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Solar Neutrinos at GALLEX [and Discussion]

W. Hampel and D. W. Sciama

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Solar neutrinos at GALLEX

By W. Hampel (for the GALLEX collaboration)†
Max-Planck-Institut für Kernphysik Heidelberg, P.O. Box 103980, 69029 Heidelberg, Germany

The production of ^{71}Ge from ^{71}Ga by solar neutrinos has been measured by the GALLEX collaboration using 30.3 t of gallium in the form of 101 t $GaCl_3$–HCl solution. The experiment is shielded by about 3300 m water equivalent of rock in hall A of the Gran Sasso Underground Laboratory in Italy. Experimental details on the chemical procedures and the ^{71}Ge counting are presented. The result for the first data taking period of GALLEX, based on 15 solar neutrino runs performed in the B tank, is 81 ± 17 (stat) ± 9 (syst) SNU. Preliminary data from six additional solar runs carried out in the A tank are also reported. When combined with the B tank exposures the joint production rate for all 21 runs is $87 \pm 14 \pm 7$ SNU. Implications of this result are discussed.

1. Introduction

The long-term averaged solar neutrino production rate measured with the radiochemical Homestake Chlorine Detector is 2.23 ± 0.22 SNU (Lande 1992) (1 SNU = 1 neutrino reaction per second in 10^{36} target atoms). There is a persistent discrepancy, called the 'solar neutrino problem' (SNP), between this result and the prediction from the standard solar model (SSM), 8.0 SNU (Bahcall & Pinsonneault 1992) (table 1, see for comparison also Berthomieu *et al.* (1993) and Turck-Chièze & Lopes (1993)), which is usually attributed to a deficiency of solar ^{8}B neutrinos ($E_\nu <$ 15 MeV). This conclusion has been confirmed by the Kamiokande-II water Cerenkov detector which observes only (48 ± 8)% of the ^{8}B neutrino flux expected from the Standard Solar Model (Nakamura 1993).

Both detectors have energy thresholds much above the maximum energy (0.42 MeV) of the pp neutrinos which are produced in the primary fusion reaction in the Sun. It has long been recognized that an experiment capable to observe these pp neutrinos could provide (i) a test of the SSM in view of the solar neutrino problem; (ii) the experimental verification that hydrogen burning via the pp chain is indeed the principal energy source of the Sun; (iii) information on neutrino oscillations with squared mass differences much smaller ($\geqslant 10^{-12}$ eV^2) than those accessible in terrestrial experiments.

† GALLEX collaboration: **MPIK Heidelberg:** P. Anselmann, W. Hampel, G. Heusser, J. Kiko, T. Kirsten, E. Pernicka, S. Pezzoni, R. Plaga, U. Rönn, M. Sann, C. Schlosser, R. Wink, M. Wojcik; **KfK Karlsruhe:** R. v. Ammon, K. H. Ebert, T. Fritsch, K. Hellriegel, E. Henrich, L. Stieglitz, F. Weyrich; **LNGS l'Aquila:** M. Balata, N. Ferrari, H. Lalla; **Università di Milano:** E. Bellotti, C. Cattadori, O. Cremonesi, E. Fiorini, L. Zanotti; **TU München:** M. Altmann, F. v. Feilitzsch, R. Mößbauer, U. Schanda; **Observatoire de la Côte d'Azur, Nice:** G. Berthomieu, E. Schatzman; **WIS Rehovot:** I. Carmi, I. Dostrovsky; **II-Università di Roma:** C. Bacci, P. Belli, R. Bernabei, S. d'Angelo, L. Paoluzi; **DAPNIA CE Saclay:** S. Charbit, M. Cribier, G. Dupont, L. Gosset, J. Rich, M. Spiro, T. Stolarcyk, C. Tao, D. Vignaud; **Brookhaven National Laboratory, Upton, N.Y.:** R. L. Hahn, F. X. Hartmann, J. K. Rowley, R. W. Stoenner, J. Weneser.

