Reanalysis of the Gallex solar neutrino flux and source experiments†

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Abstract

After the completion of the gallium solar neutrino experiments at the Laboratori Nazionali del Gran Sasso (Gallex: 1991-1997; GNO: 1998-2003) we have retrospectively updated the Gallex results with the help of new technical data that were impossible to acquire for principle reasons before the completion of the low rate measurement phase (that is, before the end of the GNO solar runs). Subsequent high rate experiments have allowed the calibration of absolute internal counter efficiencies and of an advanced pulse shape analysis for counter background discrimination. The updated overall result for Gallex (only) is 73.4±7.1 SNU. This is 5.3% below the old value of 77.5±7.8 SNU [1], with a substantially reduced error. A similar reduction is obtained from the reanalysis of the 51Cr neutrino source experiments of 1994/1995.

Key words: Solar Neutrinos, Gallium experiment, GALLEX, neutrino mass

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1. Introduction

The Gallex detector at the Gran Sasso Underground Laboratory (LNGS) in Italy has monitored solar neutrinos with energies above 233 keV from 1991 to 1997 by means of the inverse β-decay reaction 71Ga(νe,e−)71Ge [1][2][3][4][5]. Together with the subsequent GNO experiment solar neutrinos have been recorded from 1991 to 2003, with a break in 1997 [6][7]. The experimental procedure for a typical Gallex or GNO solar neutrino run has been as follows: 30.3 t of gallium in the form of a concentrated GaCl3-HCl solution are exposed to solar neutrinos for a time period between three and four weeks. In the solution, the neutrino-induced 71Ge atoms as well as the inactive Ge carrier atoms added to the solution at the beginning of a run form the volatile compound GeCl4, which at the end of an exposure is swept out of the solution by means of a nitrogen gas stream. The nitrogen is then passed through a gas scrubber where the GeCl4 is absorbed in water. The GeCl4 is finally converted to GeH4 which together with xenon is introduced into a proportional counter to determine the number of 71Ge atoms by observing their radioactive decay (half-life 11.43 d [6]).

In order to reduce the background in 71Ge counting with proportional counters the pulses recorded by the data acquisition system were analyzed by a pulse shape discrimination method. In contrast to GNO, the published Gallex data have so far been analyzed with a rather simple procedure, where pointlike ionizations are distinguished from extended background events by the time in which the proportional counter signal rises from 10% to 70% of the amplitude recorded by the transient digitizer. A more sophisticated method has been developed [9][10][11] and tested already in Gallex [12]. However, in order to determine the cut efficiency for such a procedure, a calibration data set with high statistics measured with the full counting system is required. In order not to damage the low counter backgrounds, such data could only be acquired at the very end of Gallex in the frame of the 71As experiment [13], in which a rather large number of 71Ge decays (∼ 10⁸) has been recorded. Using this data set, a new pulse shape discrimination method has now been developed and applied to the Gallex data [14].

There are two additional motivations to reanalyse the Gallex solar neutrino data as well as the data from the two 51Cr neutrino source experiments that were performed in Gallex [15][16]. At first, 10 out of 22 coun-
ters used in the Gallex solar neutrino measurements and 4 out of 14 counters used in the Gallex $^{51}$Cr neutrinos source experiments have been absolutely calibrated in the frame of the GNO experiment [7][17]. Secondly, there is now an improved value for the solar neutrino signal and its error available which has to be subtracted from the measured signal in the analysis of the $^{51}$Cr data.

2. Pulse shape analysis in $^{71}$Ge counting

$^{71}$Ge decays back to $^{71}$Ga by K, L or M electron capture. The hole in the corresponding shell is filled by transitions of electrons from higher shells. The released energy is mostly transferred to electrons from the same or higher shells which subsequently are emitted as Auger-electrons. Only in the case of L to K transitions a substantial fraction of cases leads to the emission of a K-alpha X-rays (9.3 keV) because of the rather high fluorescence yield of the K shell (0.528). The range of Auger-electrons in the counter gas is rather small (< 1 mm) and therefore the volume extension of the energy deposition is always small. On the other hand, the mean free path of a 9.3 keV X-ray is about 1 cm and hence similar to the counter dimensions. The X-ray is therefore either able to leave the counter undetected or to produce a second separated energy deposit where the ratio of the two energies is at a fixed value of ≈ 8. Neglecting M events (which are below the selected energy threshold) this leads to three different kinds of events: (a) a single electron cloud corresponding to an energy of 10.4 keV, (b) a single electron cloud of about 1.2 keV, and (c) two electron clouds of 1.1 keV and 9.3 keV, respectively. Contrary, background events are mainly caused by higher energy electrons coming from beta decays or they are induced by gamma rays via Compton effect. These events don’t produce pointlike ionizations but an ionization track in the counting gas which leads to a slower rise time of the signals. An identification of pointlike ionizations, double ionizations or extended (multiple) events therefore allows to distinguish in many cases between $^{71}$Ge decays and background events.

