 40 | A119 | 12.10.94-02.11.94 | 21.0 | 72 | 99.0 | 97.7 | p | (SC)139 | 32.6 | 37.8 | 27.05.95 | 196.6 |
| SR 41 | A120 | 02.11.94-23.11.94 | 21.0 | 74 | 97.0 | 95.0 | p | (SC)138 | 33.0 | 38.2 | 27.05.95 | 175.4 |
| SR 42 | A121 | 23.11.94-14.12.94 | 21.0 | 70 | 101.0 | 98.1 | p | (SC)130 | 33.0 | 38.3 | 24.06.95 | 183.3 |
| BL 28 | A122 | 14.12.94-15.12.94 | 1.0 | 76 | 98.9 | 93.7 | p | (SC)136 | 33.0 | 38.3 | 24.06.95 | 182.5 |
| SR 43 | A123 | 15.12.94-11.01.95 | 27.0 | 72 | 97.8 | 97.7 | p | (Si)119 | 29.1 | 31.1 | 22.7.95 | 182.9 |
| SR 44 | A124 | 11.01.95-08.02.95 | 28.0 | 74 | 97.2 | 95.9 | a | (SC)137 | 32.3 | 37.5 | 19.08.95 | 179.2 |
| SR 45 | A125 | 08.02.95-08.03.95 | 28.0 | 70 | 98.8 | 98.6 | p | (Si)106 | 29.9 | 32.0 | 12.09.95 | 178.5 |
| BL 29 | A126 | 08.03.95-09.03.95 | 1.0 | 76 | 96.4 | 94.0 | a | (SC)135 | 33.1 | 38.4 | 12.09.95 | 180.1 |
| SR 46 | A127 | 09.03.95-07.04.95 | 29.0 | 72 | 99.3 | 98.5 | p | (Fe)39 | 28.9 | 34.3 | 30.09.95 | 166.0 |
| SR 47 | A128 | 07.04.95-03.05.95 | 26.0 | 74 | 95.9 | 95.7 | p | (Si)114 | 29.2 | 31.3 | 28.10.95 | 171.4 |
| SR 48 | A129 | 03.05.95-31.05.95 | 28.0 | 70 | 98.9 | 98.5 | a | (Si)113 | 30.2 | 32.4 | 12.12.95 | 184.8 |
| BL 30 | A130 | 31.05.95-01.06.95 | 1.0 | 76 | 94.8 | 94.5 | a | (Fe)118 | 28.0 | 33.2 | 12.12.95 | 182.3 |
| SR 49 | A131 | 01.06.95-28.06.95 | 27.0 | 72 | 99.6 | 98.2 | a | (Fe)112 | 29.1 | 34.4 | 13.01.96 | 187.4 |
| SR 50 | A132 | 28.06.95-26.07.95 | 28.0 | 74 | 98.5 | 95.9 | p | (Si)108 | 30.2 | 32.3 | 13.01.96 | 164.2 |
| SR 51 | A133 | 26.07.95-23.08.95 | 28.0 | 70 | 102.1 | 99.0 | p | (Fe)103 | 29.1 | 34.4 | 02.03.96 | 185.7 |
| BL 31 | A134 | 23.08.95-24.08.95 | 1.0 | 76 | 99.7 | 97.2 | p | (SC)139 | 32.6 | 37.8 | 02.03.96 | 183.7 |
| SR 52 | A135 | 24.08.95-13.09.95 | 20.0 | 72 | 102.4 | 99.5 | p | (SC)138 | 33.0 | 38.2 | 02.03.96 | 165.7 |
| SR 53 | A136 | 13.09.95-04.10.95 | 21.0 | 74 | 100.5 | 95.7 | p | (SC)136 | 33.0 | 38.3 | 29.03.96 | 171.7 |

[a] SR = solar neutrino run, BL = short exposure, blank run.
[b] 70, 72, 74, 76 indicate the use of carrier solutions enriched in $^{70}$Ge, $^{72}$Ge, $^{74}$Ge, $^{76}$Ge, respectively.
[c] Integral tank-to-counter yield of Ge-carriers, errors are $\pm$ 1.7 % .
[d] See [5] for detailed explanation
[e] a = active (NaI) counting position; p = passive counting position [2].
[f] Counters have either iron or silicon cathode. SC = silicon counter with shaped cathode.
[g] Values include rise time cut.

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The ratio of such events relative to the number of $\gamma$-triggers from the 1106 keV line yields (after subtraction of background) directly the *absolute* Ge-detection efficiency. $^{69}GeH_4$ is produced via the $^{69}$Ga(p,n)$^{69}$Ge reaction, using a 10-MeV proton beam from a tandem accelerator and subsequent chemical conversion. Highly enriched $^{69}$Ga is used to suppress unwanted $^{71}$Ge-production.

Table 3:
Results for individual solar neutrino runs in GALLEX III. The middle column lists results from applying the GALLEX standard rise-time cut. For comparison, we list in the last column the results of the independent pulse-fit method (see text). All SNU-values shown are net solar production rates of $^{71}Ge$ after subtraction for side reactions, etc. [see text. standard cut: (6.1±1.6) SNU; pulse-fit cut: (5.3±1.3)SNU]. The quoted errors are statistical only.

| **Run number** | | **K+L result (SNU) Risetime 10-70 % (GALLEX standard cut)** | **K+L result (SNU) pulse fit analysis** |
|---|---|---|---|
| SR40 | A119 | $140 \pm ^{63}_{52}$ | $173 \pm ^{65}_{54}$ |
| SR41 | A120 | $104 \pm ^{53}_{42}$ | $86 \pm ^{50}_{38}$ |
| SR42 | A121 | $-89 \pm ^{68}_{0}$ | $48 \pm ^{39}_{31}$ |
| SR43 | A123 | $43 \pm ^{47}_{37}$ | $54 \pm ^{47}_{36}$ |
| SR44 | A124 | $-22 \pm ^{31}_{22}$ | $-22 \pm ^{31}_{23}$ |
| SR45 | A125 | $44 \pm ^{51}_{41}$ | $55 \pm ^{47}_{36}$ |
| SR46 | A127 | $56 \pm ^{38}_{29}$ | $50 \pm ^{36}_{26}$ |
| SR47 | A128 | $49 \pm ^{44}_{31}$ | $36 \pm ^{35}_{25}$ |
| SR48 | A129 | $24 \pm ^{43}_{32}$ | $29 \pm ^{42}_{30}$ |
| SR49 | A131 | $119 \pm ^{62}_{51}$ | $77 \pm ^{51}_{40}$ |
| SR50 | A132 | $51 \pm ^{48}_{36}$ | $61 \pm ^{50}_{37}$ |
| SR51 | A133 | $50 \pm ^{36}_{26}$ | $25 \pm ^{36}_{23}$ |
| SR52 | A135 | $22 \pm ^{33}_{22}$ | $31 \pm ^{36}_{25}$ |
| SR53 | A136 | $102 \pm ^{53}_{42}$ | $97 \pm ^{52}_{41}$ |
| GALLEX III | | $54 \pm ^{11}_{11}$ | $57 \pm ^{11}_{10}$ |