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Table 1. *Solar neutrino fluxes and capture rates for the chlorine and gallium detectors* (*Bahcall & Pinsonneault 1992*)

neutrino source and energy/MeV		flux at Earth 10^{10} cm^{-2} s^{-1}	production rate/SNU ^{37}Cl experiment	^{71}Ga experiment
pp	$\leqslant 0.42$	6.0	—	70.8
$pe^{-}p$	1.4	0.014	0.2	3.0
^{7}Be	0.38, 0.86	0.49	1.2	35.9
^{8}B	< 15	0.00057	6.2	13.8
^{3}He p	$\leqslant 18.77$	$1.2.10^{-7}$	0.005	0.01
^{13}N	$\leqslant 1.20$	0.049	0.1	3.0
^{15}O	$\leqslant 1.73$	0.043	0.3	5.0
^{17}F	$\leqslant 1.74$	0.00054	0.004	0.06
total		6.60	8.0	132

Two independent groups, SAGE (Abazov *et al.* 1991) and GALLEX (Anselmann *et al.* 1992*a*) have recently published first results from a new radiochemical solar neutrino detector which in principle is capable of observing the pp neutrinos. In the present paper we report experimental details and updated results from GALLEX (Anselmann *et al.* 1993).

2. Outline of the experiment

The gallium detector is based upon the neutrino capture reaction ^{71}Ga(ν_e, e^-)^{71}Ge. The energy threshold (233.2 ± 0.5 keV) is well below the maximum energy of the pp neutrinos (420 keV). ^{71}Ge decays back to ^{71}Ga by electron capture with a half-life of 11.43 ± 0.03 d.

Table 1 lists the neutrino fluxes for the different solar neutrino sources according to the SSM (Bahcall & Pinsonneault 1992) along with the corresponding capture rates for the Cl and Ga detectors. The total rate of 132 SNU for the gallium detector is dominated by 74 SNU from the pp and $pe^{-}p$ neutrinos resulting from the basic fusion reaction in the pp chain (see table 1).

The experimental procedure for GALLEX is as follows: 30.3 t of gallium in the form of a concentrated $GaCl_3$–HCl solution are exposed to solar neutrinos. In the $GaCl_3$–HCl solution, the neutrino induced ^{71}Ge atoms (as well as the inactive Ge carrier atoms added to the solution at the beginning of a run) form the volatile compound $GeCl_4$, which at the end of an exposure is swept out of the solution by means of a gas stream (nitrogen). The nitrogen is then passed through a gas scrubber where the $GeCl_4$ is absorbed in water. The $GeCl_4$ is finally converted to GeH_4, which together with xenon is introduced into a proportional counter to determine the number of ^{71}Ge atoms by observing their radioactive decay.

3. Gran Sasso underground laboratory

The most important side reaction for ^{71}Ge production in $GaCl_3$ solution by sources other than solar neutrinos is the ^{71}Ga(p, n) reaction (threshold energy 1.02 MeV), the protons being generated in the $GaCl_3$ solution as secondaries from (α, p) and (n, p)

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reactions and from cosmic ray muon interactions. To keep the muon induced background low enough, GALLEX is installed in hall A of the Gran Sasso Underground Laboratory (LNGS). This underground facility, shielded by about 3300 m of water equivalent, has been built by the Italian INFN (Istituto Nazionale di Fisica Nucleare) in the middle of a high-way tunnel through the Abruzzi mountains, about 150 km east of Rome.

A determination of the ^{71}Ge production in a $GaCl_3$ solution at the CERN muon beam combined with the cosmic ray muon flux measured at the Gran Sasso underground site yields a production rate equivalent to 3.7 ± 1.1 SNU (Anselmann *et al.* 1992*a*). From the measured fast neutron flux at the GALLEX site a neutron induced background rate equivalent to 0.15 ± 0.10 SNU has been estimated (Anselmann *et al.* 1992*a*).

Within hall A, GALLEX is accommodated in two buildings. The GALLEX main building ($12 \times 10 \times 9$ m^3) houses the process tank containing the $GaCl_3$ solution, a spare tank (70 m^3 each) and the equipment for Ge extraction, the GeH_4 synthesis and the counter filling. ^{71}Ge counting is performed in the low-level counting laboratory ($10 \times 10 \times 6$ m^3).

4. Chemistry

(*a*) *Target solution*

The GALLEX target consists of 30.3 t gallium in the form of a concentrated $GaCl_3$–HCl solution (total mass 101 t). As mentioned above, the (α, p) side reaction puts severe constraints on the concentration of the α-emitting elements U, Th and Ra in the solution. The upper limits determined by neutron activation and radon counting (U $<$ 0.04 ppb, Th $<$ 0.04 ppb and ^{226}Ra $\leqslant$ 0.04 pCi kg^{-1}) yield an α-induced ^{71}Ge production rate less than the equivalent of 0.2 SNU (Anselmann *et al.* 1992*a*). For safety and redundancy reasons, GALLEX has two nearly identical target tanks (A and B). They are made from vinylester resin reinforced with glass fibre backing and have an inner teflon (PVDF) liner.