The new pulse shape discrimination method described here is performed in three steps. At first, the original pulses are slightly smoothed. This is necessary due to electronic and digital noise affecting the pulse shape, particularly for low energy events. A piecewise polynomial fit was used. For each data point $P(t_i)$ a region of $t_i±8$ ns (corresponding to 20 data points on each side) was fitted with a second order polynomial $p(t)$. Finally each data point $P(t_i)$ was replaced by $p(t_i)$. This method has the advantage that it provides an adequate noise reduction but conserves even sharp structures on bigger time scales.

A pointlike energy deposition in the counter leads to a cloud of primary electrons which is δ-shaped (neglecting diffusive effects) when reaching the gas amplification zone in the proportional counter. Under ideal conditions (perfect radial electric field, constant ion mobility) the shape of the resulting preamplifier output pulse $V(t)$ can be written as $P_{\delta}(t) = V_0 \log(1+t/t_0)$ [12]. A general pulse shape can then be described by a convolution of the pulse shape caused by a pointlike charge cloud with a function $j(t)$ which parameterises the number of electrons arriving at the gas amplification zone as a function of time: $P(t) = P_{\delta}(t) \otimes j(t)$. In order to reveal $j(t)$ from a measured pulse $P(t)$ one has to numerically deconvolute $P_{\delta}(t)$ from $P(t)$. This is the second step in the applied pulse shape analysis and is performed by a Fourier analysis (i.e. transforming the measured pulse into the frequency domain) where deconvolution is simply a division (for more details see [14]).
The resolution of this peak search algorithm was defined single charge cloud. Identification of the major peaks of the proportional counter and each peak is caused by one is directly connected to the radial charge distribution in shape analysis and is performed as follows:

- Determination of the maximum position $t_{\text{max}}$.
- Determination of the full width at half maximum (FWHM). In cases of asymmetry on each side the half width was determined and the smaller value was chosen.
- The peak was approximated as a Gaussian $g(t_{\text{max}}, \sigma)$ where FWHM = $2.35\sigma$.
- Subtraction of Gaussian and repeat the procedure.

The resolution of this peak search algorithm was defined as follows: if the distance between the maxima of two peaks was smaller than the mean of the half widths both peaks were combined into a single peak. Regarding Figure 1, the distance of the two leftmost peaks is slightly above the resolution threshold.

The total deposited energy is proportional to the number of primary charges and therefore to the total integral $\int j(t) \, dt$. The fraction $C_j$ of energy deposited in one single charge cloud is therefore given by the peak integral normalised with the total energy

$$C_j = \frac{\int g(t_{\text{max}}, \sigma) \, dt}{\int j(t) \, dt}.$$  \hspace{1cm} (1)

For single events, where the energy deposit is concentrated in one single charge cloud, one expects a ratio of $C_1 \approx 1$ while $C_2$ and $C_3$ are caused by noise and therefore are small. Actually $C_1$ is often even slightly larger then 1 due to the fact that the negative noise part decreases $\int j(t) \, dt$. In contrast, for multiple events, $C_1$ is obviously smaller than 1 with a simultaneous increase of $C_2$ and $C_3$. In the case of K double events one expects to recover the given ratio $C_1/C_2 \approx 8$.

Following these expectations, criteria for event selection were defined. To decide whether a parameter is suitable to distinguish background from $^{71}$Ge events one needs reference pulses for both kinds of events. A sample of background events can be obtained from the solar runs themselves, since each sample was measured for about 180 days, but after 50 days ($\approx 3\tau$) the $^{71}$Ge atoms initially present are decayed away.

A large amount of $^{71}$Ge events were provided by the arsenic experiment \cite{13} allowing to collect the parameter distribution with good statistics. Figure 2 shows the distributions of parameter $C_1$ for $^{71}$Ge decays and background events. It is obvious that an adequate constraint on $C_1$ allows to select $^{71}$Ge decays and to reject a large part of background events.