The important result from this new method is the good agreement (±2 %) between the newly determined absolute efficiencies and the previously used values with all their inherent uncertainties. This 2 % margin is well within our assigned systematic counting efficiency errors ( ±4.5 %, see Table 5 [below]). Larger uncertainties are now *experimentally* excluded. We note that we have not yet used these new counter efficiencies in the present paper; individual final adjustments for all counters used in GALLEX will be made only after the $^{69}$Ge-method has been applied to many more counters.

**3. Results from GALLEX III**

The GALLEX III series includes runs from A119 to A136, comprising consecutive solar runs SR40 - SR53 and blank runs BL28 - BL31. The run characteristics are given in Table 2. Among the 14 solar runs, 9 are 4-week and 5 are 3-week exposures. Mass spectrometric Ge-yield corrections were applied to make corrections for a natural germanium impurity, which appears to have been inadvertently introduced along with the HCl gas that had been added after every GALLEX III run in order to compensate for the regular HCl loss in the extraction process (‘reacidification’). The corrections range typically from 0 to 3 % (compare corrected and uncorrected yields in Table 2), but in one solar run (A136) it is as high as 5.1 %. We have evidence that the differences in levels of Ge-impurities are related to minute quality differences of the HCl supply, probably in turn related to the purity of their containment vessels or to the storage time within these vessels (‘standing time’). This effect became obvious when we obtained apparent Ge yields >100 %; after correction, all of the yields are <100 %.

The counting conditions in GALLEX III are as before in GALLEX II, with both active and passive counting positions being used. Also a random sampling of counter types was applied, however with more shaped cathode counters being used as they became available only more recently.

Figure 1 shows the energy/rise-time distribution for all counts registered during the first mean-life of $^{71}$Ge (upper part) and during the 4$^{th}$ mean-life (lower part). The fading out of genuine $^{71}$Ge counts in the K- and L-acceptance windows after 3 mean-lives is obvious.

The total GALLEX III exposure time (without the 4 days for blank exposures) is 353 days. 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 the middle column of Table 3, after the usual subtraction for side reactions and radon background effects (see below).

For data evaluation we have subjected the counting data to our standard energy-, rise-time-, and Rn-cuts and to the subsequent maximum likelihood analysis. However, it is important to note that an alternative and largely independent pulse shape analysis method has also been developed in our collaboration [14]. It is based on a fit of an analytical expression describing a single or multiple ionisation event to the recorded pulse shape. It serves to reveal the microscopic charge deposition structure from the recorded signal. This independent method reproduces the standard cut results from the global fits to each GALLEX

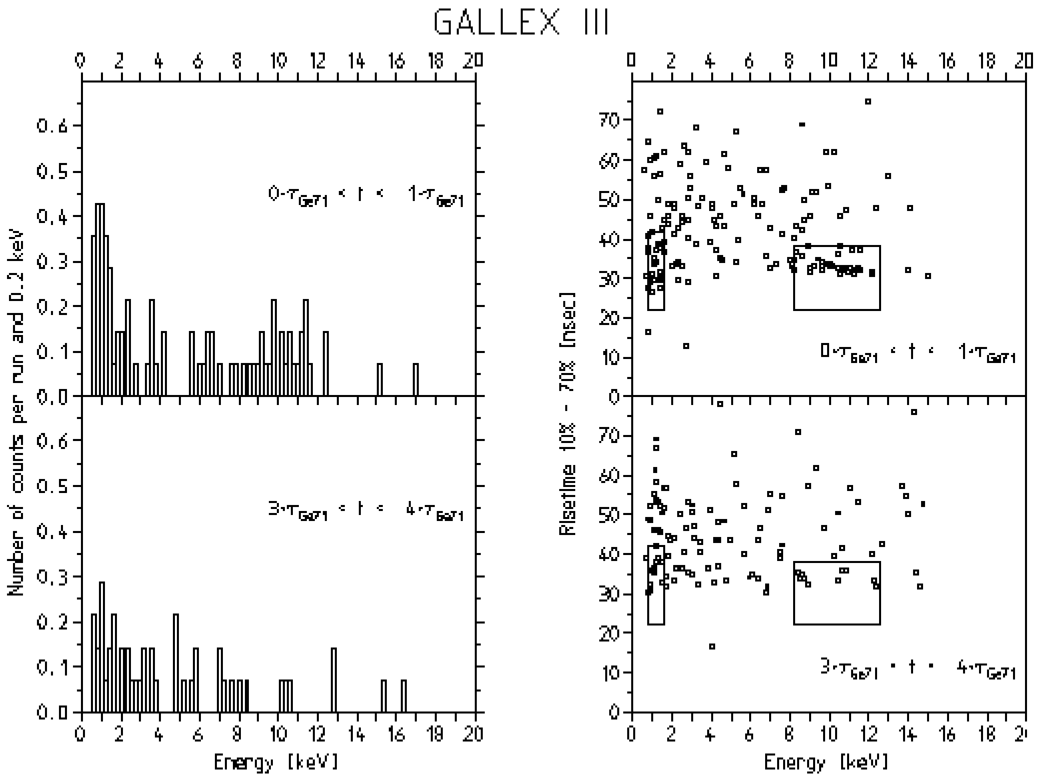


**Figure 1**: Energy spectra >0.5 keV for all pulses surviving the rise-time cut (left), and energy/rise-time distributions for all pulses >0.5 keV (right) registered in the 14 GALLEX III solar neutrino runs.
(top): during the first 16.5 days ($0\text{-}1\tau_{71}$)
(bottom): during days 50-66 ($3\tau_{71}$ - $4\tau_{71}$).
The L-and K- acceptance windows are indicated by the boxes. The L-peak (≈1 keV) and the K-peak (≈10 keV) of the Ge energy spectrum are clearly seen and they are evidently decaying. It is also clear that the ratio of $^{71}$Ge-signal to background is larger for the K-peak than for the L-peak.