Until April 1992 the solar neutrino measurements were performed in the B tank (GALLEX-I). On 30 April 1992, the $GaCl_3$ solution was transferred to the A tank which is equipped with a central reentrant tube designed to hold a ^{51}Cr neutrino source (see §9). After various tests were performed, measurements of the solar neutrino flux were resumed in August 1992 (GALLEX-II).

(*b*) *Germanium extraction and conversion*

At the beginning of a new run (i.e. start of exposure) a carrier solution containing about 1 mg stable Ge carrier is added to the $GaCl_3$ solution. For this the non-radioactive isotopes ^{72}Ge, ^{74}Ge and ^{76}Ge are sequentially used to monitor carryover from one run to the next. After three or four weeks of exposure, desorption starts by purging the target solution with 1900 m^3 of nitrogen in 20 h. Because tank A is equipped with a more efficient sparger system, the desorption time there is reduced to 12 h. Germanium is removed from the solution as volatile germanium chloride ($GeCl_4$). The gas stream is passed through a system of water scrubbers where the $GeCl_4$ is absorbed. At the end of desorption all the germanium is contained in a volume of about 30 l in the first scrubber. A series of smaller columns serves to further concentrate the germanium in a volume of about 1 l of water.

The final concentration step is an extraction into CCl_4 and a back-extraction into 50 ml of tritium-free water. This step also serves to separate the germanium from any tritium in the tank or the absorber system, since tritium would contribute to the background in ^{71}Ge counting. The last part of the chemical procedure is the conversion of $GeCl_4$ to the gas GeH_4 by means of the reducing reagent sodium borohydride ($NaBH_4$). The GeH_4 is dried and purified by gas chromatography. Its volume is then measured in order to determine the overall yield of the chemical procedures. Finally, it is placed together with xenon into a miniaturized proportional counter. The volume ratio Xe:GeH_4 is 70:30, the total counting gas pressure is about 800 Torr.

The total chemical yield (i.e. the ratio of the Ge amount in the counter to the amount of Ge carrier added to the target solution at the beginning of the run) was on the average 85.6 % for the runs up to B34. Starting with B35, a slight modification of the absorber columns increased this average to 91.8 %. Due to the faster desorption in the A tank, total yields are now 95.9 % (average A59 to A70).

(c) *The ^{68}Ge problem*

Shortly before the target solution had been brought underground in June 1990, most of the cosmogenic ^{68}Ge ($T_{\frac{1}{2}} = 271$ d) had been extracted from the solution. This ^{68}Ge was produced mainly through the ^{69}Ga(p, 2n) reaction by cosmic ray secondary protons as long as the $GaCl_3$ solution was above ground. ^{68}Ge decays by electron capture, it thus contributes to the counting background above which the ^{71}Ge solar neutrino signal has to be observed and therefore increases the statistical error. After the transfer of the $GaCl_3$ solution into the B tank, the rest of this cosmogenic ^{68}Ge had to be removed. This, however, turned out to be more difficult than expected. It seemed that a small fraction (a few percent) was picked up by trace impurities (polysilic acids?) from which it was only slowly released. The problem was finally solved by heating the $GaCl_3$ solution to 42 °C over a period of six months. This lead to a rapid increase of the ^{68}Ge release. After cooling the solution down, the release rate was 3.6 ^{68}Ge atoms per day of exposure, a value which allowed the start of the solar neutrino measurements. In April 1992, after transfer to the A tank, the solution was heated again, to 46 °C. This led to a further reduction of the ^{68}Ge release rate (0.5 ^{68}Ge atoms/day at the beginning of run A59 (Anselmann *et al.* 1993)).

5. ^{71}Ge counting

(a) *Proportional counters*

The ^{71}Ge decay rates expected in GALLEX, even if the SSM signal were to be observed, would be below 1 per day. The measurement of such low decay rates is an extreme low-level task and can only be achieved with miniaturized proportional counters. ^{71}Ge decays by K (87.7 %), L (10.3 %), and M (2.0 %) electron capture. Neglecting the M events, the energy deposition from Auger electrons and X-rays emitted in the decay results in an energy spectrum with two peaks: an L peak at 1.2 keV and a K peak at 10.4 keV.