Finally, a comparison with events from calibrations with an external X-ray source (cerium) which were performed for all solar runs \cite{2} provides the individual pulse shape parameter bounds for each run and a precise determination of the pulse shape cut efficiencies. The $C_1$ distribution for cerium events is very similar to germanium events. For each calibration the location and width of the $C_1$-peak is estimated and an acceptance window for $^{71}$Ge events is defined. The efficiency of this cut was determined using the arsenic runs for L events to $s_{L1} = 0.960 \pm 0.006$. The efficiency for K events is about 80% due to the fact that the $C_1$ cut rejects nearly all of the double events. To increase the number of accepted K double events an additional cut was defined using the ratio $C_1/C_2$. Due to the limited energy resolution of
3. Solar run analysis

3.1. Event selection

In a first step, all obvious background events are removed by several cuts. These cuts are identical to those described in [2], except for the pulse shape cut, which was applied according to the procedure described in the previous section.

All remaining candidate events (without energy cut) are plotted in Figure 3 divided into early ($t < 3\tau$) and late ($t > 3\tau$) events. The characteristics of a typical $^{71}$Ge energy spectrum with the two peaks at 1.2 and 10.4 keV, respectively, are quite obvious in the early spectrum (solid line). The peak positions and widths as well as the intensities of both peaks are lying within the expected ranges.

3.2. Maximum Likelihood Analysis

The final cut to the data is the energy cut, by which only events are selected which are inside the L and K energy windows (see [2]). After this cut there remain 726 and 452 events for the L and the K energy window, respectively. These events were used for a maximum likelihood analysis which was described in [18] for the chlorine experiment and was adapted for GALLEX and GNO. The total production rate $P$ of $^{71}$Ge is

$$P = P_\odot/d^2 + P_{\text{fix}}$$

where $P_\odot$ is the solar production rate which has to be corrected by the individual Earth-Sun distance for each run $d_e$ (given in units of 1 AU), and $P_{\text{fix}} = (0.039 \pm 0.011)$ atoms per day which is a fixed component caused by side reactions (see [5]). $P_\odot$ is one of the free parameters of the likelihood function $L$. In addition one assumes the background rates in the two energy windows $b_L$ and $b_K$ as independent free parameters for each of the 65 GALLEX runs. Altogether the likelihood function has to be maximised for 131 free and independent parameters. This is done by using the Fortran library MINUIT provided by CERN to minimise $-\log L$. The combined result for all GALLEX runs is

$$P_\odot = \left[ 73.4^{+6.1}_{-6.0} \right]^{+3.7}_{-4.1} \text{ SNU}$$

The statistical error determination is given in maximum likelihood theory by a variation of $P_\odot$ until

$$\log L_{\text{max}} = \log L(P_\odot) = \frac{1}{2}$$

while $\log L(P_\odot)$ was maximised regarding the remaining free parameters which leads to $1\sigma = P_\odot(L_{\text{max}}) - P_\odot$. A possible asymmetry of the error is considered by investigation of both sides of $L_{\text{max}}$.

The systematic error includes the uncertainty of counter efficiencies, which decreased to 2.6% due to the more precise calibrations [7]. The error of the pulse shape cut efficiency was estimated to 2.0%. The contribution of other components are unchanged compared to previous publications, a compilation is given in Table 1.

| Efficiencies [7] | ±2.6% |
|------------------|-------|
| Energy cut [2]   | ±2.0% |
| Pulse shape analysis | ±2.0% |
| Chemical yield [1] | ±2.1% |
| Target mass [3]  | ±0.8% |
| $^{68}$Ge correction [1] | $^{+0.9\%}_{-2.6}$ |
| Side reactions [1][19][20] | ±1.5% |
| Rn cut [1]       | ±1.5% |

Table 1: Systematic error contributions

For the maximum likelihood analysis the half-life of $^{71}$Ge is usually fixed to its known value of 11.43 d. However, it can also be treated as an additional free parameter. This yields 10.3 ± 1.2 d, which is in agreement with the expected value. Moreover, due to the radon cut inefficiency and the short half-life of $^{222}$Rn and its
daughters one expects a small bias towards a shorter half-life. Besides the energy spectrum characteristics, this is a strong proof of the Gallex data set consistency.

For a comparison with the previously published results we repeated the rise time analysis. The event selection procedure described in section 3.1 was used identically except the pulse shape analysis was replaced by the rise time method. The new counter efficiencies were considered as well as the correction due to the earth-sun distance variation (which so far had not been applied in the Gallex data analysis). The result

\[ P^\odot = \left[ 77.4^{+6.4}_{-6.2} \text{(stat.)}^{+3.9}_{-4.3} \text{(syst.)} \right] \text{SNU} \]  

(5)

is in very good agreement with the value of \( 77.5 \pm 6.2 \text{(stat.)}^{+4.7}_{-4.5} \text{(syst.)} \) SNU given in [1]. All changes average to near zero, except for the pulse shape analysis.