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data set to ± 5 %, whereas, as expected, these different analysis methods give results for *individual* runs that can be different, but still agree within their respective large error bands. The last two columns in Table 3 compare the results from these two methods of data analysis. In Table 3, note the case of SR 42, which gives a large negative value with the empirical standard cut, but *not* for the 'analytical' method. Acceptance or rejection of a few pulses can cause drastic changes in this situation. Whether there is a general underlying reason which enables the 'analytical' pulse-fit method to better discriminate background events that cause 'unphysical' results remains to be explored. If the outcome were that the 'analytical' result for SR 42 is misjudged in the standard cut, the standard GALLEX III result without this run would increase by 6.5 SNU.

Ref.[15] contains a recent discussion of the occasional occurrence of 'unphysical' microscopic data (such as for SR 42) and their proper treatment in low

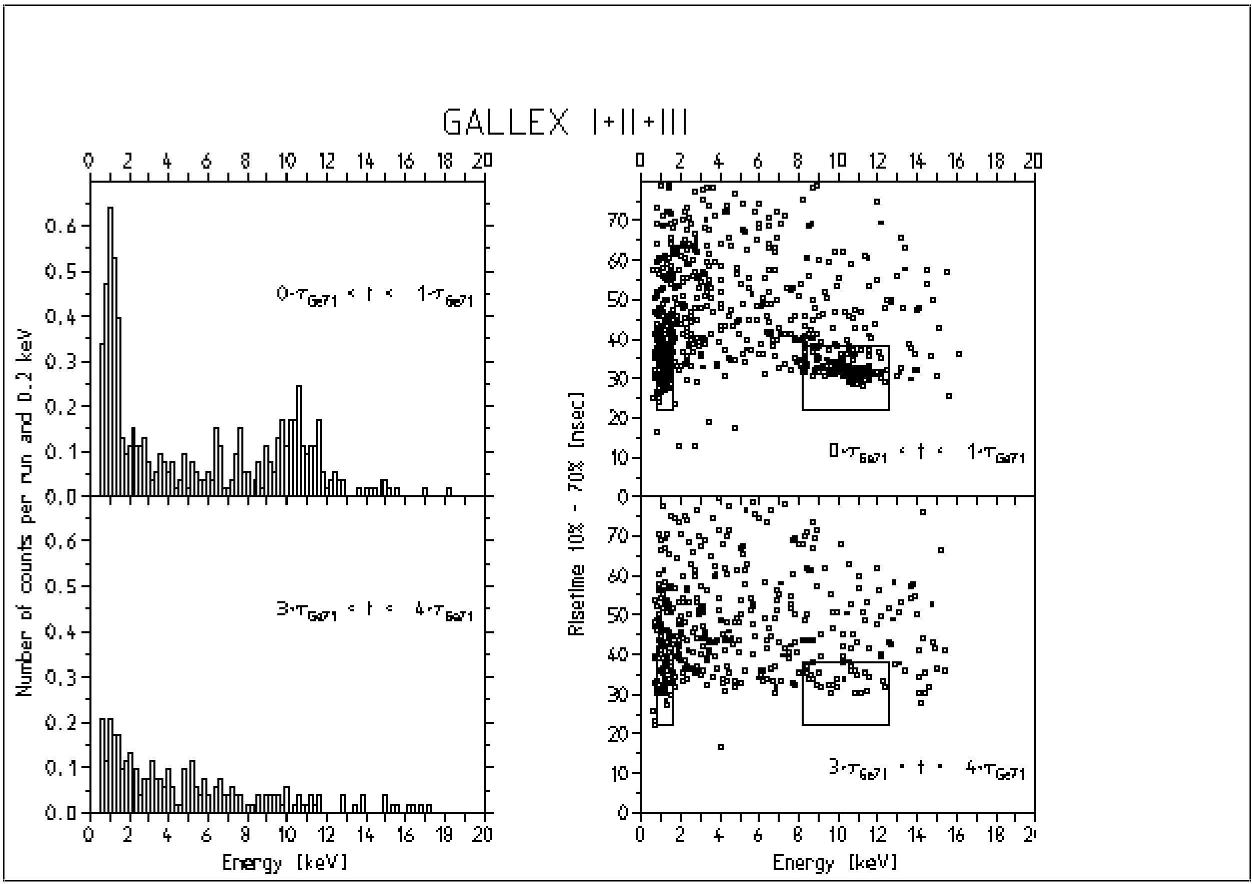


**Figure 2:** Energy spectra and rise-time distributions as in Figure 1, but for all 53 solar neutrino runs from GALLEX I, GALLEX II, and GALLEX III.

rate counting data. This approach is fully consistent with the GALLEX data treatment method. Obviously, this subject is particularly relevant for the blank run data set, where the expected physical signal is near 0 (actually =7 SNU from expected solar and side reaction productions). For the conditions under which the likelihood function has no extremum, see Sann [16]. Among the 4 blanks from GALLEX III a negative result occurs for BL28 (see Table 2).

The result from all 4 GALLEX III blanks together (after subtraction of the expected production) is 4 ± 9 SNU (1σ), that of all 31 blanks from GALLEX (I+II+III) is [-1.5 ± 5.1 (stat.) ± 1.4 (syst.)] SNU (1σ), consistent with a null result.

The net result of GALLEX III is [53.9 ± 10.6 (stat.) ± 3.1 (syst.)] SNU (1σ) or 54 ± 11 SNU (1σ) with errors combined. This is after subtraction of 6.1 SNU, namely (4.3 ± 1.2)SNU from side reactions and (1.8 ± 1.0) SNU for Rn-cut inefficiency (Table 4). The largest correction is for muon induced $^{71}$Ge production. Its value has been recently updated (Table 4) from new measurements in the CERN muon beam [18].

| | GALLEX III | GALLEX(I+II+III) |
|---|---|---|
| Muon induced background [18] | 2.8 ± 0.6 SNU | 2.8 ± 0.6 SNU |
| Fast neutrons [17] | 0.15 ± 0.1 SNU | 0.15 ± 0.1 SNU |
| $^{69}Ge$ produced from muons and $^{8}B$-ν's, and falsely attributed to $^{71}Ge$ [2] | 1.0 ± 1.0 SNU | 1.0 ± 1.0 SNU |
| Rn outside the counters [2] | 0.3 ± 0.3 SNU | 0.3 ± 0.3 SNU |
| **Subtotal** | **4.3 ± 1.2 SNU** | **4.3 ± 1.2 SNU** |
| Rn-cut inefficiency | 1.8 ± 1.0 SNU | 2.2 ± 1.1 SNU |
| **Total to subtract** | **6.1 ± 1.6 SNU** | **6.5 ± 1.6 SNU** |

Table 4: Side reaction subtractions to be applied to solar neutrino runs. For details how these values are derived, see [2].