All provisions typical for low-level counting have to be applied in order to reach the extremely low background rates required: for the proportional counters itself this implies miniaturization and the use of ultrapure (with respect to radioactive contamination) materials. The counter body is made from Suprasil quartz. A special quartz blowing technique allows to standardize the counter dimensions. The cathode is either made from zone-refined iron (Fe counters) or machined from a single Si crystal (Si counters). The anode is a 13 μm tungsten wire. The active volume (volume inside the cathode) is typically 87 % of the total gas volume (*ca.* 1 cm^3). For further details of the GALLEX proportional counters see Wink *et al.* (1993).

(*b*) *Counter shield*

The counters are placed in a copper box containing the preamplifier. The boxes are inserted either in one of eight counting positions in the well of a NaI pair spectrometer ('active side') or in one out of 16 positions within a massive copper block ('passive side'). Both the NaI detector and the Cu block are installed inside a steel vessel filled with 8.6 t of low radioactivity lead. The shield can be opened by moving one of the two sliding end doors (3.0 tons of Pb each). Radon in the air surrounding the counters can produce background counts by γ and β radiation emitted in the decay of its daughter nuclides ^{214}Pb and ^{214}Bi. In order to keep this background contribution as low as possible, the shielding tank is air sealed by a glove box system installed around it. Counters are inserted into the shield or removed from it by means of an air lock. The radon content inside and outside the shield is continuously monitored by two Lucas chambers with 5 h integration time. While the radon content of the air outside the shield (depending on the venting situation in hall A) fluctuates between *ca.* 50 and 100 Bq m^{-3} (in extreme cases 1000 Bq m^{-3} was reached) the level inside the shield is usually $\leqslant 1$ Bq m^{-3}. From a calibration measurement we know that such a level amounts to (0.0015 ± 0.0005) counts per day in the counting windows (see below) on the active side. On the passive side the effect is 20 times lower (Anselmann *et al.* 1993). The counter shield together with the electronics is installed inside a Faraday cage.

(*c*) *Electronics*

The output pulses from the preamplifiers are fed into a wide-band low-noise amplifier (for pulse shape analysis) and into a shaping amplifier (for pulse height analysis). The output pulse from the first is routed through a fast self-switching multiplexer system to a fast transient digitizer (which records the first 200 ns of each preamplifier output pulse) and to two slow transient digitizers with different time bases. Also, all events from both halves of the NaI pair spectrometer which are within a preset coincidence time window with a proportional counter pulse are recorded. All modules are read out over a CAMAC bus which is linked via an optical fibre cable to a μVax II computer outside the Faraday cage.

(*d*) *Pulse shape analysis*

The remaining background in the ^{71}Ge energy windows is of the order of 1 count per week in the L peak and 1 count per three weeks in the K peak. To further reduce the background pulse shape analysis is used. In this way it is possible to discriminate between the fast rising pulses from point-like ^{71}Ge decays and the slower rising pulses from spatially extended tracks caused by higher energy electrons (β particles from the residual radioactivity in the counter materials or Compton electrons produced by external γ-rays). The rise-time selected in the data analysis to discriminate between fast and slow pulses is the time elapsing between 10 % and 70 % of the pulse height. The rise-time windows have been defined so that 97.7 % of all ^{71}Ge events in the L peak energy window are accepted by the rise-time cut. For the K peak, the corresponding fraction is 95 %.

The resulting average background levels are 0.04 cpd in the L peak and 0.02 cpd in the K peak window for counters operating at the passive side. At the active side,

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background rates are about a factor of two larger (after removal of counts in coincidence with a NaI event). This is caused by the potassium in the glass of the NaI photomultipliers.

(*e*) *Counter calibration*

To calibrate the energy and rise-time scale of the GALLEX counters, a ^{153}Gd–Ce X-ray source is used. The europium X rays following the electron capture decay of ^{153}Gd ($T_{\frac{1}{2}} = 242$ days) excite the characteristic K_{α} and K_{β} X-rays from a Cerium target. These are used to illuminate the entire proportional counter volume rather homogeneously leading (in addition to the photopeak from the 35 and 40 keV X-rays) to three peaks at energies 1.03, 5.09 and 9.75 keV which result from the escape of Xe X-rays.