3.3. Single runs and Gallex I-IV

The single run results are listed in Table 3 and Table 4 and are plotted in Figure 4. The histogram in Figure 5 shows the distribution of results in bins of 20 SNU.

Even though the statistical error of a single run result is usually asymmetric, one expects a normal distribution as shown by Monte Carlo simulations [1]. This expectation was tested by a Kolmogorov-Smirnov-test. The test value is defined as the maximum deviation \( D \) between the cumulative distribution functions of the given data set and the expected normal distribution. One obtains \( D = 0.076 \) for the Gallex data set. For randomly generated samples one gets higher values of \( D \) in 54% of all cases and a 90% confidence level of \( D_{0.9} = 0.1 \). For a second test (which is related to the latter one but more sensitive concerning outliers) the test value was defined as the total integral of absolute deviations between the cumulative distribution functions. In 19% of cases randomly generated samples created higher values than the original data set. From these points of view there is no reason to doubt the hypothesis of a normal distribution.

The statistical errors of single runs are rather big, because even a single accepted or rejected event is able to change the result of a run by 10 SNU or even more. Therefore a run by run comparison between pulse shape and rise time analysis is not very meaningful. Only combinations of many runs are suitable to provide enough statistics to decrease the error to a significant level. Therefore the 65 runs were sorted into groups. For historical reasons we stayed with the grouping in four periods of data taking which occurred in a natural way by interruptions for construction works or source experiments. Nevertheless, this kind of grouping is arbitrary and should have no effect on the results.

The results of the four Gallex periods are shown in Figure 6 and are listed in Table 2 with rise time and pulse shape analysis, respectively. While the results of

| Gallex period | rise time \( \pm 1\sigma \) [SNU] | pulse shape \( \pm 1\sigma \) [SNU] |
|---------------|---------------------------------|---------------------------------|
| I             | 84.0^{+17.6}_{-16.7}            | 75.1^{+17.3}_{-16.2}            |
| II            | 77.2^{+9.9}_{-9.5}              | 82.8^{+10.0}_{-9.9}             |
| III           | 51.2^{+10.8}_{-10.0}            | 49.5^{+10.7}_{-9.8}             |
| IV            | 122.1^{+18.4}_{-17.5}           | 89.2^{+16.6}_{-15.5}            |

Table 2: Results of the Gallex periods I-IV with rise time and pulse shape analysis. The errors are \( 1\sigma \) (stat.).

Figure 4: Single results of the 65 Gallex solar runs (error bars are \( \pm 1\sigma \) statistical).

Figure 5: Distribution of the Gallex single run results in bins of 20 SNU.
| GaLeX I | Expos | pulse shape analysis | runs | start | duration (d) | $b_L$ | $b_K$ | $P_0$ (SNU) |
|---|---|---|---|---|---|---|---|---|
| 1 | b29 | 14-MAY-1991 | 21.0 | 0.028 | 0.000 | 105$^{+69}_{-58}$ |
| 2 | b31 | 5-JUN-1991 | 20.8 | 0.020 | 0.033 | 6$^{+56}_{-57}$ |
| 3 | b32 | 26-JUN-1991 | 21.0 | 0.115 | 0.057 | 344$^{+128}_{-112}$ |
| 4 | b33 | 17-JUL-1991 | 21.0 | 0.079 | 0.000 | 66$^{+52}_{-51}$ |
| 5 | b34 | 7-AUG-1991 | 21.0 | 0.064 | 0.043 | +67$^{−47}_{−90}$ |
| 6 | b35 | 28-AUG-1991 | 22.3 | 0.035 | 0.024 | 56$^{+74}_{−73}$ |
| 7 | b36 | 19-SEP-1991 | 19.7 | 0.000 | 0.000 | 82$^{+59}_{−45}$ |
| 8 | b38 | 10-OCT-1991 | 21.0 | 0.064 | 0.059 | 73$^{+76}_{−63}$ |
| 9 | b39 | 30-OCT-1991 | 21.0 | 0.058 | 0.003 | 133$^{+87}_{−68}$ |
| 10 | b41 | 21-NOV-1991 | 19.9 | 0.218 | 0.114 | 40$^{+53}_{−43}$ |
| 11 | b42 | 11-DEC-1991 | 28.0 | 0.098 | 0.010 | 80$^{+73}_{−68}$ |
| 12 | b45 | 29-JAN-1992 | 21.0 | 0.034 | 0.032 | 19$^{+58}_{−43}$ |
| 13 | b47 | 20-FEB-1992 | 19.8 | 0.028 | 0.020 | 106$^{+59}_{−34}$ |
| 14 | b49 | 12-MAR-1992 | 18.8 | 0.092 | 0.000 | −12$^{−31}_{−83}$ |
| 15 | b50 | 31-MAR-1992 | 29.0 | 0.008 | 0.018 | 115$^{+86}_{−48}$ |