The distribution and the statistical errors of the individual GALLEX III results behave according to expectation, with random scatter around their mean (see below, Figure 4). The total number of observed decays of $^{71}Ge$ due to solar neutrinos in GALLEX III is 56, or 4 per run. The mean-life fit for $\tau_{71}(^{71}Ge)$ is
$\tau_{71}$= 12.6 ± 3.2 d (1σ) for GALLEX III; and
$\tau_{71}$= 13.9 ± 2.0 d (1σ) for GALLEX(I+II+III); the true value is 16.49 d.
The systematic errors are specified in Table 5:

| | GALLEX III | GALLEX(I+II+III) |
|---|---|---|
| Counting efficiency including energy- and risetime cuts | ± 4.5 % | ± 4.5 % |
| target size and chemical yield | ± 2.2 % | ± 2.2 % |
| $^{68}Ge$ correction error | $\pm^{0.0}_{0.7}$ % | $\pm^{1.4}_{3.5}$ % |
| side reaction subtraction error | ± 3.0 % | ± 2.3 % |
| **Total systematic error** | **± 5.8 %** | $\pm^{\mathbf{5.7}}_{\mathbf{6.5}}$ **%** |

Table 5: Main factors contributing to the systematic error.
For details how these values are derived, see [2].

## 4. Discussion

The GALLEX III central value of 53.9 SNU is 23.9 SNU or 2.3 σ below 77.8 SNU, the central value for GALLEX(I+II) (Table 6). Obviously, there are three principal possibilities that might account for this fact: (1) statistics, (2) a solar signal that varies with time, and/or (3) unnoticed changes in the sensitivity of the gallium detector. To judge these options it is necessary to evaluate GALLEX III (14 runs) in context with GALLEX I (15 runs) and GALLEX II (24 runs), together with the result of the new global value from all 53 solar runs [central value 69.7 SNU, GALLEX (I+II+III)]. The parentheses in our notation, e.g. (I+II+III), shall indicate that the value is deduced from a joint maximum likelihood evaluation of all runs of the bracketed periods.

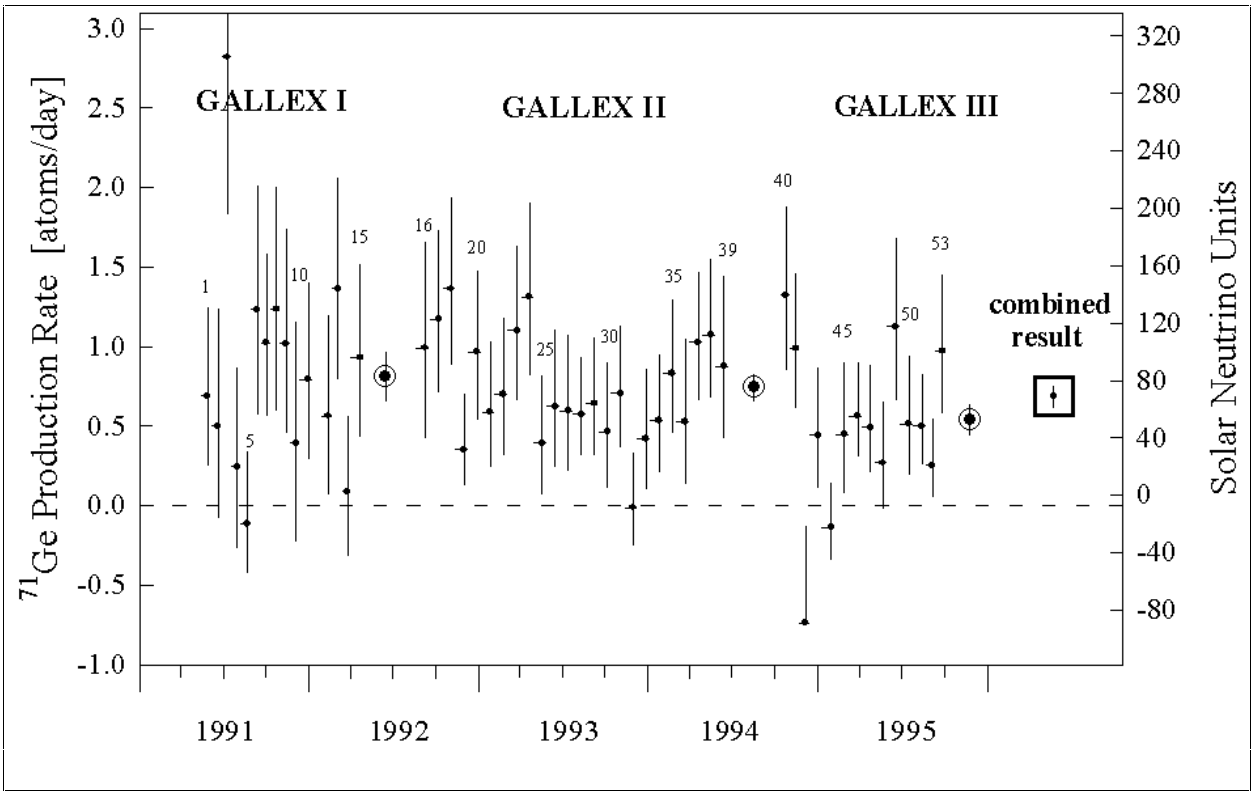


**Figure 3:** GALLEX I, II, and III single run overview. Results for the 14 solar neutrino runs of GALLEX III (labels 40-53), shown together with the earlier results from GALLEX I [2] (labels 1-15) and from GALLEX II [5] (labels 16-39). The left hand scale is the measured $^{71}$Ge production rate; the right hand scale, the net solar neutrino production rate (SNU) after subtraction of side reaction contributions. Error bars are $\pm 1\sigma$, statistical only. The label "combined" applies to the mean global value for the total of all 53 runs. We have enhanced its visibility by a square box, but its error is the small bar inside the box. Horizontal bars represent run duration; their asymmetry reflects the "mean age" of the $^{71}$Ge produced.