Typical energy resolutions (FWHM) of the GALLEX counters are 43 % for the L peak and 26 % for the K peak. Average absolute counting efficiencies (including the rise-time cut) are 28.6 % in the L window and 33.9 % in the K window for the nine counters with Fe cathodes used in the GALLEX runs. The corresponding average value for the six counters with Si cathodes are 29.7 % (L) and 31.7 % (K) (Anselmann *et al.* 1993).

6. Data evaluation

The data body finally used for data analysis in GALLEX consists of a time sequence of counts with energy and rise-time information. From these the events due to ^{71}Ge decays have to be selected. For this, cuts have to be applied to the data to eliminate obvious background events. In addition, events caused by two low-level activities, ^{222}Rn plus daughter nuclides and ^{68}Ge (see §4*c*) have to be taken into account.

Since ^{71}Ge decays without accompanying γ-rays, all counts in coincidence with a NaI event are first removed (this cut applies only to runs counted on the active side). The next step is the removal of events due to the decay of ^{222}Rn ($T_{\frac{1}{2}} = 3.8$ days) and its daughter nuclides. On the average about three ^{222}Rn atoms end up in the counter. Therefore, all counts before (15 min) and after (3 h) an overflow count ($E \geqslant 16$ keV) are eliminated. This efficiently vetoes ^{222}Rn cascades where at least one of the two initial α-particles is seen within the active volume of the counter. In addition (starting with run B39) double pulses recognized in one of the slow transient digitizers as a ^{214}Bi–^{214}Po decay event lead to the elimination of all counts in the preceding 3 h. Both these cuts remove counts due to ^{222}Rn and its daughters with (91 ± 5) % efficiency (Anselmann *et al.* 1993).

Figure 1 displays the distribution of counts obtained after the above mentioned cuts in a rise-time versus energy plot. Data from all but two of the 15 solar neutrino runs performed in the B tank are combined in this plot (rise-time information was not available for the runs B41 and B42). Figure 1*a* shows those counts collected in the first mean life of ^{71}Ge (16.49 days) after start of counting. For comparison, figure 1*b* is for the same duration of counting, but extending backwards in time from the end of counting (more than half a year after start of counting). Solid circles represent those counts which are within the energy and rise-time window of the L or K peak as explained in §5*d*. The excess of counts in the windows at the beginning of counting is evident.

These window events are then taken as input for a maximum likelihood analysis. Using the time distribution of the counts, such an analysis separates the events into