| GaLeX II | Expos | pulse shape analysis | runs | start | duration (d) | $b_L$ | $b_K$ | $P_0$ (SNU) |
|---|---|---|---|---|---|---|---|---|
| 16 | a59 | 19-AUG-1992 | 28.0 | 0.046 | 0.018 | 120$^{+58}_{−56}$ |
| 17 | a61 | 17-SEP-1992 | 27.0 | 0.034 | 0.019 | 138$^{+64}_{−53}$ |
| 18 | a63 | 15-OCT-1992 | 27.0 | 0.059 | 0.016 | 146$^{+46}_{−34}$ |
| 19 | a65 | 12-NOV-1992 | 27.0 | 0.038 | 0.000 | 38$^{+44}_{−29}$ |
| 20 | a67 | 10-DEC-1992 | 27.0 | 0.000 | 0.000 | 123$^{+34}_{−32}$ |
| 21 | a69 | 7-JAN-1993 | 27.0 | 0.051 | 0.021 | 48$^{+46}_{−35}$ |
| 22 | a71 | 4-FEB-1993 | 27.0 | 0.083 | 0.037 | 77$^{+52}_{−41}$ |
| 23 | a73 | 4-MAR-1993 | 29.0 | 0.016 | 0.012 | 114$^{+38}_{−46}$ |
| 24 | a75 | 3-APR-1993 | 25.0 | 0.035 | 0.024 | 151$^{+70}_{−58}$ |
| 25 | a77 | 29-APR-1993 | 27.0 | 0.044 | 0.038 | 31$^{+45}_{−29}$ |
| 26 | a79 | 27-MAY-1993 | 27.0 | 0.036 | 0.026 | 59$^{+55}_{−42}$ |
| 27 | a81 | 24-JUN-1993 | 27.0 | 0.040 | 0.017 | 80$^{+54}_{−32}$ |
| 28 | a83 | 22-JUL-1993 | 27.0 | 0.057 | 0.006 | 43$^{+43}_{−31}$ |
| 29 | a85 | 19-AUG-1993 | 27.0 | 0.014 | 0.006 | 101$^{+50}_{−30}$ |
| 30 | a87 | 16-SEP-1993 | 27.0 | 0.029 | 0.042 | 37$^{+43}_{−31}$ |
| 31 | a89 | 14-OCT-1993 | 27.0 | 0.019 | 0.038 | 82$^{+53}_{−40}$ |
| 32 | a91 | 11-NOV-1993 | 27.0 | 0.042 | 0.025 | 11$^{+37}_{−25}$ |
| 33 | a93 | 9-DEC-1993 | 27.0 | 0.014 | 0.021 | 37$^{+51}_{−36}$ |
| 34 | a95 | 6-JAN-1994 | 27.0 | 0.024 | 0.011 | 108$^{+86}_{−35}$ |
| 35 | a97 | 3-FEB-1994 | 27.0 | 0.032 | 0.018 | 92$^{+42}_{−36}$ |
| 36 | a99 | 3-MAR-1994 | 27.0 | 0.021 | 0.010 | 41$^{+54}_{−44}$ |
| 37 | a101 | 31-MAR-1994 | 27.0 | 0.034 | 0.014 | 102$^{+51}_{−31}$ |
| 38 | a103 | 28-APR-1994 | 27.0 | 0.056 | 0.014 | 81$^{+54}_{−35}$ |
| 39 | a105 | 26-MAY-1994 | 27.0 | 0.036 | 0.020 | 135$^{+70}_{−36}$ |

Table 3: Single solar run results with stat. error (1σ) for GaLeX I and II.
### Table 4: Single solar run results with stat. error (1σ) for Gallex III and IV.