### *4.1 Consistency of the combined results from GALLEX (I+II+III)*

The individual run results for GALLEX III (from Table 3) are plotted in Figure 3 together with the respective data for GALLEX I and GALLEX II. Joint maximum likelihood fits have been done for combinations of GALLEX observation periods: (I+II), all previous data [5]; (II+III), all A-tank runs; and (I+II+III), all solar runs. The respective results are given in Table 6. In addition, we have analysed the response of the result to a total removal of the rise time cut. If anything, there is a slight tendency towards higher rates for the K-peak in GALLEX III and for the L-peak in GALLEX II, but all the differences are within the $1\sigma$-bands, and hence are not significant. The energy/rise-time/decay-time signature of pulses from decaying $^{71}$Ge is again illustrated, now for *all* solar runs, in Figure 2, analogous to Figure 1 (for GALLEX III only).

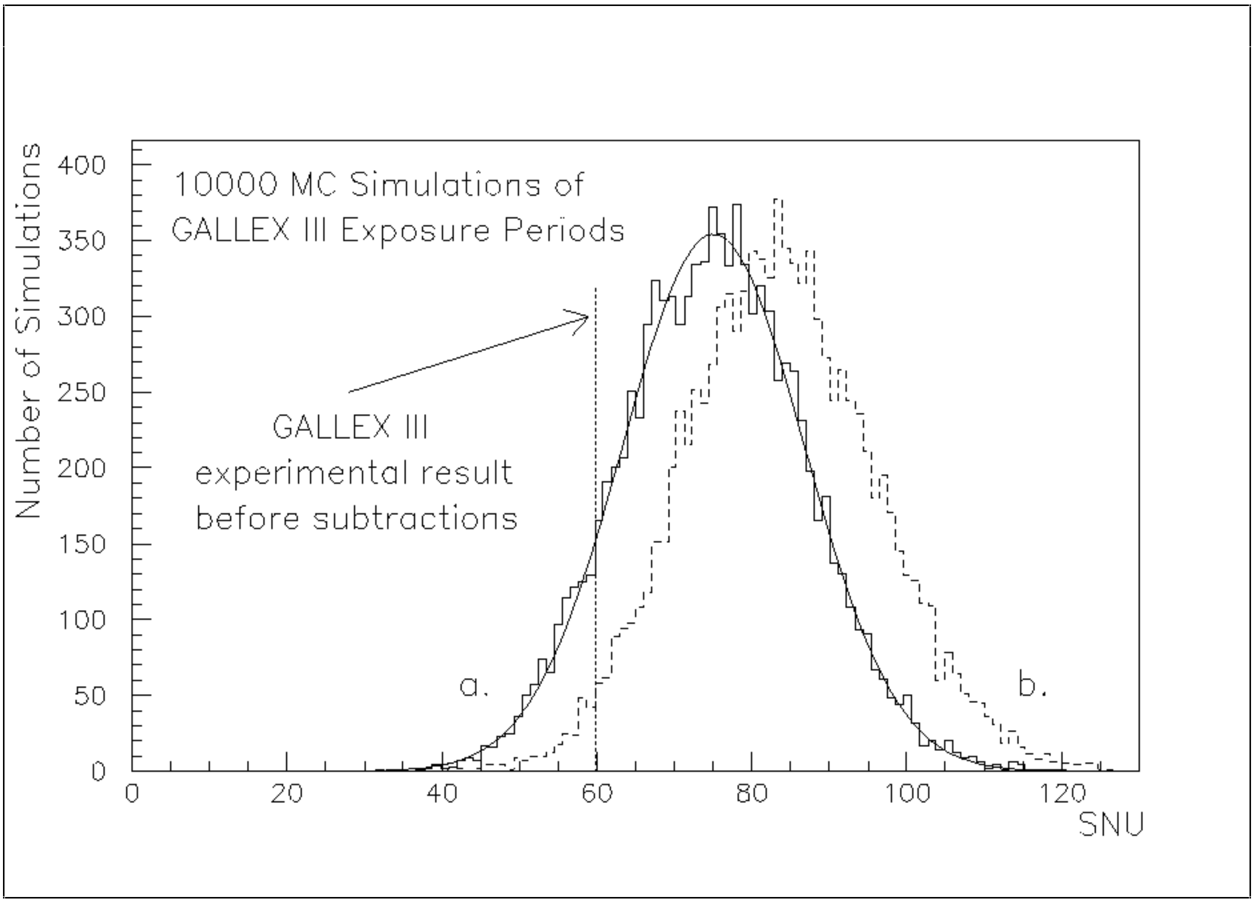


**Figure 4:** 10000 Monte-Carlo simulations of GALLEX III exposure periods.
(a) Production rate input = 76.2 SNU, as in GALLEX(I+II+III) before subtraction for side reactions. The smooth solid line depicts the Gaussian fit.
(b) Production rate input = 84.4 SNU, as in GALLEX(I+II) before subtraction for side reactions.
The experimental value for GALLEX III (before subtraction of side reactions) is shown by the vertical dotted line at 60 SNU.

We now examine the statistical implications of our results. For example, we do an analysis in which the GALLEX I, II, and III values with their statistical errors are compared to the overall GALLEX(I+II+III) result, which is assumed to be the 'true value' in the $\chi^2$-calculations. That is

$$\chi^2 = \sum_{i=1}^{3} \frac{\left[GX_i - GX(I+II+III)\right]^2}{\sigma_i^2}$$

This analysis yields a $\chi^2$-value of 3.27, which, (for 2 degrees of freedom) results in a (two-tailed) confidence level of 20%:

(i) GALLEX I, GX II, GX III vs. GALLEX(I+II+III): $\chi^2$ = 3.27 ; c.l. = 20 %.

Though this figure is on the lower side of the range expected from statistical fluctuations, it is fully consistent with the proposition that the GALLEX signal is constant in time. The respective quantities for two-period intercomparisons (1 d.o.f., 2-tailed c.l.) are analogously calculated as