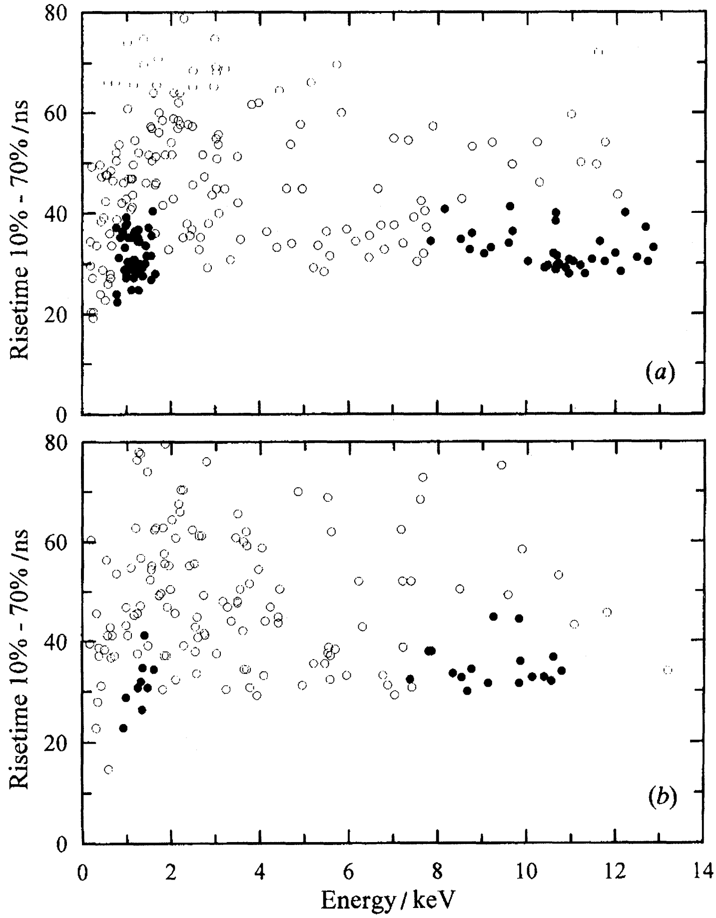

Figure 1. Rise-time versus energy plot for unvetoed events observed in all but two of the 15 solar B runs (GALLEX I). Part (*a*) is for the first 16.49 live days of counting (one ^{71}Ge mean life). Part (*b*) displays the last 16.49 days taken backwards from the end of counting. Solid dots denote counts which fall into either the L or K window, open circles are counts outside the windows.

a component decaying with the ^{71}Ge half-life and a time-independent background component. In addition, we include a small fixed component decaying with 271 days half-life to account for the residual ^{68}Ge (see §4*c*).

7. Results

The maximum likelihood analysis, taking into account the known exposure times, extraction yields, counting efficiencies and counting times of individual runs, yields a mean ^{71}Ge production rate of 88 ± 17 SNU for all 15 solar B runs. This value has to be corrected for non-solar contributions. In addition to the side reactions mentioned already in §§3 and 4*a* there are contributions which mimic ^{71}Ge decays: the inefficiency of the radon cut described in §6 (2.1 ± 1.0 SNU), fluctuations of the radon content inside the counter shield (0.3 ± 0.3 SNU), and ^{69}Ge produced by muons and solar ^{8}B neutrinos (1.0 ± 1.0 SNU). This yields a total of $7+7/-9$ SNU equivalent for the non-solar contributions (Anselmann *et al.* 1993). The error includes an additional contribution (± 4.3 SNU) coming from systematic errors in counting

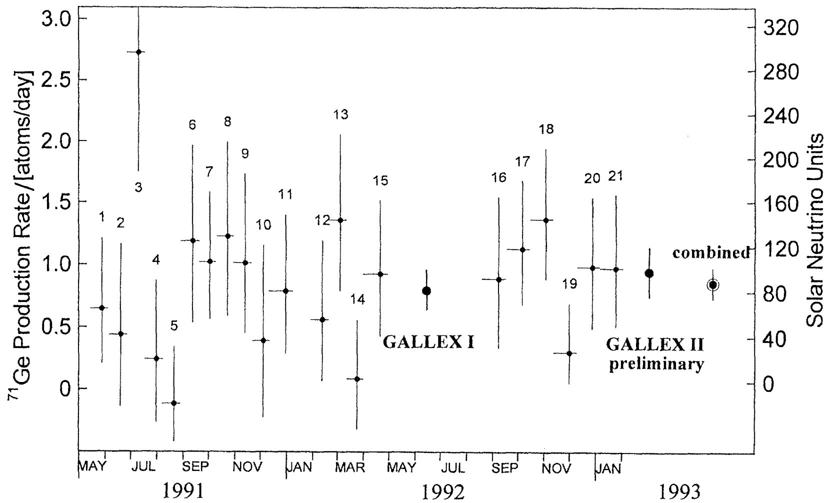

Figure 2. Final results for all solar B runs (1–15). The production rate is given in atoms per day (left-hand scale) and, after subtraction of the non-solar contributions, in Solar Neutrino Units (right-hand scale). Error bars are $\pm 1\sigma$. The point labelled 'GALLEX I' is the combined result for all B runs. Preliminary results for the first six A tank runs are also shown (16–21). Their combined value is denoted 'GALLEX II'. The data point labelled 'combined' is the global average for all 21 solar neutrino runs.

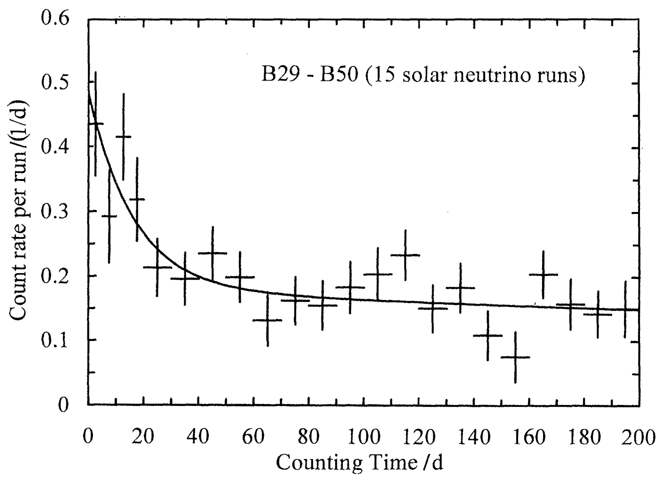

Figure 3. Measured count rate per run (corrected for dead time) versus the counting time for all 15 solar B runs of GALLEX. The solid line represents the output from the maximum likelihood analysis (see text).