| Gallex III Runs | Exposure start date | Expos. duration (d) | $b_L$ | $b_K$ | $P_0$ (SNU) |
|-----------------|---------------------|---------------------|-------|-------|-------------|
| a119            | 12-OCT-1994         | 21.0                | 0.058 | 0.011 | 173$^{+66}_{-55}$ |
| a120            | 2-NOV-1994          | 21.0                | 0.031 | 0.007 | 65$^{+46}_{-34}$ |
| a121            | 23-NOV-1994         | 21.0                | 0.028 | 0.010 | 56$^{+41}_{-32}$ |
| a123            | 15-DEC-1994         | 27.0                | 0.039 | 0.036 | 47$^{+44}_{-35}$ |
| a124            | 11-JAN-1995         | 28.0                | 0.079 | 0.049 | $-28^{+30}_{-22}$ |
| a125            | 8-FEB-1995          | 28.0                | 0.039 | 0.021 | 64$^{+51}_{-41}$ |
| a127            | 9-MAR-1995          | 29.0                | 0.038 | 0.000 | 52$^{+37}_{-26}$ |
| a128            | 7-APR-1995          | 26.0                | 0.030 | 0.000 | 25$^{+32}_{-20}$ |
| a129            | 3-MAY-1995          | 28.0                | 0.067 | 0.036 | 7$^{+42}_{-32}$ |
| a131            | 1-JUN-1995          | 27.0                | 0.042 | 0.016 | 90$^{+62}_{-48}$ |
| a132            | 28-JUN-1995         | 28.0                | 0.058 | 0.017 | 55$^{+51}_{-38}$ |
| a133            | 26-JUL-1995         | 28.0                | 0.014 | 0.000 | 29$^{+32}_{-20}$ |
| a135            | 24-AUG-1995         | 20.0                | 0.010 | 0.020 | 29$^{+36}_{-23}$ |
| a136            | 13-SEP-1995         | 21.0                | 0.027 | 0.013 | 56$^{+34}_{-34}$ |
| a146            | 14-FEB-1996         | 21.0                | 0.135 | 0.015 | 104$^{+31}_{-38}$ |
| a148            | 7-MAR-1996          | 22.0                | 0.010 | 0.053 | 47$^{+32}_{-48}$ |
| a149            | 29-MAR-1996         | 19.0                | 0.053 | 0.012 | 60$^{+35}_{-40}$ |
| a151            | 18-APR-1996         | 20.0                | 0.019 | 0.033 | 28$^{+40}_{-40}$ |
| a157            | 27-JUN-1996         | 20.0                | 0.063 | 0.020 | 68$^{+55}_{-50}$ |
| a158            | 17-JUL-1996         | 21.0                | 0.025 | 0.019 | 91$^{+48}_{-52}$ |
| a161            | 29-AUG-1996         | 20.0                | 0.105 | 0.061 | $-98^{+52}_{-53}$ |
| a162            | 18-SEP-1996         | 22.0                | 0.041 | 0.000 | 100$^{+39}_{-39}$ |
| a163            | 10-OCT-1996         | 41.0                | 0.062 | 0.012 | 125$^{+59}_{-49}$ |
| a165            | 21-NOV-1996         | 20.0                | 0.024 | 0.009 | 106$^{+55}_{-51}$ |
| a166            | 11-DEC-1996         | 29.0                | 0.053 | 0.000 | 201$^{+59}_{-28}$ |
| a167            | 9-JAN-1997          | 13.0                | 0.025 | 0.015 | 83$^{+61}_{-42}$ |
periods I, II and III are in good agreement, the difference for period IV is remarkable. The statistical error bars have a small overlap, but one should keep in mind that both results were derived from the same data set and should be strongly correlated. To estimate the correlation in a quantitative way we compared the single run results of the periods I, II and III. The correlation coefficient $r_{xy}$ is defined as

$$r_{xy} = \frac{\text{cov}(x, y)}{\sigma_x \sigma_y}$$  \hspace{1cm} (6)

with the covariance

$$\text{cov}(x, y) = \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})$$  \hspace{1cm} (7)

One gets $r_{xy} = 0.826$ and therefore $r^2_{xy} = 0.682$, where the latter is conventionally interpreted as the part of the variance of $x$ caused by changes in $y$ (and vice versa). If one applies this expectation to the GALLEX IV results, only a third of the variation is caused by statistical fluctuations. From this point of view the difference between the two results is very unlikely.

Concerning the rise time results it was already noted in \cite{1,2} that the scattering of the four results is unusual. A $\chi^2$-test for compatibility with a constant mean yields a probability of less than 1% ($\chi^2 = 12.7$ with 3 degrees of freedom, assuming symmetric errors). However, it was shown that the scattering is decreased if different kinds of grouping are applied (e.g. four random divisions) resulting in probabilities up to 26.7%. For the results obtained by pulse shape analysis one calculates $\chi^2 = 7.1$ corresponding to a probability of 7%, mainly due to the lower GALLEX IV value.