Table 6: Results from Solar Exposure Periods

| | GALLEX I * (B-tank runs) | GALLEX II* | GALLEX III (this paper) | GALLEX (I+II)* | GALLEX (II+III) (all A-tank runs) | GALLEX (I+II+III) (all solar runs) |
|---|---|---|---|---|---|---|
| Time period | 14.05.91 - 29.04.92 | 19.08.92 - 22.06.94 | 12.10.94- 04.10.95 | 14.05.91 - 22.06.94 exc. 30.4.- 18.08.92 | 19.08.92 - 04.10.95 exc. 23.6 - 12.10.94 | 14.05.91 - 04.10.95 exc.5-8/92 + 6-10/94 |
| net exposure days [d] | 324 | 649 | 353 | 973 | 1002 | 1326 (3.63 yrs) |
| runs | 15 | 24 | 14 | 39 | 38 | 53 |
| result, L only [SNU] (stat. error only) | 111 ± 28 | 68 ± 14 | 41 ± 17 | 79 ± 13 | 58 ± 11 | 66.9 ± 10.5 |
| result, K only [SNU] (stat. error only) | 64 ± 21 | 82 ± 13 | 61 ± 14 | 77 ± 11 | 73 ± 10 | 71.5 ± 8.8. |
| result, L+K [SNU] (stat. and syst. error) | $83.4 \pm 17.2 \pm ^{6.8}_{9.0}$ | $75.9 \pm 9.7 \pm ^{4.2}_{4.6}$ | 53.9 ± 10.6 ± 3.1 | $77.8 \pm 8.5 \pm ^{4.4}_{5.4}$ | $67.0 \pm 7.2 \pm ^{3.7}_{4.0}$ | $69.7 \pm 6.7 \pm ^{3.9}_{4.5}$ |
| result, L+K [SNU] errors combined[&] | $83.4 \pm ^{18.5}_{19.5}$ | $75.9 \pm ^{10.5}_{10.7}$ | 53.9 ± 11.0 | $77.8 \pm ^{9.6}_{10.1}$ | $67.0 \pm ^{8.1}_{8.2}$ | $69.7 \pm ^{7.8}_{8.1}$ |

Errors quoted are 1σ-errors. [&]Statistical and systematic errors combined in quadrature.

* The small differences between these updated GALLEX I and GALLEX II valuesand the previous values in [2,5] are mainly due to using the improved value for the correction for muon induced production ([18],see section 3).

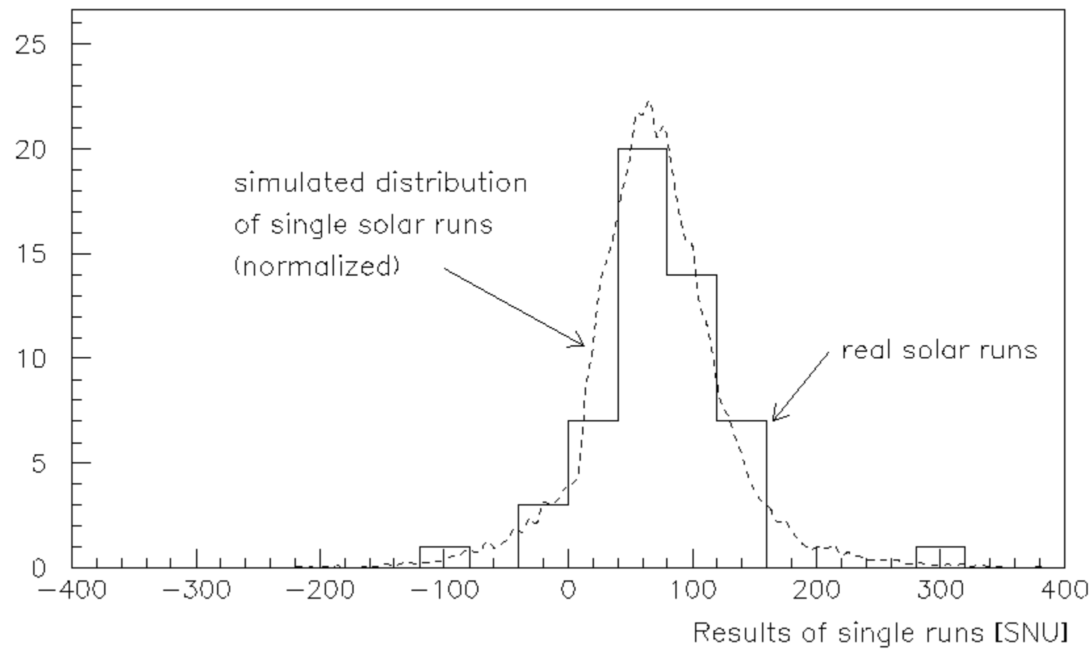


**Figure 5:** Histogram for 53 GALLEX single run results. Superimposed is the Monte-Carlo distribution deduced from 20000 single run simulations using the actual conditions of GALLEX I, II, and III in appropriate proportions (dashed line).

(ii) GALLEX II, GX III vs. GALLEX (II+III): $\chi^2$ = 2.37 ; c.l. = 13 %

(iii) GALLEX I, GX III vs. GALLEX (I+III) : $\chi^2$ = 2.16 ; c.l. = 14 %

(iv) GALLEX I, GX II vs. GALLEX (I+II) : $\chi^2$ = 0.14; c.l. = 70 %.

For the cases

(v) GALLEX III vs. GALLEX (I+II+III) and

(vi) GALLEX III vs. GALLEX (I+II)

we have performed realistic Monte-Carlo simulations under exactly the conditions of the GALLEX III runs. The resulting distributions of 10000 simulations each of GALLEX III-measurement periods for the (uncorrected for side reactions) input values of 76.2 SNU [GALLEX(I+II+III)] and 84.4 SNU [GALLEX(I+II)] are shown in Figure 4, histograms (a) and (b), respectively, where the GALLEX III result (60 SNU, uncorrected) is 1.5 $\sigma$ and 2.3 $\sigma$ below the respective reference values. From these distributions we deduce the probability to find values even below our GALLEX III result to be 9 % (one-tailed) if referenced to the global result that includes the GALLEX III data; and 2 % (one-tailed) if the GALLEX III data are (inappropriately) compared to the orthogonal subset GALLEX(I+II) (case vi).

To compare these results with those given above for cases (i-iv), we give their corresponding 2-tailed c.l. values, namely 18 % and 4 %.

For case (vi), we have done an additional statistical test that is specifically designed, and therefore appropriate, to test whether two orthogonal data sets have the same mean. In this 'difference-variable test', we check to see if the difference between the values of the two data sets obeys a normal distribution with a variance that is the sum of the individual variances. For case (vi), the difference, $\Delta$ = 23.9 SNU, and the standard deviation, $\sigma$ = 13.6 SNU. The ratio, $\Delta^2/\sigma^2 = \chi^2$. The resulting value of $\chi^2$ = 3.09, the two-tailed c.l. is 8 %.

We have also investigated the question whether the scatter of single run results is compatible with the assumption of a constant production rate. For this we have performed the maximum likelihood ratio test (see [5] for details). The resulting goodness of fit confidence level of 51 % is again in full agreement with the hypothesis of a constant production rate.

The single run distribution for all 53 solar neutrino runs is shown in Figure 5 together with a Monte-Carlo generated distribution of 20000 single run results for an (uncorrected) production rate of 76.2 SNU under the conditions of normal single runs, using the actual conditions of GALLEX I, II, and III in appropriate proportions. Note that the histogram of the solar run data shows no tendency towards bimodality.