efficiencies, chemical yield and target size. The resulting net ^{71}Ge production rate ascribed to solar neutrinos is thus 81 ± 17 (stat) ± 9 (syst) SNU. This final value differs only little from the previously published preliminary result (83 ± 21 SNU) (Anselmann *et al.* 1992*a*).

Figure 2 presents the results of all 15 solar B runs along with the combined value (denoted 'GALLEX I'). In figure 3, the measured count rate per run (corrected for dead time) averaged over the 15 solar B runs is plotted versus the counting time. The solid line is the output from the maximum likelihood analysis. As mentioned above, it has three components (^{71}Ge, ^{68}Ge and background). The decay of the ^{71}Ge component in the early time of counting is clearly visible. In order to provide a quantitative measure of the goodness of fit, a χ^2 value has been calculated for the 22 data bins plotted in figure 3. The outcome, 16.8, has been compared with a χ^2 distribution generated for our experimental conditions by means of a Monte Carlo simulation (Anselmann *et al.* 1993). The resulting confidence level corresponds to a 66% probability that a fit worse than the actual one is obtained.

At the end of April 1992 the $GaCl_3$ solution was transferred to the A tank (see §4*a*). Solar neutrino measurements were resumed in August 1992. Up to April 1993, nine solar neutrino runs were carried out in the A tank. Preliminary results of the first six of these are also reported here (Anselmann *et al.* 1993). Figure 2 shows the results (runs labelled 16–21). The combined value for these six runs is also plotted (denoted 'GALLEX II'). Its value is $97 \pm 23 \pm 7$ SNU. When combined with the data from the B tank exposures, the joint result (denoted 'combined' in figure 2) for all 21 runs is $87 \pm 14 \pm 7$ SNU (Anselmann *et al.* 1993).

Within GALLEX I (B tank), five blank runs (exposure times $\leqslant 1$ day) were performed. Until April 1993, nine additional blank runs were carried out in the A tank, six of which counted for a sufficient time to allow a preliminary analysis. Blank runs serve to identify or to exclude any contribution to the measured signal which does not depend on the exposure time. Combining all 11 blank runs yields a rate corresponding to (-4 ± 10) SNU (after the solar ^{71}Ge rate expected for a 1 day exposure is subtracted), a value which is fully consistent with zero.

8. Discussion

The GALLEX result is in contradiction to the published value of the SAGE Collaboration, $20 + 15/-20$ (stat) ± 32 (syst) SNU, which is based on five single runs (Abazov *et al.* 1991). In 1992 results from seven additional SAGE runs were reported (Gavrin 1992). The preliminary value from a combined analysis of all 12 runs is $58 \pm 20 \pm 14$ SNU. This implies that SAGE is now also seeing a signal from the Sun.

To compare the capabilities of both gallium detectors, the number of observable decays of solar neutrino induced ^{71}Ge per 85 SNU has been calculated for both experiments. This number is 11 for the five SAGE runs published in 1991 and 35 for all 12 SAGE runs reported so far. The corresponding number for the 21 GALLEX runs is 98. Because of the much better statistics, the GALLEX value is used in the subsequent discussion.

The most important conclusion to be inferred from the GALLEX result is the observation of the pp neutrinos (Anselmann *et al.* 1992*b*). There is no way of producing the observed signal without having a substantial contribution from the pp (and pep) neutrinos (see table 1). This holds for all plausible scenarios which are under discussion to explain the SNP. More than 50 years after Bethe (1939) suggested the proton–proton reaction as the starting reaction for hydrogen fusion into helium, its operation in the Sun has been experimentally verified. On the other hand, the gallium result confirms the solar neutrino deficit observed by the Chlorine and Kamiokande experiments.