As already discussed in \cite{1} eight of the twelve runs of the GALLEX IV period had problems with electronic noise, which led to a missing baseline in case of low energy (L) events. While the uncertainty of the rise time determination increases, the evaluation of pulse shape parameters described in section \cite{2} is not or only weakly affected by the location of the baseline level. However, a separate analysis of L and K events reveals that the high GALLEX IV result obtained with the rise time method cannot exclusively be assigned to the L events (see figure 7).

The event selection with the pulse shape analysis is more stringent compared to the rise time analysis, therefore it provides a better background reduction (see Figure 9) at the cost of a lower cut efficiency especially for K events. The diagram in Figure 8 shows the number of events selected by both types of analysis for GALLEX IV. The difference in the number of accepted K events is as expected, but it is remarkable that the number of accepted L events is almost equal. Therefore, the lower GALLEX IV result is caused by the time distribution of accepted events.

3.4. Combination with GNO

After the end of GALLEX the gallium neutrino observation at LNGS was continued by the GNO collaboration that performed 58 solar runs between 1998 and 2003.
The experimental setup was basically the same as for GALLEX except for the electronics, which had been redesigned in order to replace and modernise the GALLEX counting system. The event selection was based on a pulse shape analysis in which a theoretical pulse shape was fitted to the measured pulse. A neural network trained by a large amount of reference events decided on the basis of the fit parameters whether an event was accepted or rejected \[22\].

The results of the three GNO measuring periods are shown in Table 5 together with the four GALLEX periods, II-III and III-IV respectively. Two intense \(^{51}\)Cr neutrino sources were produced by neutron capture on \(^{50}\)Cr by irradiation of isotopically enriched chromium in the core of the Siloë reactor in Grenoble. The energies of the emitted neutrinos are about 750 keV (90\%) and 430 keV (10\%).

For an accurate knowledge of the source activities \(A\) the latter were determined by different methods (for details see \[16\]). With the theoretical capture cross section of gallium \(\sigma = 58.1^{+2.1}_{-1.6} \times 10^{-46} \text{ cm}^2\) one can predict the expected neutrino signal to compare it with the measurement. The sources were placed in a tube inside the gallium tank for exposure times of a few days up to 4 weeks. Else, the experimental procedure was the same as for solar runs.

Compared to the previous published results in \[16\], the reanalysis of the source experiments considers the following changes:

- new counter efficiencies due to more precise calibrations (6 of 18 source runs were affected).
- the update of the solar production rate by the combined GNO result, which has to be treated as additional side reaction in the source experiments.
- event selection with pulse shape analysis instead of rise time. For an easier comparison the rise time results are given, too.

\[ \chi^2 \] -fits to the seven GALLEX-GNO periods for both a constant and a linear dependence (where \( \bar{t} \) is the average time).

Table 5: \( \chi^2 \) -fits to the seven GALLEX-GNO periods for both a constant and a linear dependence (where \( \bar{t} \) is the average time).

| Fit | \( m \) | \( c \) | \( \chi^2 \) | d.o.f | \( p \) |
|-----|--------|--------|------------|-------|-------|
| \( y(t) = c \) | 66.4 | 9.44 | 6 | 15.0% |
| \( y(t) = \bar{m}t + c \) | -1.08 | 66.4 | 8.55 | 5 | 12.8% |

The combination was calculated as a weighted mean using the statistical errors (with the approximation of symmetry). The systematic error was obtained by a quadratic combination of both single errors.

4. Source experiments

For a complete test of the experimental performance the GALLEX collaboration arranged two source experiments \[15\] \[16\] in between the solar periods II-III and III-IV respectively. Two intense \(^{51}\)Cr neutrino sources were produced by neutron capture on \(^{50}\)Cr by irradiation of isotopically enriched chromium in the core of the Siloë reactor in Grenoble. The energies of the emitted neutrinos are about 750 keV (90\%) and 430 keV (10\%). For an accurate knowledge of the source activities \( A \) the latter were determined by different methods (for details see \[16\]). With the theoretical capture cross section of gallium \( \sigma = 58.1^{+2.1}_{-1.6} \times 10^{-46} \text{ cm}^2 \) one can predict the expected neutrino signal to compare it with the measurement. The sources were placed in a tube inside the gallium tank for exposure times of a few days up to 4 weeks. Else, the experimental procedure was the same as for solar runs.

Compared to the previous published results in \[16\], the reanalysis of the source experiments considers the following changes:

- new counter efficiencies due to more precise calibrations (6 of 18 source runs were affected).
- the update of the solar production rate by the combined result of GALLEX + GNO, which has to be treated as additional side reaction in the source experiments.
- event selection with pulse shape analysis instead of rise time. For an easier comparison the rise time results are given, too.
have measured the contribution of the first two excited states in $^{71}$Ge to the $^{71}$Ga neutrino capture cross section. Reanalysing the data from these two source experiments using the pulse shape discrimination and improved counting efficiencies yields $r = 0.882 \pm 0.078$ (see Table 7). This ratio is 1.5σ away from the expectation value 1.0 where a 5% contribution from the first two excited states is included.

If the results from the $^{51}$Cr and $^{37}$Ar source experiments performed in the frame of SAGE [24, 25] are also included, the total ratio is $0.87 \pm 0.06$ (though an experiment equivalent to the GALLEX $^{71}$As experiment has not been performed for SAGE). This low value indicates that the contribution of the first two excited states is rather small. This is in agreement with the finding by Hata and Haxton [26] that the assumed proportionality between $(p,n)$ forward scattering cross sections and Gamow-Teller strength is not always valid for weaker GT transitions.

If it is adopted that the excited state contribution to the $^{51}$Cr cross section is closer to 0% than to 5% as estimated by Bahcall, then this is also true for the $^{7}$Be neutrino capture cross section where the assumed contribution is 6% according to Bahcall [23] (derived from the $(p,n)$ experiments). As a consequence the $^{7}$Be contribution of $34.8^{+4.8}_{-3.5}$ SNU [27] to the total solar neutrino capture (without oscillations) should be reduced to 32.7 SNU with a slightly reduced error.

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References

[1] GALLEX Collaboration, W. Hampel et al., Physics Letters B 447 (1999) 127-133.
[2] GALLEX Collaboration, P. Anselmann et al., Physics Letters B 285 (1992) 376-389.
[3] GALLEX Collaboration, P. Anselmann et al., Physics Letters B 314 (1993) 445-458.
[4] GALLEX Collaboration, P. Anselmann et al., Physics Letters B 357 (1995) 237-247.
[5] GALLEX Collaboration, W. Hampel et al., Physics Letters B 388 (1996) 384-396.
[6] GNO Collaboration, M. Altmann et al., Physics Letters B 490 (2000) 16-26.
[7] GNO Collaboration, M. Altmann et al., Physics Letters B 616 (2005) 174-190.
[8] W. Hampel, L. P. Remsberg, Physical Review C 31 (1985) 666.
[9] A. Urban, Ph. D. Thesis, Technische Universität München 1989.
[10] U. Schanda, Ph. D. Thesis, Technische Universität München 1993.
[11] M. Altmann, Ph. D. Thesis, Technische Universität München 1996.
[12] M. Altmann, F. v. Feilitzsch, U. Schanda, Nuclear Instruments and Methods in Physics Research A 381 (1996) 398-412.
[13] GALLEX Collaboration, W. Hampel et al., Physics Letters B 436 (1998) 158-173.
[14] F. Kaether, Ph. D. Thesis, Universität Heidelberg 2007.
[15] GALLEX Collaboration, P. Anselmann et al., Physics Letters B 342 (1995) 440-450.
[16] GALLEX Collaboration, W. Hampel et al., Physics Letters B 420 (1998) 114-126.
[17] F. Kaether, Master Thesis, Universität Heidelberg 2003.
[18] B. T. Cleveland, Nuclear Instruments and Methods 214 (1983) 451-458.
[19] M. Cribier et al., Astroparticle Physics 4 (1995) 23-32.
[20] M. Cribier et al., Astroparticle Physics 6 (1997) 129-141.
[21] T. Kirsten, Nuclear Physics B (Proc. Suppl.) 77 (1999) 26-34.
[22] L. Pandola, Ph. D. Thesis, Università degli Studi dell’Aquila, 2004.
[23] J. N. Bahcall, Physical Review C 56 (1997) 3391.
[24] SAASS Collaboration, J. N. Abdurashitov et al., Physical Review C 60 (1999) 055801.
[25] SAASS Collaboration, J. N. Abdurashitov et al., Physical Review C 73 (2006) 045805.
[26] N. Hata, W. Haxton, Physics Letters B 353 (1995) 422-431.
[27] J. N. Bahcall, C. Peña-Garay, New Journal of Physics 6 (2004) 63.