### *4.2 Analysis for a possible time variation in the GALLEX signal related to solar activity*

As noted in Sect. 4.1 and Fig. 5, the statistical tests of the GALLEX I,II and III data sets indicate that they are all consistent with one distribution, with a mean value that has not significantly varied over the 5-year operating lifetime of GALLEX. In this section, we present a further test that specifically compares the GALLEX data with solar sunspot activity.

As in our previous publication [5], we have analysed the GALLEX(I+II+III) data in terms of a possible (anti?)correlation with the sunspot activity of the Sun by fitting the data to a production rate varying in time as

$$P(t) = a + b\,[(N_s(t) - \langle N_s \rangle) / \langle N_s \rangle],$$

where a and b are free parameters in the fit, $N_s(t)$ is the sunspot number at time t, and $\langle N_s \rangle$ is the sunspot number averaged over the whole GALLEX(I+II+III) exposure time. The result is a = 66.1 ± 7.7 SNU and b = 15.4 ± 11.7 SNU with a goodness of fit confidence level of 54 %. We note that the time independent part of the production rate is close to the GALLEX (I+II+III) mean value. That b is small and consistent with zero within 1.4 $\sigma$ again indicates that, within the limited statistics given, there is no compelling evidence in the GALLEX data for such a time dependence.

The finding that the solar data are consistent with a production rate constant in time does not invalidate other hypotheses that might give similar or even better time dependent (linear, periodic, or other) fits. This is in the nature of the statistical scatter of all solar neutrino experiments in the era before Superkamiokande. The confidence with which some kind of periodic or sporadic variability may be excluded has decreased as a result of the statistical departure of GALLEX III. It illustrates the need for a larger detector, as has been proposed in the GNO project [20] (see section 5).

### *4.3 Tests of the stability of the GALLEX experimental conditions*

Having shown that the (low) GALLEX III result has a reasonable probability to be part of a normal distribution, and not following up for the time being on the possible but unnecessary option of a time variable neutrino flux, we shall now address the remaining principal possibility, namely an hypothesised unnoticed change in the experiment's response function that causes a systematic error during the GALLEX III operation, as opposed to the earlier periods.

#### *4.3.1. Cr-source experiments*

Fortunately, with its $^{51}$Cr neutrino source GALLEX has an ideal tool to check the overall response of its detector [4]. Our first source experiment was done in fall 1994, after GALLEX II and before GALLEX III. The result was a detector response to low energy neutrinos of (100 ± 11)% (see Ref.[12], updated from [4]and [11]), indicating that systematic errors of the experiment or the error of the cross sections assumed for low energy neutrino capture of $^{71}$Ga are restricted to ±11% (1$\sigma$).

As planned, a second source experiment was performed in late 1995, after completion of GALLEX III [12]. It was done by reirradiating the same 35.6 kg of enriched chromium in the Siloe reactor in Grenoble which had been used for the first experiment. Improved operating conditions and a longer irradiation time produced a source with an activity of (68.7 ± 0.7) PBq (preliminary value) as measured by various independent techniques. Hence, the second experiment was performed in the GALLEX tank with a source that was about 10% stronger than the first one (see [12] for more details).

The source was introduced into the thimble of the target tank on 5 October 1995 and removed on 13 February 1996. We had decided to do 2 initial short runs of 3.3 and 4 days duration, followed by exposures with times similar to those of the solar runs (two 3-week runs, followed by three 4-week runs).

Counting of these source runs is not yet completed, but we have a preliminary result from the analysis that (a) fits the counting data from each source exposure in the usual way, with a $^{71}$Ge-component and a constant background, and (b) requires the resulting $^{71}$Ge intensity from one exposure to another to decrease with the $^{51}$Cr half-life ($T_{1/2}$=27.7 d), taking into account the constant solar contribution as determined by GALLEX.

Figure 6 shows the results of the individual measurements in terms of the $^{71}$Ge production rate at the start of the given exposure, together with the *expected* production curve for comparison. The ratio between the activity deduced from $^{71}$Ge-counting and the directly measured activity is
R = 0.83 ± 0.10 (1$\sigma$); the joint analysis of both source experiments together yields R = 0.92 ± 0.08 (1$\sigma$) [12].

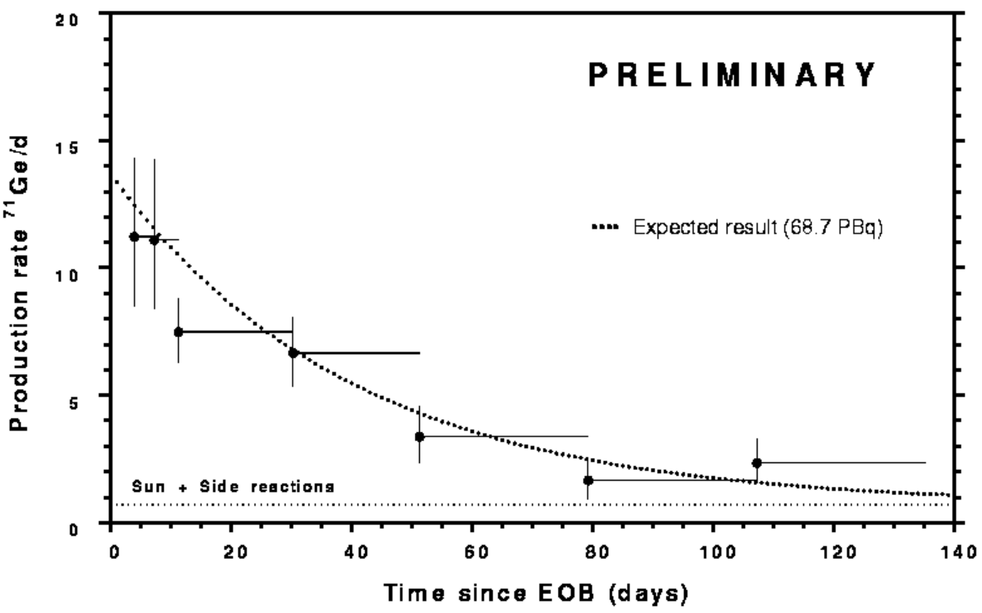


**Figure 6:** Number of $^{71}$Ge atoms produced per day in the second Cr-source experiment. The dotted line corresponds to the expected rate for a source activity of 68.7 PBq.

### *4.3.2 Run duration*

The two results from the two $^{51}$Cr-source experiments are each within 1σ of the mean, whose value is close to the minimum expected value of 0.95, as discussed in [12]. We consider these results to be evidence for the consistency of the source experiments. Nevertheless, we proceed to examine our data for some hypothesised variations in the experimental conditions.

The first parameter to consider in this context is any dependence on changes in the duration of the runs, having in mind a conjectured time dependent process in the target solution which might convert some Ge into a non-extractable form. All earlier relevant tests in this regard and experience with stable Ge-carrier recovery yields were negative, but an even better way to check such a possible influence is to use the Cr-source. While Source I had more short exposures of a few days, to maximise the use of the source (see [4] for details), the run durations for Source II were chosen to resemble more closely the duration of solar exposures (more long exposures of 3-4 weeks), at the price that the contribution of the solar production 'background' (constant in time, as opposed to source-$^{71}$Ge) has a larger influence than for Source I. The result from a comparison of 'short' runs from both sources with 'long' runs from both sources is

Source(I+II, <5 d): R = 1.01 ± 0.25 (stat.) (1σ),

Source(I+II, >5d): R = 0.89 ± 0.15 (stat.) (1σ).

The difference in these values is 0.12 ± 0.29, consistent with 0.

Turning now to the solar runs, we note that there is only little duration variance, basically between 3-week and 4-week runs. The maximum likelihood analysis for GALLEX(I+II+III, $t_{run}$<24d) yields 74.2 ± 13.4 (stat.) SNU, that for GALLEX(I+II+III, $t_{run}$>24d) yields 68.0 ± 7.8 (stat.) SNU. The difference here is 6.2 ± 15.5 SNU, again consistent with 0.

### *4.3.3 Target status and extraction kinetics*

One may ask whether the status of impurities in the gallium target solution had changed over the years that GALLEX has been operating, even though there are no positive indications for such changes. We have recently reanalysed the target solution for >25 trace elements (including for instance U,Th,Zn,As,Fe,Ba..) with sub-ppb sensitivity and found no change compared to the analysis done 5 years ago. Nevertheless, one could construct an ad-hoc scenario in which undetectably low (ppt) concentrations of some inorganic or organic impurities, X, react with excited $Ge^*$ in the solution to form unextractable XGe. To get any effect, this mechanism requires the existence of carrier-free regions in the GALLEX tank solution, as a consequence of hypothesised dead volumes that are not reached by the mixing procedure when the Ge-carrier is added. Then, some $^{71}$Ge could be retained as $X^{71}$Ge together with $XGe_{carrier}$, and when this compound later decomposes (after months), the $^{71}$Ge has of course already decayed. However, a minimum quantity of carrier-Ge is always present in the solution. The Ge-concentration level even immediately after an extraction is always $>5x10^{-13}$ mol/l, so there are no carrier-free regions in the GALLEX tank. Furthermore, previous experiments have proven that $^{71}$Ge and $^{69}$Ge directly produced by fast neutrons and protons in carrier-free gallium chloride solution are well extracted after one day of standing in the solution.

The Ge extraction and mixing procedures had been developed in extensive studies, both in lab-bench experiments and in a 1.3-ton Ga prototype experiment, prior to the start of GALLEX operations. To check on the present conditions, after some years of operation, we have performed in February/March 1996 some test experiments after the removal of the 2nd source. In these experimental tests it was assured that:

- $\geq$ 94 % of the carrier is present in the solution. This was concluded by determining the amount of Ge in the gas phase above the gallium chloride solution shortly after mixing, by sweeping out and measuring the Ge in this volume. The proportion of Ge in the gas phase was found to be $\approx$5.3 %, compared to $\approx$3.8 % theoretically expected after equilibration.

- the carrier is properly desorbed from the solution. A proper decrease over more than two orders of magnitude during desorption is assured in every run.

No indications have been found for the existence of any traps in the solution that would have held back Ge carrier above the percent level in previous runs. This conclusion is based on the upper limits, derived from the mass spectra of extracted Ge, of the anomalous carryover of the Ge-spike isotopes which were used in the preceding runs (Note that we routinely apply alternating isotopy of the Ge-spikes from run to run in order to stay in control of such ‘carry-over’ and ‘memory’-effects).

In conclusion, the tests that have been performed so far have not revealed any evidence that supported the postulated changes in the characteristics of the GALLEX experiment. However, at undetectably low concentration levels, these tests can not definitely rule out all such scenarios either. Hence, we will perform further tests in the future (see sect. 5).

### *4.4 The overall GALLEX result*

The updated GALLEX result after 53 solar runs is 69.7 $\pm^{7.8}_{8.1}$ SNU. It agrees very well with the latest update for the result of the SAGE experiment (1990-1993 data) 72 ± 13 SNU (1σ) [19]. The general implications of the fact that our result is substantially below the predictions of the various standard solar models (range 120 - 140 SNU) have been discussed in our last publication [5] and are not repeated here.

## 5. Future plans

We take solar data since 14 February 1996 in the run sequence GALLEX IV, which will continue until December 1996, interspersed with a $^{71}$As spiking test and a fast neutron source test. The projected total 1σ error after 60 solar runs is 9 % (≈ 6 SNU). In December 1996, GALLEX will stop taking solar data, as scheduled. Although GALLEX will have truly fulfilled its task at this time, it is clear that many more years would be required to fully use all the potential of such an experiment and to improve all of its phases. Even though the „learning curve“ has been quite steep in GALLEX, it may still not have reached a plateau after only 5 years, compared to, for example, the Homestake Chlorine experiment with >25 years of operation.

Continued monitoring of the pp-neutrino flux beyond 1996 is highly desirable in order, among other reasons, to provide the necessary reference frame for the findings of the upcoming generation of solar neutrino experiments. These are restricted to the observation of $^{8}$B- or, in the case of Borexino, of $^{7}$Be-neutrinos. To this end, a Gallium Neutrino Observatory (GNO) at Gran Sasso has been recently proposed [20]. If upscaling to 100 tons of gallium from the present 30 tons could be achieved, then it would be possible for GNO to exclude all standard and many non-standard solar models (or the standard model of weak interactions) at a >3σ level.

## Acknowledgements

We wish to acknowledge the competent and skilful technical staffs in Brookhaven, Gran Sasso, Grenoble, Heidelberg, Karlsruhe, and Saclay. Their performance has been crucial for the successful operation of the experiment. The generous help and advice of L.Lembo also during the second neutrino source experiment is appreciated. One of us (Y.Z.) wishes to acknowledge V.E.Yantz and E.A.Janovich for the discussions concerning counter efficiency measurements with $^{69}$Ge.

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