Astrophysical solutions to the SNP (i.e. the construction of so-called 'non-standard solar models') have been proposed since the SNP was revealed. Most of these models have been tailored to reduce the solar central temperature and thus lower the ^{8}B and, to a smaller extent, the ^{7}Be neutrino flux (Bahcall 1989). For those non-standard solar models which predict a value close to the measured value for either the Chlorine or the Kamiokande detector, the corresponding expectation for the Gallium detectors is between 90 and 110 SNU (Hampel 1993), in full agreement with the measured GALLEX signal. The different reduction factors observed for the Chlorine and Kamiokande experiments, however, tend to exclude this solution to the SNP (Hampel 1993).

This leaves the other widely discussed solution to the SNP, matter enhanced neutrino oscillations (MSW effect), as the more likely candidate. If neutrinos do have a rest mass and if in neutrino interactions the different flavours are mixed (as in the case of weak interactions of quarks), then a certain fraction of the electron-type neutrinos (ν_e) produced in the solar core may be converted to muon- or tau-type neutrinos (ν_μ, ν_τ) during their passage through the solar matter (Bahcall 1989). Since the radiochemical Cl and Ga detectors are sensitive to ν_e only and since in the energy range which is relevant for the Kamiokande detector the cross section for ν_μ–e^- or ν_τ–e^- scattering is a factor of seven smaller than for ν_e–e^- scattering, neutrino oscillations would lead to a reduced signal for all three detectors. Also, because the extent of flavour conversion depends on neutrino energy, quite different suppression factors for the three experiments may result.

If the SSM is accepted as given and mixing is restricted to the two-neutrino case, then the expected suppression factors for all three experiments can be calculated as a function of two parameters, Δm^2 (the difference of the squared masses of the two mixing neutrino eigenstates) and $\sin^2 2\theta$ (where θ is the mixing angle). There remain only two small areas in the two-dimensional Δm^2–$\sin^2 2\theta$ parameter space in which the suppression factors for all three experiments are (at the 90% confidence level) in agreement with the observations (see fig. 2 in Anselmann *et al.* (1992*b*)). The updated GALLEX result does not significantly change the location of these allowed areas but it slightly reduces their size due to the reduced experimental error.

9. Future plans

There are two main goals for the future of GALLEX. The first is to reduce the statistical and systematic uncertainties of the GALLEX result. We intend to continue the experiment until a minimum of four years of solar neutrino observation is reached. This would reduce the final statistical error to about ± 9 SNU.

The second goal is to perform an experiment with an artificial ^{51}Cr neutrino source in the summer of 1994. This will provide the most direct integral test of the whole experimental procedure. ^{51}Cr decays by electron capture (half-life 27.7 days) and emits monoenergetic neutrinos with energies of 746 keV (81%), 751 keV (9%), 426 keV (9%) and 431 keV (1%). The ^{51}Cr will be produced by neutron activation of chromium metal isotopically enriched to 38% in ^{50}Cr (natural isotopic abundance 4.35%). The expected initial activity of the source is 1.9 MCi (or 70 PBq), this would allow us to measure the source signal to about 10% accuracy (Anselmann *et al.* 1993).

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Discussion

D. W. Sciama (*SISSA*, *Italy*). One of the conceivable solutions of the solar neutrino problem is related to the possible existence of magnetic or transition magnetic moments of neutrinos. Recently, Akhmedov, Lanza & Petcov (*Phys. Lett*. B **303**, 85, 1993) have studied the implications of the recent results of SAGE and GALLEX experiments for the solution of the solar neutrino problem in the framework of the resonant neutrino spin-flavour precession scenario. If the magnetic moments are large enough, a significant fraction of left-handed ν_e can precess into right-handed neutrinos or anti-neutrinos of the same or different flavour in the strong toroidal magnetic field of the convective zone of the Sun. The resulting neutrinos are sterile or almost sterile for currently operating neutrino detectors.

Neutrino spin precession and resonant spin-flavour precession can account for both the observed deficiency of solar neutrinos as compared to the predictions of the standard solar model and the suggested time variation of the solar neutrino flux in anti-correlation with solar activity for which there is some evidence in the chlorine experiment. This follows from the strong field-strength dependence of the precession efficiency and the fact that the toroidal magnetic field of the Sun is strongest at maxima of solar activity.

Another important result of this paper is that time dependence of the detection rates turns out to be very sensitive to the magnetic field profile which can make it possible to discriminate between various magnetic field configurations and to obtain information about the magnetic field in the solar interior.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES